IntechOpen

Sustainable Buildings

Interaction Between a Holistic Conceptual Act and Materials Properties

Edited by Amjad Almusaed and Asaad Almssad

SUSTAINABLE BUILDINGS - INTERACTION BETWEEN A HOLISTIC CONCEPTUAL ACT AND MATERIALS PROPERTIES

Edited by **Amjad Almusaed**
and **Asaad Almssad**

Sustainable Buildings - Interaction Between a Holistic Conceptual Act and Materials Properties
http://dx.doi.org/10.5772/intechopen.69917
Edited by Amjad Almusaed and Asaad Almssad

Contributors

Enes Yasa, Lianzhong Li, David Sanz, Ismael Sevilla, Francisco Javier Castilla, Jose Luis Serrano, Juan F. Rodriguez, Manuel Carmona Franco, Arzuhan Burcu Gültekin, P.L. Ng, Žymantas Rudžionis, Ivan Y.T. Ng, Albert K.H. Kwan, Amjad Zaki Almusaed, Esin Kasapoglu, Salih Taner Yildirim

Notice

First published in London, United Kingdom, 2018 by IntechOpen
eBook (PDF) Published by IntechOpen, 2019
IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, The Shard, 25th floor, 32 London Bridge Street
London, SE19SG – United Kingdom
Printed in Croatia

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Additional hard and PDF copies can be obtained from orders@intechopen.com

Sustainable Buildings - Interaction Between a Holistic Conceptual Act and Materials Properties
Edited by Amjad Almusaed and Asaad Almssad

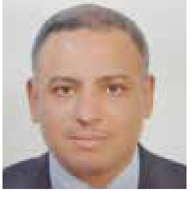
p. cm.

Print ISBN 978-1-78923-402-2

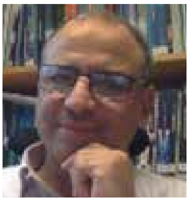
Online ISBN 978-1-78923-403-9

eBook (PDF) ISBN 978-1-83881-441-0

Meet the editors



Dr. Amjad Almusaed was born on January 15, 1967. He holds a PhD degree in Architecture (Environmental Design) from "Ion Mincu" University, Bucharest, Romania. He followed it with a postdoctoral research in 2004 on the Sustainable and Bioclimatic Houses, from the School of Architecture in Aarhus, . Dr. Almusaed has more than 28 years of experience in sustainability in architecture and landscape with innovative orientation. He has carried out a great deal of research and technical survey work and has performed several studies, in the area mentioned above. He is an active member in many international architectural associations. He published and edited many papers, articles, researches, and books, in different languages.



Asaad Almssad has more than 28 years of experience both in the industry as well as in teaching and research, inter alia, Umeå University, Karlstad University, and others, both European and non-European institutions. His research focuses on building structures, materials, sustainable building, and energy efficiency in building systems. His viewpoint of the building and its components is that the orientation of new researchers tends to move the human actions under building roof toward the energy efficiency and healthy living spaces. He has authored and coauthored more than 30 research papers and many books. Now, he is employed as a docent at Karlstad University, Karlstad, Sweden.

Contents

Preface

No society can exist without a healthy, natural base; hence, environmental awareness and efficiency are crucial. However, the ultimate goal of sustainability is not just healthy ecosystems but healthy community. In our age, a building is not complete and is certainly not a good building if it is not reasonably sustainable. So the goal of sustainability has far-reaching effects on architecture. The first step to create a sustainable building in collaboration with the employment of a sustainable building material is to deal with the one and other, with local building built of suitable building materials, by creating shelters and living space in different climates and regions, in the desert, on seashores, in the mountains, on the plains and on hillsides, and in the natural jungles and those of the megacities, where people of different ages and cultures understand the world differently. In our age, the environmental imperative is recognized by and unites all cultures. Though it is not easy to define, sustainability in building a domain, as understood today, always has three basic dimensions: ecological-bioclimatic, economic, and social. Sustainable building means sound and environmentally friendly construction combined into a whole for resistance, the environment, and health. Sustainable building requires perspectives from several different directions and to think in systems solutions. In particular, the environmental work is not seen as separate activities from other operations. Key areas to consider are sound, light, and aesthetics as a sustainable building is expected to be at least 100 years. Energy is another important area to consider, to reduce carbon emissions. Choice of construction materials and practices is important, among other things, to avoid creating a sick building and thereby protect the individual and avoid occupational health. A sustainable building context embodies not only that of nature but also of us. Our present technologies, artificial environs, are counter to nature. Our encumbering impact upon and mutilation and defilement of nature's ecosystems have been an affair of unconstrained and rapid attrition. The exponential demand for energy, the rate of technological obsolescence, pyramiding waste, lavish expectation, the rate of social change, new paradigms of energy-intensive industry and business, invasion of computers, and adroit marketing leave their critical impact upon our society. As the structure of society changes, so does architecture. Consequently, architecture has to serve the daily life and the needs of society, through the architectural functional spaces, in which it must cover all the needs of lodger starting by functioning through the material to the spiritual need satisfaction, suitable to the real way of life. The art of building environmental engineering is providing a balanced quality of environment at minimum total costs and with the minimum use of fossil fuels for providing energy. To achieve a positive environment, it is necessary to understand what environment is, how it affects people, how properties interact, and then how the ideals may be obtained in practice on an economic basis. Human quality refers to a broad perspective on human health and quality of life. It is also called social quality. This aspect ensures that you consider health, comfort, and a good indoor climate in the building.

Like security, security and the widest possible accessibility for all. The sustainable building must be capable of constant adjustment. Dependent as the building is on utilizing climate, it must also accommodate the climate's capriciousness. Like all buildings, it must meet the fluctuating demands of its occupants and, to a greater or lesser extent, the needs of the future. The sustainable building must be sustainable in the following respects:

- Sustainable buildings should be environmentally friendly to conserve the Earth's resources and healthy in order to contribute to the good health of the users.
- Sustainable buildings must be aesthetically pleasing and functional for creating job satisfaction for the users and the environment.
- Sustainable buildings and the materials shall be resistant to keep for at least 100 years.
- A sustainable building should strive for such a low life-cycle cost as possible in order to promote a sound economy for all parties.

The book reports on guidelines dealing with the most suitable actions for sustainable building concept in building branches, according to a novel alignment. The attention is concentrated on the interface among building creation concept and sustainable systems required, selecting competent building materials that have to be considered judiciously, to find the most suitable answers for healthy building with reducing the level of using energy to be efficient.

The book intended to be produced according to the chapter's orientation and include besides book requirement. The book is divided into four sections and eight chapters as follows:

Part I "Introduction into Target Theme" includes a chapter with the title "Introductory Chapter: Overview of a Competent Sustainable Building." It makes an overview of the meaning and the target of sustainable building and sustainable building material.

In Part II "Sustainable Building Design, Process, and Management," many forms and the concept of sustainable building are discussed. The section is divided into three chapters; the first is "A Holistic Conceptual Scheme for Sustainable Building Design in the Context of Environmental, Economic, and Social Dimensions" where the concept of holistic upon a sustainable building design represents an essential tool toward optimization of the design process, which appears as an objective reply to the negative effect of the environment. The second chapter is "Risk Management in Construction." This chapter discusses the idea where a real and objective process in the sustainable building process requires a well-structured resources management, where the process of construction in building science takes not only a long time to realize a product, but also it has to be coordinated on the site; consequently, it requires different schedules, programs, and temporary solutions for each project. The third chapter is with the title of "Optimization of Design for the Voids of Building Facades in View of Wind Condition" where building design and optimization of building design are important tools of sustainable building concept, where the bioclimatic design concepts and climatic elements such as air and ventilation systems can be employed optimally in building design, courtyard, and gap area rates, and energy efficiency has to take in evidence in the design process.

Part III "Energy Efficiency upon Sustainable Building Design" includes one chapter "Advanced Control Strategies with Simulations for a Typical District Heating System to Approaching Energy Efficiency Buildings." The chapter discusses the idea where building design process in the last years takes a new orientation to build more economic buildings. Energy efficiency is the most important subject of the economy and environment factor of sustainability, where thermal comfort, energy consumption, and indoor air temperature control.

Part IV "Sustainability in Building Materials Proprieties: Study Cases" contains three chapters; the first "Development of Sustainable High-Strength Self-Consolidating Concrete with Fly Ash, Shale Ash, and Micro-silica" discusses the development of a special building material such as concrete that can ensue by combination of concrete proprieties by adding fly ash, shale ash, and microsilica in building materials. The second "Research on Strength, Alkali-Silica Reaction, and Abrasion Resistance of Concrete with Cathode Ray Tube Glass Sand" explains the importance of understanding that in the process of creating sustainable building materials, it can be useful and objective to use different building systems and materials, which require being durable and mechanical. Concrete is one of the most utilized building materials enhancement of this product, where the use of CRTS can improve successfully the specific properties of concrete according to the fraction of glass aggregate; a special adding of chemical substances in concrete can give better results in terms of mechanical properties and other proprieties. The third chapter "Thermoregulation Microcapsules for Indoor Walls" discusses thermal properties that represent an important characteristic in the selecting process of a sustainable material, where energy efficiency, by using software, is a fundamental tool for designing buildings with almost zero energy consumption and is the main target of sustainable building.

This book is a scientific product that can be useful for architects, engineers, and specialists in building branch and for all who had an interest in sustainable building, where sustainability in building conception and selection of sustainable building materials will be energetic elements of this research book. Finally, we would like to express our sincere sense of appreciation and thankfulness to all the authors for their valuable contributions. Finally, we are very grateful to Mr. Edi Lipović Author Service Manager, for his positive managing and coordination to convert the proposed book project into this objective book with such care.

Amjad Almusaed
Basra University, Archcrea Institute
Iraq and Denmark

Asaad Almssad
Karlstad University
Sweden

Section 1

Introduction to the Target Theme

Chapter 1

Introductory Chapter: Overview of a Competent Sustainable Building

Amjad Almusaed and Asaad Almssad

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.77176

1. Introduction

Between the human being and the protective building space, always a relationship with a reciprocal character a permanent arrangement, where the human being interest is to create the necessary poise to his different well-unfolded activities, under that cover as space. The building is a major element of human life. It is a major concern, a major purchase, and has a major effect upon our lives [1]. We spend over 90% of our time indoors. Today, the technological archetypes of the modern buildings are formed of a mixture of many components such as materials, energy, and construction configuration systems, which influence directly on human life and health. In marketing vision, architectural product being creations of the human work, a time-consuming good, as any other manufacture, it has not only to be produced but also to get the user's disposal [2]. Although in sustainable design, the building becomes the system, subsystem should be examined. The climate has a solid impact on the conceptions of habitat forms and configuration of internal space [3]. While the holistic integration of systems is critical to sustainable building, every system within the system has its climatic advantage or disadvantage. The human being entered the third millennium without the hope of achieving permanent peace on our beautiful earth, sustainable development, and equality for all, where the earth is our sustainer, the chain of ecological survival. In the future, sustainable considerations will be a regular part of our basic beliefs and knowledge. Both of our norms and behavior as the physical environment must be automatically based on an environmentally balanced mind-set, not alone but along with many other considerations. Within planning, means that the green will be taken far to be more seriously that reuse of our cities will gain even more importance that green areas will be actively involved and that traffic patterns will be turned upside down. Reliability is the key to our human continuum and our prime resource for building. Earth sheltering, earth handling, and earth escaping are more clearly pronounced in the vocabulary of architectural planning and design. Trees for shade and windbreak can bear a consideration in architecture and landscaping. But general landscaping is regarded apart from the architecture, whereas in intelligent bioclimatic design, it is most effectual as an integral part of the architecture and interresponsive with its inland farming and landscaping. The building experience managed to isolate the building from the unfavorable climatic conditions, determining an inside microclimate able to provide for physical comfort. At lower latitudes, the climate moderates and summer heat, as well as rain, becomes significant. Windows are designed to admit the winter sunshine while excluding it in the summer. Insulation is used to minimize heat loss, and ventilation helps to counteract heat gain. Sustainability is an overall vision of creating quality in all parts of the building by making a whole positive in building manipulation, where an appropriate balance must be ensured between the environmental, social, and economic considerations, but also with the context in which the building is part—the city and society. In other words, the overall construction industry faces a significant transformation. A change that really matters to the development community, that keeping in mind that ecology means the doctrine of keeping communities, so take care of things. Sustainability is not mysterious, but requires common sense, consideration, and action. It became clear to understand that sustainable building is a designation of the edifice that meets UN criteria for sustainability [4]. A sustainable city is organized so as to enable all its citizens to meet their own needs and to enhance their well-being without damaging the natural world or endangering the living conditions of other people, now or in the future [5]. The concept of "sustainable building" comes from the concept of "sustainable development." It was coined in the Brundtland Commission's report after the first green conference in the UN's Director had taken place in Stockholm 1972. The main task, of sustainability in building design, is to a great extent reduce the energy consumption of other buildings and other environmental loads, which has also been the cause of the authorities since the oil crisis in 1973. Since the oil crisis, there are still tightening rules for building energy consumption through the building regulations; but new rules in building regulations only apply to the new construction, which is limited in number to the total building stock. Therefore, in the case of renovations and extensions to existing buildings, it is up to the homeowner to take into account the environment. Sustainability in building sector means that account should be taken of the construction on the environment, both in the long term and in the short term. In addition, through all phases of a construction process, from the production of building materials until it returns as waste. But also the environmental burden that settlement means in the form of property, where building sustainable is to build for the future. In this concept, it is necessary to meet our generation's needs without destroying the ability of future generations to meet their own necessities. That is, a building is sustainable in both environmental, economic, and social terms. In other words, it means that a building is responsible for the environment as little as possible, that the building's overall economy from construction to demolition is as good as possible and that construction is as good as possible for people to live. In pursuit of sustainable solutions, there are many examples of choices and solutions that can immediately be sustainable, but which cannot be considered sustainable in the full perspective. For example, a unilateral focus on energy savings without regard to the indoor climate can result in imbalances between environmental and social quality, thus resulting in a nonsustainable solution. Another example is an unqualified requirement to use locally produced materials to minimize transport without looking at the energy used for the production of the materials.

There has been a tendency for sustainability in construction to be perceived and introduced as single measures that can make the building sustainable. However, sustainable construction implies that planning and decision-making are based on an overall perspective, which cannot be ensured by individual measures. Low-energy buildings, environmentally friendly construction, green construction, and sustainable construction—are these all the same concepts? The answer is no—although they all aim to reduce energy consumption and to some extent limit environmental impact, sustainability differs significantly from the others [6]. The basic quality requirements for buildings will be expanded to include low resource consumption, recycling building materials, etc. In the sustainable building, planning and decision-making must be based on an overall perspective, which aims not only at low energy consumption, a good economy, or a good indoor climate. Instead, it should be said that the construction as a whole is sustainable and contributes to solving the environmental and societal challenges that we face. Environmental quality in the building comprises:

- Minimizing local, regional, and global environmental impacts as well as consumption of energy, resources, and water throughout the life cycle of the building.
- The building's resource utilization is optimized to minimize the formation of building materials and optimize recycling and recycling in all phases of the construction.
- Efficient land use and conservation or improvement of the area's biodiversity.

Sustainability is an overall vision of creating quality in all parts of the building and creating a whole, both in the building itself, where an appropriate balance must be ensured between environmental, social, and economic considerations, but also with the context in which the building is part of the city and society. In the face of sustainable solutions, there are many examples of choices and solutions that can immediately be sustainable, but which, in the clearest sense, cannot be regarded as sustainable. In another view, troglodyte architecturally sculpted out of the hillside landscapes of Morocco, the igloo of the Eskimos, Arabian courtyard houses, the Malaysian tree dwelling and even the Scandinavian thatched cottage. All these have features that aim at orientates, to shape buildings and to construct them from materials so that the protected space can sustain the hot or cold rigorous of the regional climate. The value of vernacular architectural spaces was not generally recognized until Violet le Due wrote his book [2]. Environmental quality for a building can be achieved by reducing the discharge of problematic problems associated with construction and optimizing resource utilization. There must be a focus on this in all building life cycle phases. Under the environmental quality, the focus is on designing a building that includes both low resource consumption and the choice of environmentally sound materials. Sustainable buildings avoid as far as possible the use of problematic environments that can harm both the environment and health [7]. The land area used for construction is also considered an important resource that should be used with care and as efficiently as possible. Here, the focus should be on whether the environment's environment can be improved, biodiversity maintained or increased and how the water development is best organized. The environmental aspect of sustainability has traditionally been added to the highest value. In addition, in many cases, both builders and advisers have been equated with low-energy buildings and environmentally friendly construction. The vision of the sustainable building is a form of space that is adapted to the place. It is powered by local renewable resources, uses renewable resources for heating and lighting, produces only waste that can be recycled on site, has a good indoor climate, can be demolished and recycled or transformed into nature, creating a good lifestyle and giving goodwill to its residents. Energy consumption in the drive contributes to a beneficial part of the environmental impact of a building and it is, therefore, relevant to focus on this, but environmental sustainability is broader than that and focuses on environmental impacts, use of problematic resources, and the use of resources as a whole [8]. For example, a unilateral focus on making a building self-sufficient with energy could result in both the economic investment and the resource consumption and environmental impacts, overall, exceeding the benefits of energy savings and thus the overall result cannot be termed sustainable. This may be the case, for example, if a building is insulated with such insulation that the energy consumption for the production of the last amount of insulation does not earn a living through savings on the building’s heat consumption.

2. Sustainability in the building field

2.1. The values of sustainable building elements

Sustainable building elements are those which express to value one type climate-cultural, and corresponding to specific functions. The forms of those building elements are much diversified, the ones being consecrated as symbols established, a long time ago, in many hundreds or [2, 11]. The vernacular architecture plays this role, as a source of valorous semiotics expresses. The architectural profession feels politically responsible and offers its co-operation in developing a sustainable policy for architecture to make the architecture of today, the cultural heritage of tomorrow. The direct environmental impact of building environment upon construction, maintenance, and operation as well as demolition/disposal is several and diverse. Buildings’ fixed installations with ventilation systems, appliances, pumps, TVs, lighting, computers, and a number of smaller appliances often use unnecessarily much electricity. The indoor climate is affected by many factors, including the use of problematic chemicals. These come from building materials and appliances and furniture, etc., and have a harmful as well as a detrimental effect on the external environment discharge of phthalates in the aquatic environment. The construction of a building and/or living in a building will always cause a strain on the surroundings. It is difficult to remove such strain: The ecological house is not found. But a house can always be made more organic and less environmentally harmful. The sustainable building is nothing absolute. It is, therefore, more correct to use the words more “or less extraordinary and good” or optional sustainability. Throughout the building’s value chain, it is necessary to work out from ambitious and long-term visions. Only in this way can we accelerate development and achieve the requirements. Employed on sustainability can be summarized in two basic paradigms that can give an overall understanding of the concept and are used as a common vision and set aside for specific projects. Sustainability in construction must be ensured by:

- Think in a long-term

Take advantage of a life cycle perspective and I will take it all building lifecycle—not just look at construction and use here and now.

- Think in a wide form

It takes in evidence using a holistic perspective and observes the building as a whole and as part of the larger context, it encompasses local, regional, and global consequences, not just the constructional. This means that the arrangement and planning of buildings and renovations must be considered broad and long term with a balance between the qualities. Carrying strain, where the rate must be in line with the entire value chain of the building, and sustainable solutions will benefit all players in shorter or longer terms. The following sections elaborate on the whole and life cycle, in addition, perspective, as well as the environmental, social, and economic quality of construction is being developed. Overall perspective—think wide. For example, a unilateral focus on energy savings without regard to the indoor climate can result in imbalances between environmental and social quality, thus resulting in a nonsustainable solution. Another example is the use of locally produced materials to minimize transport without looking at the energy used for the production of the materials. Sustainable building, building materials life cycle, after which participants have such knowledge of the societal interests and principles of sustainable construction that they can select materials and building processes in order to carry out energy-efficient and sustainable construction. Sustainability is often perceived as a loose and nonbinding term. The fact is, however, that sustainable building is well described in international standards.

2.2. The concepts and aspects of sustainable building

The sustainable building concept is to protect and minimize withdrawals from resources and ecosystems, long-term resource efficiency, low operating costs, healthier indoor environment, and the preservation of social and cultural values. The concept is very ambitious and is based on a holistic approach throughout the life cycle of the building, from raw material recovery over the use phase, to demolition, disposal, and recycling. On a building level, the assessment of sustainability is based on three aspects: environmental aspects, social aspects, and economic aspects. The sustainable building consists of environmental, social, and economic dimensions. In the sustainable building, these three dimensions are seen as basic qualities, which must be balanced against a life cycle perspective and for the construction as a whole. The three qualities, which together characterize a sustainable construction, cover a number of different factors that must be included in the planning of sustainable construction. However, it is planned and decided on an overall perspective, which cannot be ensured by a single action. In the sustainable building, planning and decision-making must be based on an overall perspective, which aims not only at low energy consumption, a good economy, or a good indoor climate, for example. Instead, it should be noted that construction as a whole is sustainable and contributes to solving the environmental and social challenges. Sustainable building is defined on the basis of three aspects: environment, human, and economic. In the sustainable construction, there must be a mutual balance.

2.2.1. Environmental aspect

The sun is the ultimate power source and it is made up of layers of hot gases. The sun's beneficence is most pervasive and obvious as a provider of warmth and light. Sun is the unique source of climate factors, which determines the architecture and building design. The evaluation of a number of climatic factors measured in the open field, such as solar radiation, temperature, and wind, forms a necessary, but insufficient part of this task. In the case of building information about the effect of a given temperature, the available solar radiation and wind are at least as important. Another problem is the difference in a climate that is difficult to quantify between weather stations and building location. A professional evaluation of the sustainable building meaning concludes that it represents a system which is based on human thermal comfort consideration. Accordingly, it is sufficient to distinguish four main climate types (cold, temperate, warm dry, and warm humid). To describe the climate in relation to energy use, it is necessary to work from quantifiable characteristics, which most clearly relates to the heating or cooling requirements of a building. A regulate analysis of the connotation of the word "environment" in the sustainability domain explains clear circumstances of a being or thing (social, economic, and physical) [9]. A human being may be aware or unaware of environmental influences. The environment makes an objective relation between the occupants of the building and the environment. Vernacular architecture is highly responsive to its immediate environment because the owners and buildings understood their environment better than we do ours today. This is due to several differences in lifestyle. Today, we move building more frequently and few of us work out of doors. Thus, we do not understand from experience how much windier it can be in one part of a field than in another. Today, we must do more investigation of local microclimate using instruments to help us make such decisions. The building local microclimates play an important role in determining the energy requirements of a building. Both the summer ventilation and cooling loads and the winter heating load can be reduced by well-considered local microclimate use. Close observation is required to highlight the preferred areas on a site. Existing vegetation, geology, and topography all play a part in creating a unique microclimate for every site. There are analytical tools available for simulating the wind flow patterns around buildings, trees, and landforms and for an onsite investigation of microclimate. Energy saving is an essential factor to reduce the emission of carbon dioxide, which is a cause of global warming, and ventilation is only a unique method to control the indoor air quality and also regarded as an effective method to sweep out the indoor [10]. In contemporary terminology, traditional, architecture, in the climatic zones with excessive temperatures in particular—may be called "architecture aware" of energy, "environment adapted" or "architecture bioclimatic," where conventional energy abounds, architecture is seeking its usual balance ever, mainly determined by the environmental condition. Environmental quality has an impact on nature, environment, climate, and the planet's resources. In a natural lighting study, for example, the diminishing of energy uses in buildings and progression of consumer physical comfort by means of practical daylighting strategies takes on more and more meaning and relevance [11]. Considering the environment, you minimize energy consumption, all resources and water consumption in the building's life cycle. One optimizes the utilization of the building, in order to minimize the construction waste and focus on recycling in all phases of the construction. At the same time, you minimize or completely avoid using harmful substances in the building. It is necessary to understand that the conservation of energy through better building shelter is logical, but is not a priority for either current or future building owners. This is primarily the result of economic consideration. For energy conservation to be elevated to the top of the national policy agenda, it needs to be demonstrated that it can lead to significant cost savings within a relatively short payback period without a reduction in the quality of the internal environment. Heat management of different building components is the most effective assess for energy efficiency [12]. The building as an expensive and long-term investment requires best environmental and energy efficiency practices. Architects and engineers from different backgrounds have shown that environmental action, economics, and building design are no contradiction. Thermal zoning is a vital consideration in recently designed environmental building. A thermal zone represents an enclosed space in which the air is free to flow around and whose thermal conditions are relatively consistent. In most cases, any interior space can be closed off with a door would be a separate zone [13]. The approach to the sustainable building will not only evaluate alternative construction materials, product life span, and energy efficiency, but also encourage the improvement of local microclimate quality, by design with regard to bioclimatic architectural principles.

2.2.2. *Economic aspect*

Economic quality means that there is a balance between total costs and the quality of the building. This aspect means, among other things, that there is a balance between the building's overall economy and the overall quality of the building, and that the buildings are effectively utilized. The price of any product "architectural or building material" does not have to reflect the product's quality. It is important for designers and architects to understand how a product's purchase price relates to its life cycle cost. It will be crucial for the activity of the opportunity to lower their administrative costs. A sustainable building requires that the developer gives priority to long-term solutions. The short-term interest is not compatible with sustainable building. The short-term thinking leads to building contractors and project designers are not interested in low operating and maintenance costs, except when it can be a positive factor for the boost in the sale of the property. Economic encouragements and motivation are necessary to achieve the long-term benefits of building sustainable, where short-term economic interests are often at odds with building sustainable. Short-sightedness creates problems and all parties eventually deplete economies. The daily debate is about the prices of building materials, has to be lower in order for it to be cheaper to produce, for example, housing. The reason for choosing the less resistant materials for new construction, renovation, or upgrading is that it is too expensive to choose higher quality options [14]. The development of "cheaper" building materials has in some cases pushed up construction materials and working methods that subsequently proved to have adverse effects for both health and environment. Economic sustainability focuses on optimizing the operation of a building and, in addition to focusing on operating costs, includes the possibility of higher rental rates, better rental opportunities, increased productivity of the building user, value stability, and better financing options. The economic method to achieve sustainability is to focus on the low life cycle costs for building materials and methods. With an example from practice, we want to show on a construction project that reached the low investment cost, despite the choice of quality materials, choices made on the basis of focusing on low life cycle costs. An effective tool to achieve a sustainable building is to let life control on investments. It has been shown that a favorable life cycle economy often goes hand in hand with a favorable life cycle assessment. A life cycle cost is the sum of the annual operating and maintenance costs and because the investment translated to today's costs. Calculation of life cycle cost is a method used to optimize an investment and to be able to assess the investment that provides the lowest total cost. The investment cost is normally 10–15% of a building's total life cycle cost, over a life span of 50 years. Thus, the choice of materials in the investment stage affects 85–90% of a building's total life cycle cost positively [15]. The better solution, the longer the life span and the cheaper it becomes in the long run. So it is in the early stages of the construction project as the building's continued cost development is determined. Products that last longer are often more expensive to buy, but they cost less to maintain compared to a product that is cheaper to buy. Environmental investments, for example, in the form of alternative technologies, may often take a back seat in favor of cheaper and more energy-intensive solutions. In a life cycle perspective, however, the investment cost of a building is small in relation to operational costs. By already selecting the system that has the lowest life cycle cost rather than the lowest investment cost comes more health and eco-efficient solutions to turn out profitable. Many experts believe that external economic incentives can act as motivators for project development institutions. The financial incentives and motivations we found and that we think are highly relevant in order to affect the construction industry in a sustainable and desirable direction are as follows:

- Life cycle costs that give economic optimization of the investment;
- A successful construction process in order to achieve better economy;
- Economic incentives, environmental classification of buildings and housing;
- Environmental solutions to win the competition and market share.

In order to create a stable economic activity, it is important to find win-win solutions where the environment, companies, and customers will be the winner. The daily debate boils down to the price of building materials, which has to be lower in order for it to be cheaper to produce, for example, housing. But the development of the "cheaper" building materials has in some cases pushed up construction materials and working methods that subsequently proved to have adverse effects on both health and environment. In order to achieve long-lasting buildings, it is important to take account of the product's life cycle costs for promoting long-term solutions. A sustainable building requires that the developer gives priority to long-term solutions.

In practice, the focus here is, for example, on using materials and constructions that facilitate cleaning or longer life before replacing. In addition, energy consumption also contributes to economic sustainability. Economic sustainability works with the concept of total economy, which looks at the overall economy for a lifetime of a construction rather than just looking at construction costs. In an attempt to reduce climate impact, there has been a great deal of focus on reducing the energy consumption of buildings (heat loss), but the climate change of material consumption alone has proved to be of significance of both new and renovated buildings, the closer they come to the new energy classes. In order to reduce the overall environmental impact of buildings, it is important that the materials be produced with low environmental costs, as it may be as important as heat loss. A good material choice has an immediate positive effect on the environment, while a reduced heat loss has an effect that differs throughout the life of the material. In addition to the actual CO_2 consumption, environmentally sound materials can typically be recycled, or composted to avoid landfill (accumulation) and save the environment for other types of pollutants [16]. Therefore, the purpose of this material is to describe some of the materials that stand out as sustainable. The text should preferably be read in conjunction with the section on sustainability to achieve a broader understanding of the meaning.

2.2.3. Social aspect

The shaping of a socially acceptable and individually satisfying environment demands participation with the people as well as with the environment. There are many examples around the world that reveal how people under given environmental, social, and technical limits have striven to create the most suitable living conditions in accordance with nature. Good purposeful design of anything has intended meaning which blends form, function, and human values. There is a coherent unity or wholeness, which is difficult to define except by a phrase like it feels just right. The designer and examples abound in architecture, science, engineering, and the arts have interpreted a series of needs and blended these into a whole. Environmental adequacy has three essential attributes, flexibility in environmental control, identification of need and economy of material, and manpower resources [2]. The alternative wants a dynamic and engaging society that creates social and health equity and justice. It is necessary to develop the best opportunities for creating an individual life as part of the community, and everyone should be able to contribute to the community. The direction of a generally sustainable society goes not only through an increased focus on material equality and social security, but also through human equality as well as the experience of contributing to society and being appreciated as an individual [17]. However, they also have many social challenges. It is as though they have stalled or even gone back in some basic areas. The alternative will, therefore, challenge the social policy agenda through brave experiments. We must focus on well-being and we must dare to invest in people. The alternative has three visions for social sustainability:

- Balance in everyday life;
- Investing in people;
- Everyone must be able to contribute to society.

Today, there are many people who, for various reasons, are marginalized in relation to human society. As an individual, it can be hard to see what to do for the conversion to ecological sustainability, but we become stronger through communities, and the conversion will necessarily be done locally. It is therefore important to recreate local communities and groups that can act together and boost the conversion. Neighborhoods, ecosystems, and associations are already well underway. There are examples of groups in the informal economy (civil society) that are important actors and should be supported and expanded with more local initiatives that can bring about change from below. In modern life, in many areas, humans have already built up a strong welfare society and a good starting point for the development of a socially sustainable society. The dimensions of social and cultural sustainability are therefore just as important. Traditional societies often had a holistic view of their place in the cosmos and their interventions in nature, and their architecture was well adapted to the local environment. However, their technology was often far from sustainable, in part, due to a lack of global awareness and scientific knowledge, which we have today. Their sociopolitical systems—tribal, feudal, dictatorships, and so on—were not always something to get very romantic about either. The modernist world replaced the goods of old with rationality and science. Modernism sought a new, universal vision, but in doing so discarded both tradition-based wisdom and design based on local context. In addition, the specialization of knowledge and functions led to disorientation and fragmentation of the world, both physically and spiritually. The intelligent bioclimatic vision combines global view and a local context and integrates the dimension of time into architecture so that the global and the local, both the past and the future become our informants in the act of architectural creation. Buildings are complex obstructions not only because they have irregular openings, but also because they are psychological as well as physical barriers. To convert our society to a sustainable society is not only a job for the experts but is based on everyone's dedication and daily involvement. To act in a new way.

3. Building materials and sustainability

The choice and use of building materials have an environmental impact. Production, transport, and use of building materials mean consumption of energy and raw materials as well as pollution of the environment. This section deals with a range of building materials, which, with today's knowledge, can be considered as being in favor of more environmentally friendly. Another object which signifies the main concern for architects and designers is the overall environmental impact of building materials that can only be determined when the material is viewed in correlation with the building in which they are used. Why consider new material choices and habits? The building materials "share of buildings" overall climate impact in a life cycle perspective shows that:

- The share of the building materials' segment on the climate impact is great and it is absolutely necessary to work with efforts to reduce greenhouse gas emissions.
- The share of the building materials' segment of the climate impact is increasing in relation to the decreasing energy consumption in the newer houses' operational phase. However, it does not mean that it cannot be deducted to reduce energy consumption in operation as the challenge in the low-emission society is to distribute energy resources differently than today, where buildings capture about 40% of total energy consumption.

3.1. Building materials selection

To build a sustainable building in general, and resistance in particular, requires having knowledge of building materials and construction chemicals, as there are many factors to take into account. The impact of building materials on the environment embodies the essential method implicitly significant in this research to effectively determine traditional building materials in the environment, in addition to comparative analysis [18]. In order to determine the optimal use of materials, it is necessary to look at the environmental impact of materials from beginning to end, making life cycle analyses of the materials in question. The requirements of selecting building materials can be described as environmentally friendly or ecological is a difficult matter. The selection can be done on comprehensive life cycle assessments that can show the overall environmental impact of a product but may also be commonplace. The pasta is that most materials selected according to reason and feelings will show compliance with life cycle analyses. For better selection of materials, the following are necessary to be taken into account:

1. Product life;
2. The environmental characteristics of the product (pollutants) and origin;
3. The ease of use of the product;
4. Possibilities for separating, repairing, replacing, and recycling the product after use;
5. Energy consumption in manufacturing, distribution, and use during the construction phase;
6. Indoor climate conditions.

By reviewing basic building materials for foundations, exterior walls, roof constructions, etc., it should be mentioned that not all of the building materials listed below are equally easy to find in the local construction market, but by virtue of this, in supplier registers, most building materials can be obtained and procured, some building materials from building to be demolished can be recycled, just requiring a lot of time and courage to acquire the right materials. You should also have the possibility of storage space for the materials until they are used. There are demolition companies that have large stocks; it should be possible to find good building materials. Recycling of building materials is in most cases sensible, including in many cases also the recycling of materials that would be unprofitable if they were new [19]. Some points to consider when choosing building materials can then be as follows:

1. Renewable materials are usually recommended.
2. Energy consumption for production of the material should be as reduced as possible. This is a very complex area and, therefore, very important.
3. Different sources have different quality and it is, therefore, important to take into account the energy quality used in the manufacture of materials.
4. Transport of materials requires high-energy consumption. What are the physical interventions in nature that must be done for building material production? How many emissions being released? Are synthetic and stable naturally occurring materials produced in the process? Unnatural and stable substances such as polychlorinated biphenyls and

brominated flame-retardants will not break down in nature and causes instead damage to humans, animals, and nature.

5. Health effects on humans. It is necessary to analyze the impact of building materials on the people's (physical, psychological, chemically and biologically), where it affects instantly on human life. Can the materials be repaired and what maintenance frequency do they have?
6. Can the materials be reused or otherwise recycled?

The selection of building materials and methods also affects greatly the ability to reuse building materials during the recycling process. It is important to stop the loop in order to achieve a whole when a broken cycle inevitably leads to imbalances in nature. Everything taken from the earth must be reversed to a cycle to be late. When there is talk about healthy and eco-friendly building, it is often unclear as to exactly what it is that makes a building to be referred to as healthy and environmentally friendly. The reason is that there are many different areas that must be taken into account as a whole and so far there are a few who look at it from a holistic perspective. Life cycle analysis is a method to determine the environmental impact of a product or service from cradle to grave. Life cycle analyses are resource and time consuming to produce and should be made by those who produce or import products. A life cycle analysis can many times give increased knowledge about the product and pave the way for new developments when the analysis provides a wealth of knowledge about production. The selection procedure is intimately linked with the choice of design and building method. The building control of both quantity and type of material, and it is the finished construction in its entirety that is decisive for the indoor climate and building sustainability. It is already in the planning and design stage as the future sustainability of buildings is determined. When comparing materials, the fairest comparison ways will be to take into account the entire life span of the materials. Concrete, for example, is a durable material with long life and low maintenance requirements. In addition, a building in concrete is more energy efficient than a building in wood or steel because of its tight construction and good heat storage capacity. This may result in lower energy consumption in the use phase, which in some cases is considered as the most significant phase of a building's life cycle [20].

3.2. Recycling model of building materials

Recycling of sustainable building materials is the area that first received attention in the field of the environment in the construction industry. Recycling and reusable building material can be done in four steps. The first step is that the buildings be designed and maintained in such a way that they can be used flexibly for a long time. The second step is to be designed so that they can be "picked apart" and the parts used again. Some important strategies for tackling the rock of construction waste are:

- Minimize the amount of waste by having a careful planning and design, use as few materials as possible;

- Use reusable materials and construction methods that allow for the dismantling of building components;
- Recycle building and demolition waste for maximum recovery.

In the new building, it can choose to reuse the old materials such as bricks and, usually, some of these phases involve physical changes to the property and its equipment, while others are more about what we can achieve by changing our thought patterns and habits.

Author details

Amjad Almusaed[1]* and Asaad Almssad[2]

*Address all correspondence to: a.amjad@archcrea-institute.org

1 Department of Architectural Engineering, Iraq and Archcrea Institute, Basra University, Denmark

2 Department of Engineering and Chemical Sciences, Construction Engineering Karlstad University, Sweden

References

[1] Vázquez M. Building and impact on the environment: The case of the earth and other materials (Construcción e impacto sobre el ambiente: el Caso de la tierra y otros materlales). Informes de la Construcción. 2001;**52**(471):29-43

[2] Almusaed A. Biophilic and Bioclimatic Architecture: Analytical Therapy for the Next Generation of Passive Sustainable Architecture. London, England: Springer-Verlag London; 2011. p. 233

[3] Almssad A, Almusaed A. Environmental reply to vernacular habitat conformation from a vast areas of Scandinavia, Renewable and Sustainable Energy Reviews. August 2015;**48**:825-834

[4] Janssen GMT, Hendriks CHF. Sustainable use of recycled materials in building construction. Advances in Building Technology. 2002;**II**:1399-1406

[5] Almusaed A, Almssad A. Urban Biophilic Theories upon Reconstructions Process for Basrah City in Iraq, Passive and Low Energy Architecture Conference. Ahmadabad, India: PLEA; 2014

[6] Dewlaney KS, Hallowell M. Prevention through design and construction safety management strategies for high-performance sustainable building construction. Construct Manage Econ. 2012;**30**(2):165-177

[7] Zimmermann M, Althaus HJ, Haas A. Benchmarks for sustainable construction– A contribution to develop a standard. Energy Build. 2005;**37**(11):1147-1157

[8] Zabalza I, Aranda A, Scarpellini S. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. Building and Environment. 2009;**44**:2510-2520

[9] Almusaed A. Grasses, Benefits, Diversities and Functional Roles. Rijeka, Croatia: InTech Open Publisher; 2017. p. 7. ISBN 978-953-51-3494-7

[10] Almusaed A, Almssad A. Effective Thermal Insulation, The Operative Process of an Efficient Passive Building Model. Rijeka, Croatia: InTech Open Publisher; 2013. p. 89

[11] Almusaed A, Almssad A. Efficient daylighting approach by means of light-shelve device adequate for habitat program in Aarhus City. International Journal of Smart Grid and Clean Energy. October 2014;**3**(4):441-453

[12] Almusaed A, Almssad A. Biophilic architecture, the concept of healthily sustainable architecture. In: The 23th Conference on Passive and Low Energy Architecture Conference. Geneva, Switzerland: PLEA; 2006

[13] Almusaed A, Almssad A. Environmental reply to vernacular habitat conformation from a vast areas of Scandinavia, Renewable and Sustainable Energy Reviews. August 2015;**4**:825-834

[14] Calkins M. Materials for Sustainable Sites: A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials. Hoboken, New Jersey: John Wiley; 2009

[15] Almusaed A, Intelligent Sustainable Strategies Upon Passive Bioclimatic Houses: From Basra (Iraq) to Skanderbeg (Denmark). Aarhus Denmark: Postdoc Research, Aarhus School of Architecture; 2004. p. 231

[16] Malmqvist T, Glaumann M, Scarpellini S, Zabalza I, Aranda A, Llera E, Díaz S. Life cycle assessment in buildings: The ENSLIC simplifed method and guidelines. Energy. 2011. p. 35

[17] Valdes-Vasquez R, Klotz LE. Social sustainability considerations during planning and design: A framework of processes for construction projects. Journal of Construction Engineering and Management. 2013;**139**(1):80-89

[18] Almssad AAA. Building materials in eco-energy houses from Iraq and Iran. Case Studies in Construction Materials. June 2015;**2**:42-54

[19] Thormark C. Recycling Potential and Design for Disassembly in Buildings. Lund, Sweden: Department of Construction and Architecture, Lund University; 2001

[20] Almssad A, Lindberg G. Betongkonstruktion. Lund: Studentlitteratur; 2015. p. 11

Section 2

Sustainable Building Design "Process and Management "

Chapter 2

A Holistic Conceptual Scheme for Sustainable Building Design in the Context of Environmental, Economic and Social Dimensions

Arzuhan Burcu Gültekin, Handan Yücel Yıldırım and
Harun Tanrıvermiş

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74031

Abstract

Sustainable building design concept, which has emerged in the construction sector in recent years, has appeared as a response to environmental pollution caused by the construction sector. In the context of sustainable building design, it is intended to create built environment sensitive to environmental, economic, and social problems. Within the scope of this study, sustainable building design is contextualized by a holistic conceptual scheme considering aspects, strategies, criteria, and procedures of creating an environmental, economic, and social awareness by taking into account how to design sustainable buildings. According to the suggested scheme, strategies of environmentally sustainable building design aspect are classified as site efficiency, water efficiency, energy efficiency, and material efficiency; strategies of economically sustainable building design aspect are classified as resource efficiency and cost efficiency; and strategies of socially sustainable building design are classified as health and well-being and public awareness. Furthermore, related criteria for each strategy and related procedures for each criterion are determined. This scheme is intended to indicate the responsibilities of the construction sector in the context of environmental, economic, and social sustainability and to guide the actors of the construction sector and the researchers in this sense.

Keywords: construction sector, sustainable building design, environmentally sustainable design, economically sustainable design, socially sustainable design

1. Introduction

Environmental pollution that occurred as a consequence of industrial development, population growth, and urbanization is one of the extremely important problems of our day. Seventeen percent of water sources, 25% of forestry products, and 40% of energy sources are consumed by the construction sector [1–3]. For this reason, sustainable building design concept has emerged in the construction sector in recent years. The aim of sustainable building design is to create a built environment that does not disrupt the ecological balance, minimizes the harmful impacts of buildings on the environment, uses resources economically, and provides the necessary conditions for human comfort and health [4]. In this context, sustainable building design can be examined under environmental, economic, and social aspects. The effective use of the site, water, energy, and materials should be taken into consideration during the building design process within the scope of environmentally sustainable building design. Economic constraints in the construction sector have to be determined by using resources effectively and performing cost-effective analyses in the context of economically sustainable building design. Besides, health and well-being of users ought to be enhanced, and public awareness should be provided in the sense of socially sustainable building design.

In accordance with the abovementioned issues, a holistic conceptual scheme is suggested by considering aspects, strategies, criteria, and procedures in this study. According to the suggested scheme, strategies of environmentally sustainable building design aspect are classified as site efficiency, water efficiency, energy efficiency, and material efficiency; strategies of economically sustainable building design aspect are classified as resource efficiency and cost efficiency, and strategies of socially sustainable building design are classified as health and well-being and public awareness. Furthermore, related criteria for each strategy and related procedures for each criterion are determined. By this means, it is intended to create awareness among the actors of the construction sector and the researchers in terms of sustainable building design in this study. Within the scope of this intention, the aim of this study is to present a guiding scheme by considering aspects, strategies, criteria, and procedures of creating an environmental, economic, and social awareness at the local and the global level.

2. Aspects of sustainable building design

Costs of energy and natural resources used by the buildings in the construction, usage, and demolition processes are remarkably high [5]. For a more habitable and economic future, sustainable building design procedures have been developed in the world which use land efficiently, use energy effectively, experience projects to reduce water consumption, and give importance to the material efficiency and indoor air quality considering the waste problem and environmental problems [6]. Sustainable building design offers minimum operational cost for the buildings by minimizing the energy consumption, resource usage, and environmental impacts of the buildings [7]. In this context, buildings are evaluated within the framework of international building certification systems that contribute to minimizing the environmental impacts of the buildings and lead the way to the designers, and they are certificated according to sustainability classifications. The most widely accepted and commonly used building certification systems in the world can be stated as Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED).

BREEAM is the first sustainability assessment method for master planning projects, infrastructure, and buildings. It addresses a number of lifecycle stages such as new construction, refurbishment, and in use. BREEAM guides designers, researchers, and related actors to excel, innovate, and make effective use of resources. According to the BREEAM system developed by the Building Research Establishment (BRE), buildings become entitled to obtain pass, good, very good, excellent, and outstanding certificates. Globally in 76 countries, there are 562,455 BREEAM certified developments and almost 2,266,120 buildings registered for assessment as of November 2017, since it was first launched in 1990 [8].

LEED is a system, which identifies buildings as healthier, more environmentalist, and more economical than traditional buildings, for certifying high-performance buildings and sustainable neighborhoods [9]. LEED provides a framework to create healthy, highly efficient, and cost-saving green buildings available for all building types. LEED reveals sustainable design, construction, and operating criteria in building and urban scale. According to the LEED system developed by the US Green Building Council (USGBC), buildings become entitled to obtain platinum, gold, silver, and certificated certificates. Globally in more than 165 countries and territories, more than 2.2 million square feet built-up area is LEED certified, with more than 90,000 projects using LEED as of November 2017, since it was first launched in 1998 [10].

It is often observed that only the environmental aspect of sustainability is directly taken into account when green building certification systems are examined. However, in the design of sustainable buildings, the economic aspect that produces a long-term positive economic impact and the social aspect that improves the lives of those with whom the buildings interact need to be absolutely included in the design [9]. In this study, aspects, strategies, criteria, and procedures of sustainable building design are classified considering the conceptual frameworks of different scientific studies [4, 6, 11–17] and the LEED [10] and BREEAM [8] evaluation criteria. This classification is presented in **Table 1**.

Sustainable building design aspects can be achieved by certain criteria and procedures in design, construction, usage, and demolition processes of buildings by meeting the strategies of site efficiency, water efficiency, energy efficiency, and material efficiency in terms of *environmentally sustainable building design*; the strategies of resource efficiency and cost efficiency in terms of *economically sustainable building design*; and the strategies of health and well-being and public awareness in terms of *socially sustainable building design*.

2.1. Environmental aspect of sustainable building design

Environmental sustainability means leaving the world's future generation something better than what has been left to, protecting environmental balance and natural systems from destruction [18]. Nowadays, as environmental problems become more and more significant,

Sustainable building design scheme			
Aspects	**Strategies**	**Criteria**	**Procedures**
Environmentally sustainable building design	Site efficiency	Protection of natural habitats	See **Table 2**
		Protection of natural topography	
		Protection of fertile lands	
		Improvement of urban areas	
		Improvement of transportation systems	
		Reduction of heat island effect	
	Water efficiency	Reduction of water consumption	See **Table 3**
		Reuse of waste water	
		Unpolluted use of water resources	
	Energy efficiency	The use of passive heating, ventilating, and air conditioning	See **Table 4**
		The use of active heating, ventilating, and air conditioning	
		Utilization of daylighting	
	Material efficiency	Reduction of environmental impacts	See **Table 5**
		Reduction of wastes	
		Proper sizing of building and systems	
Economically sustainable building design	Resource efficiency	Conservation of raw materials	See **Table 6**
		Reduction of the use of nonrenewable resources	
	Cost efficiency	Reduction of initial cost	See **Table 7**
		Reduction of operating cost	
		Reduction of recovery cost	
		Satisfaction of the construction sector actors	
Socially sustainable building design	Health and well-being	Creation of livable environments	See **Table 8**
		Creation of appropriate indoor comfort conditions	
	Public awareness	Educating the public	See **Table 9**
		Development of incentives and policies	

Table 1. A holistic conceptual scheme for sustainable building design.

there has been an inclination for an environmentally sustainable building design to reduce these problems. In order to ensure that the buildings have environmentally sustainable characteristics, procedures are adjusted based on the strategies of site, water, energy, and material efficiency. Demand for the site, water, energy, and material increases the impact

http://dx.doi.org/10.5772/intechopen.74031

of construction sector on the environment. The local and global environments are affected by interrelated user activities and natural processes throughout the existence of buildings, and buildings impose a long lasting impact on the environment [19, 20]. In this context, the construction sector is responsible for producing sustainable environments via designing sustainable buildings. Sustainable building design includes the building materials that are sensitive to the environment; that are reusable and renewable; that minimize energy consumption; that use renewable and local sources by reducing the use of natural resources; that create healthy indoor areas; that use solar power, natural ventilation, and daylighting; and that do not require frequent maintenance and repair [21]. The emphasis for buildings should be placed on effective usage of the site, water, energy, and material within the context of environmentally sustainable building design. In this context, environmentally sustainable building design strategies can be classified as *site efficiency*, *water efficiency*, *energy efficiency*, and *material efficiency*.

2.1.1. Criteria and procedures for strategy of site efficiency

Land, which is one of the limited sources, has been decreasing due to urban expansion. For this reason, it is essential that lands must be used efficiently. The strategy of site efficiency consists of sustainable land use, habitat protection, and improvement of long-term biodiversity for the building site and surrounding land. It addresses the environment surrounding the building and emphasizes the relationships among buildings and ecosystems. In this context, the criteria for the strategy of site efficiency are classified as *protection of natural habitats*, *protection of natural topography*, *protection of fertile lands*, *improvement of urban areas*, *improvement of transportation systems*, and *mitigation of heat island effect* in this study. Additionally, related procedures for each criterion are determined and presented in **Table 2**.

Protection of natural habitats: Soil erosion, groundwater contamination, acid rain, and other industrial pollutants are damaging the health of plant communities, thereby intensifying the challenge and necessity to restore habitats [16]. For this reason, in sustainable building design, solutions should be produced to preserve the existing natural resources, flora, and fauna, and measures must be taken to ensure that the wastes are disposed of without harming the natural habitat. It ought to be attempted to improve natural habitats through appropriate planting and water use and avoidance of chemicals as much as possible in the design of sustainable buildings. Local wildlife and vegetation should be recognized as part of the building site [19]. Furthermore, wetlands and other wildlife habitats may require protection and limit the buildable area of a site [22].

Protection of natural topography: Topography refers to the configuration of surface features of a plot of land, which influences where and how to build and develop a site. A building has to be constructed in compliance with topography, with minimum disturbance of existing land forms and natural drainage patterns while taking advantage of natural ground slopes and the microclimate of the site. In addition, the amount of cut and fill area required for construction of a foundation and site development should be equalized [22]. The existing contours of a site ought to be respected. Alteration of contours affects how wind moves through a site and how water drains [20]. The drainage of surface water and ground water must be taken into account when modifying land forms, and water table has to be preserved [22]. A building

Strategy of site efficiency	
Criteria	**Procedures**
Protection of natural habitats	Preservation of existing natural resources
	Preservation of existing flora and fauna
	Disposal of wastes without harming the habitat
Protection of natural topography	Construction of the building in compliance with topography
	Preservation of water table
	Disposal of wastes without harming the topography
Protection of fertile lands	Prevention of misuse of agricultural lands
	Reduction of erosion and industrial pollutants
	Disuse of toxic pesticides
	Improvement of agricultural lands lost due to misuse
	Prevention of agricultural lands from being made available as settlement
	Carrying off fertile lands of the construction site to green areas
	Disposal of wastes without causing land pollution
Improvement of urban areas	Selection of location according to urban density
	Increase in green areas
	Promotion of mixed-use urban development
	Effective use of construction sites
	Redevelopment of brownfields
	Reclamation of abandoned mine lands
	Rehabilitation of existing settlements and buildings
Improvement of transportation systems	Development of pedestrian/bicycle transportation systems
	Extension of public transport network
	Integration of building design with public transportation
	Development of public transportation from regional parking lots to city centers
	Improvement of rail transport systems in urban areas
	Provision of human-powered public transportation
	More common use of clean fuels in transportation
	More common use of vehicles with less fuel consumption
	More common use of smart traffic practices and systems
	Rise of efficiency standards in vehicles
	Creation of pedestrian ways, pockets, and lanes
	Creation of parking systems and local parking lots
Mitigation of heat island effect	Preservation of existing tree cover
	Increase of forest areas
	Selection of right vegetation for right places around buildings
	Integration of green areas in building design
	Application of green wall systems
	Application of green roof systems

Table 2. Criteria and procedures for strategy of site efficiency.

design should not need excavation below the water table and should not be constructed into the water table [19]. Moreover, it is essential that the wastes are being disposed of without harming the natural topography.

Protection of fertile lands: Fertile lands are the basis for agricultural production, and protection of fertile lands is an extremely important matter for the economy of all countries [23]. Twenty-five percent of fertile lands have been lost or degraded in the last 50 years. Fertile lands are limited because of soil, wind and water erosion, raw material extraction, groundwater contamination, water logging, acid rain, soil nutrient mining, industrial pollutants, and toxic pesticides [24]. It is a well-known fact that it takes a long time for the infertile lands to self-reclaim, and the costs of land reclamation are so high. For this reason, some solutions should be produced to prevent misuse of agricultural lands, and some precautions must be taken to improve agricultural land lost due to misuse [25]. Lands are important not only for the agricultural sector but also for the construction sector in building scale and urban scale. In urban areas, agricultural lands should be prevented from becoming available as settlements. However, if needed, fertile lands of the construction site ought to be carried to other green areas. Additionally, the wastes from the structure and infrastructure need to be removed from the land without causing pollution.

Improvement of urban areas: The spatial growth affects urban areas in terms of increased traffic, pollution, and energy consumption. Appropriate planning of urban areas can help to reduce urban sprawl, soil sealing, and biodiversity loss [26]. The scope of the planning is to locate the settlements and green areas according to urban density. These measures have to also promote mixed-use development (the mixing of residential, commercial, office, and retail spaces) that will reduce transport demand and in turn reduce pollution [27]. Moreover, appropriate planning decisions for construction sites can minimize invasion of heavy equipment and the accompanying ecosystem damage. Excavations in the construction site should not alter the flow of groundwater, and vegetation should only be removed when absolutely necessary for access [20]. It is also essential that lower environmental quality, idle or underutilized areas such as brownfields and abandoned mine lands, and empty buildings ought to be improved. Redevelopment and reclamation of these lands can provide a range of environmental, economic, and social benefits [28]. Furthermore, lands can be conserved by adopting a policy of zero expansion of existing urban areas. This could be achieved by adaptive the reuse of existing settlements and buildings, thereby eliminating the need for new construction [16].

Improvement of transportation systems: As the natural and economic resources are limited, sustainable development of the transportation systems in urban areas is extremely important in order to maintain future quality of life [29]. Transportation systems are an indispensable element of sustainable development due to the environmental, economic, and social impacts. Establishing a sustainable transportation system requires a comprehensive and integrated approach to policymaking and decision-making, with the aim of developing affordable, accessible, economically viable, low carbon, comfortable, people-oriented, and environment-friendly systems [30]. For all these elements to be achieved, it is necessary to integrate the procedures such as improving and expanding pedestrian and bicycle transportation systems, extending public transport network, integrating building design with public transportation, better connection with public transportation to city centers from regional parking lots, improving the attraction of public transportation [31], and enhancing rail transportation systems in urban areas. Besides these, human-powered public transportation systems, less fuel-consuming vehicles, clean fuels in transportation, smart traffic practices, and systems ought to be more widely used to reduce urban air pollution, to tackle climate change, and to contribute limiting the use of private cars. Efficiency standards for environmental performance of vehicles and comfort of users should be also improved [32], and technological solutions have to be developed aiming to reduce the negative impact per car and per kilometer [33]. Moreover, pedestrian zones and parking systems should be developed, and local parking lots ought to be increased in order to encourage nonmotorized modes, to limit the number of vehicles in the city centers, and to reduce the traffic congestion.

Reduction of heat island effect: Heat island is the most documented phenomenon of climate change [34]. A building's roof, façade, and site area influence the heat gain and retention of a building's surroundings [35] and can cause heat island effect. As a result of heat island effect, high temperatures occur in urban areas. High temperatures affect health, economy, leisure activities, and well-being of users and may also enhance air pollution, for example, by increasing surface ozone concentration with several negative impacts on human health [36]. In order to reduce heat island effect, existing tree cover should be preserved, and forest areas should be increased principally. Additionally, trees and plants help to cool the environment, making vegetation an effective way to reduce heat island effect. Planting right vegetation for right places around buildings can contribute to lower surface and air temperatures by providing shade and evapotranspiration [37]. Deciduous trees planted in the south of a building ensure solar heat gain in winter and shade in summer. Coniferous trees planted on the north protect the building from wind in winter and provide shade in summer. Integration of green areas in building design may, therefore, be essential for adaptation to and mitigation of thermal impacts of both local and global warming processes [36]. Another essential procedure for mitigation of heat island effect is greening roofs and walls combining nature and buildings. These systems can lower the surface temperatures of roofs and walls and thus can decrease the corresponding sensible heat flux to the atmosphere [34]. Greening walls with vegetation to intercept the radiation can reduce the warming up of walls, especially in dense urban areas. In the urban areas, the impact of evapotranspiration and shading of plants can significantly reduce the amount of heat that would be reradiated by walls [38].

2.1.2. Criteria and procedures for strategy of water efficiency

Water is probably the most important matter in the environment and humankind's life cycle. Protecting clean water resources has a vital importance [39]. The strategy of water efficiency consists of indoor use, outdoor use, specialized uses, and metering in the building site and surrounding land. It addresses all sources of water related to building and surroundings, including appliances, fixtures, fittings, process water, and irrigation. In this context, the criteria for the strategy of water efficiency are classified as *the reduction of water consumption*, *reuse of waste water*, and *unpolluted use of water resources* in this study. Additionally, related procedures for each criterion are determined and presented in **Table 3**.

Reduction of water consumption: Efficient water use is an environmental priority in all countries. Special attention must, therefore, be given to the reduction of water consumption in building

Strategy of water efficiency	
Criteria	**Procedures**
Reduction of water consumption	Use of waterless toilets and urinals
	Use of bio composting toilets
	Use of small volume cisterns
	Use of water-saving flushes
	Use of low-flow fixtures
	Use of timers and automatic control devices
	Use of indigenous landscaping
	Use of vegetation with less water need
	Use of low-maintenance vegetation
Reuse of waste water	Treatment and reuse of graywater
	Treatment and reuse of rainwater
Unpolluted use of water resources	Renovation of sewage systems to prevent contamination of water resources
	Control of polluting elements in sewage and storage areas
	Disposal of wastes without causing pollution in water resources
	Reduction of toxic pesticides
	Management of water resources systems

Table 3. Criteria and procedures for strategy of water efficiency.

design [40]. For this reason, losses through water installations and leakages ought to be minimized. Water-efficient devices such as waterless toilets and urinals, bio composting toilets, small volume cisterns, water-saving flushes, low-flow fixtures, timers, and automatic control devices should be utilized for indoor use. It should be noted that the use of these devices also contributes to the reduction of energy consumption, cost, and waste water. Apart from these, indigenous landscaping for outdoor building design has to be encouraged, which, once established, virtually eliminates the need for watering [41]. In the meanwhile, vegetation with less water and maintenance need to be planted for outdoor use.

Reuse of waste water: As the water resources are limited, providing water efficiency in the building and surroundings is vitally important. The efficient use of water may reduce input and output water resources. This is because the water that is supplied to a building and the water that leaves the building as waste water should be treated. Therefore, a reduction in water use produces a reduction in waste water [42]. Waste water in buildings can be classified as graywater and black water. Graywater means the low polluted wastewater from bathtubs, showers, hand-washing basins, and washing machines excluding wastewater from the kitchen and the toilet flushing system [43]. Graywater might be treated by installing graywater treatment systems in order to flush toilets and to irrigate vegetation except for edible plants. In addition, the reuse of graywater promotes a significant reduction in potable water consumption and sewage production [44]. Blackwater is any waste from toilets or urinals containing disease-causing bacteria and viruses that can result in human illness and must be discharged to the municipal sewage system. Rainwater might be seen as a resource that provides many environmental and economic benefits. Rainwater ought to be treated by installing rainwater treatment systems in order to restore natural hydrologic conditions, to reduce the possibility of flooding, and to irrigate vegetation [35].

Unpolluted use of water resources: As the world's population grows, ensuring reliable access to clean water is becoming increasingly difficult [45]. It is therefore that water resources must not be contaminated. In order to prevent contamination of water resources, existing sewage systems should be rehabilitated, and polluting elements in sewage and storage areas ought to be monitored. In the meantime, wastes have to be disposed without causing pollution, and measures must be taken to reduce toxic pesticides in water resources. In addition to all these, proper planning and managing have to be performed to increase benefits from the existing water resources.

2.1.3. Criteria and procedures for strategy of energy efficiency

Energy requirement increases approximately 5% every year mainly due to industrialization, rapidly growing population, and improvement in the living standards [3]. Ever-increasing consumption of fossil fuel reserves providing the major portion of the energy needs, directly or indirectly, gives rise to the ozone layer depletion, air pollution, and climatic change. In this respect, efficient utilization of energy has become more crucial than ever in construction sector [39, 46]. Strategy of energy efficiency consists of utilization of renewable energy resources for natural heating, ventilating, air conditioning, and illumination. It addresses the use of the passive and active systems in the building and surroundings. In this context, the criteria for the strategy of energy efficiency are classified as the *use of passive heating, ventilating, and air conditioning*; *the use of active heating, ventilating, and air conditioning*; and *utilization of daylight*. Additionally, related procedures for each criterion are determined and presented in **Table 4**.

The use of passive heating, ventilating, and air conditioning: Parts of the major energy consumption in buildings are the heating, ventilating, and air conditioning (HVAC) systems. These systems can be accepted as indoor climate controls that regulate humidity and temperature. With the total amount of HVAC's energy consumption in buildings, they are closely related to the local climatic condition, whether it is necessary to heat the space or cool it. Heating systems are to collect and to store the solar heat and to retain the heat within the building. On the contrary, cooling systems are to provide cold or to protect the building from direct solar radiation and to improve air ventilation. Space heating is the most important building energy user in cold countries, whereas air conditioning is a major contributor to peak electricity demand in hot climate countries or during summer [47]. In this regard, Trombe walls, metal walls, double-skin façades, greenhouses, Venturi chimneys, wind scoops, atriums, building shading devices, cross ventilation, and labyrinth systems ought to be used as passive systems. Aside from these, the use of high-performance windows and wall, ground, ceiling, and roof insulation prevents heat gain or loss and thus reduces energy consumption. In accordance with local climatic conditions, procedures of appropriate building distance, position, form, façade color, location, and building envelope surface must be taken into account in passive building design. Vegetation is also a procedure that affects the building design in terms of heat gain and loss. In this sense, deciduous trees ought to be planted on the south of a building and coniferous trees on the north (see Section 2.1.1), and existing green areas should certainly be preserved.

Strategy of energy efficiency	
Criteria	**Procedures**
Use of passive heating, ventilating, and air conditioning	Use of Trombe walls for natural heating and air conditioning
	Use of metal walls for natural heating and air conditioning
	Use of double-skin façades for natural heating and air conditioning
	Use of greenhouses for natural heating and air conditioning
	Use of Venturi chimneys for natural ventilating
	Use of wind scoops for natural ventilating
	Use of atriums for natural heating and air conditioning
	Use of building shading devices for natural air conditioning
	Use of labyrinth systems for natural heating, ventilating, and air conditioning
	Use of wind energy by cross ventilation method for natural ventilating
	Use of effective insulation systems
	Selection of appropriate distance to other buildings compatible with local climatic conditions
	Selection of appropriate position for building compatible with local climatic conditions
	Selection of appropriate building form compatible with local climatic conditions
	Use of appropriate colors on façades compatible with local climatic conditions
	Determination of building envelope surface compatible with local climatic conditions
	Selection of appropriate location for building
	Selection of right vegetation for right direction around buildings
	Preservation of existing green areas
Use of active heating, ventilating, and air conditioning	Use of photovoltaic panels for power generation
	Use of solar collectors for water heating
	Use of wind turbines for power generation
	Use of water source heat pumps for power generation and water heating
	Use of geothermal heat pumps for power generation and water heating
	Use of energy efficient appliances and equipment with timing devices
Utilization of daylighting	Use of light shelves
	Use of solar tubes
	Use of heliostats
	Use of anidolic ceilings

Table 4. Criteria and procedures for strategy of energy efficiency.

The use of active heating, ventilating, and air conditioning: The main goal for energy conservation is to reduce the consumption of fossil fuels as well as increasing the use of renewable energy resources such as solar, wind, water, and geothermal [16]. This could be achieved by utilizing active heating, ventilating, and air conditioning systems in buildings, which is essential in terms of energy efficiency. In order to maximize energy efficiency, active systems should be integrated with passive systems in building design. Active heating, ventilating, and air conditioning systems, which enable the efficient use of renewable energy sources in buildings, contain mechanic and electronic appliances and equipment. Photovoltaic panels, solar collectors, wind turbines, water source heat pumps, geothermal heat pumps, energy efficient appliances, and equipment with timing devices should be integrated to building design in the scope of active systems. The installation cost of active systems is considered as an additional initial cost of the building. However, these systems ensure a significant decrease in operating costs.

Utilization of daylighting: Typically, one third of the energy used in many buildings is consumed by electric lighting. Therefore, in recent years daylighting has become a major topic in energy efficient building design next to passive solar heating and cooling [48]. Good daylighting design can reduce electricity consumption for lighting; improve standards of visual comfort, health, and amenity for the users [49]; and provide a better indoor light environment than artificial lighting. Artificial lighting not only consumes a large amount of electricity but also dissipates waste heat into indoor space, which causes the increase of cooling loads. If the effective use of daylighting is integrated in building design, the cooling and lighting energy can decrease [48]. Daylighting can be achieved by bringing natural light into buildings with some systems such as light shelves, solar tubes, heliostats, and anidolic ceilings.

2.1.4. Criteria and procedures for strategy of material efficiency

Materials are the fundamental components of a building. Construction sector consumes approximately 3 billion tons of raw materials which comes up to 40% of total usage per year globally [46]. The production and consumption of building materials has diverse impacts on the local and global environments. Extracting, processing, manufacturing, transporting, and recycling building materials cause environmental impacts to some extent [50]. The strategy of material efficiency consists of reducing these impacts through the entire life cycle of building materials from extraction to the end of life, as well as reducing the construction wastes and sizing the building properly. It focuses on procurement of materials that are sourced in a responsible way and have a low embodied impact over their life cycle [8]. In this context, the criteria for the strategy of material efficiency are classified as *reduction of environmental impact*, *reduction of waste*, and *proper sizing of building and systems* in this study. Additionally, related procedures for each criterion are determined and presented in **Table 5**.

Reduction of environmental impacts: Buildings maintain their relationship with the environment throughout their life cycles on local or global scales and cause a number of environmental impacts [51]. In this context, the sustainable construction sector is responsible for designing buildings which do not disturb the balances of ecosystems, which secure human health, welfare, and comfort; which ensure economic use of materials; which encourages conservation of nonrenewable energy resources; which saves transportation energy; and thus which contributes to minimizing environmental impacts. It is essential to use local, natural, high-performance, long-lasting, durable, nontoxic, noncarcinogenic, antibacterial, low embodied energy, and low volatile organic compound (VOC) building materials. Furthermore, the use of building materials made of renewable sources, with less maintenance need, and those extracted without ecological damage are of great importance as well as the use of certified wood materials and reporting tools such as Environmental Product Declarations [52] and Health Product Declarations [53].

Strategy of material efficiency	
Criteria	**Procedures**
Reduction of environmental impacts	Use of local building materials
	Use of natural building materials
	Use of high-performance building materials
	Use of long-lasting building materials
	Use of durable building materials
	Use of nontoxic and noncarcinogenic building materials
	Use of antibacterial building materials
	Use of low embodied energy building materials
	Use of low volatile organic compound (VOC) building materials
	Use of building materials made from renewable sources
	Use of building materials with less maintenance need
	Use of building materials extracted without ecological damage
	Use of certified wood materials
	Use of environmental and health product declarations
Reduction of wastes	Use of reusable building materials
	Use of recyclable building materials
	Use of reclaimed building materials
	Use of recycled building materials
	Use of nonconventional products as building materials
	Rehabilitation and reuse of existing structures
	Rehabilitation and reuse of existing infrastructures
	Sorting, storage, and disposal of wastes by waste management
Proper sizing of building and systems	Design of sufficient-sized interior spaces
	Reduction of building envelope surface
	Use of simple geometrical forms for building design
	Utilization of flexible and modular building design
	Utilization of standard building material sizes

Table 5. Criteria and procedures for strategy of material efficiency.

Reduction of wastes: The rate of construction sector-based wastes corresponds more than 30% of the total wastes. Within this scope, it is of great importance to target sustainable building design in the construction sector [54]. It should be noted that buildings that are demolished become the resources for new buildings [55]. During the process of building design, it is necessary to select reusable, recyclable, reclaimed, recycled building materials and nonconventional products in order to lower embodied energy of materials; to reduce the need for new landfills; to reduce air, water, and soil pollution; to minimize transportation requirements; to reduce the use of raw materials; and to enable the economic use of materials. On the other hand, rehabilitation and reuse of existing structures and infrastructures instead of brand-new ones are other effective procedures that reduce construction sector-based wastes. Apart from these, waste management of construction and demolition phases in terms of sorting, storage, and disposal of wastes should be implemented.

Proper sizing of building and systems: It is necessary to optimize the building size in order to reduce overall building material use, wastes, embodied energy, energy loads, and costs and to conserve resources. This can be achieved by ensuring functionality between spaces and circulation according to target utilization rates (number of square meters per person or unit), by designing individual spaces to fulfill multiple functions, and by dumping unused spaces [56]. Furthermore, reducing building envelope surface, using simple geometrical mass forms; designing flexible and modular spaces; and utilizing standard commercially available material sizes are the other procedures for proper sizing.

2.2. Economic aspect of sustainable building design

Economic sustainability is defined as the use of various strategies for employing existing resources optimally, so that a responsible and beneficial balance can be achieved over the longer term [57]. Economic sustainability is inextricably linked to both environmental and social sustainability [58]. Sustainable building design does not only improve the quality of environment and comfort of users but also has many economic benefits as well. The initial cost of the building can be higher than a conventional building owing to the innovative use of sustainable building materials, systems, and equipment through integrated sustainable building design process. However, sustainable buildings decrease annual costs in terms of energy, water, maintenance and repair, and other operating costs so that the life cycle cost is lower than the cost of conventional buildings. In addition to the mentioned cost savings, sustainable buildings also provide indirect economic benefits such as increasing comfort and productivity of users, reducing absenteeism, and increasing property value, to both the actors of the construction sector and users [59]. Reducing costs based on construction wastes, pollution, infrastructure, and transportation can also be considered as indirect economic benefits. In this context, economically sustainable building design criteria can be classified as *resource efficiency* and *cost efficiency*.

2.2.1. Criteria and procedures for strategy of resource efficiency

The construction sector is a major consumer of all resources, and therefore the actors of the construction sector have pursued to design sustainable buildings focusing on increasing the efficiency of resource use [16]. Resource efficiency refers to the conservation of raw materials and nonrenewable resources based on life cycle conception to design buildings that consume fewer resources and that leads to less environmental impacts. The strategy of resource efficiency comprises both energy and material efficiency (see Sections 2.1.3 and 2.1.4). Whereas energy efficiency considers the economical use of nonrenewable resources, encouraging the use of renewable resources, material efficiency is about the economical use of raw materials and reduction of wastes. Resource efficiency addresses human impacts on natural resources, economic requirements for land use, environmental impacts, amount of material used, and the ratio of gross domestic product (GDP) to material used [60]. In this context, the criteria for the strategy of resource efficiency are classified as *conservation of raw materials* and *conservation of nonrenewable resources* in this study. Additionally, related procedures for each criterion are determined and presented in **Table 6**.

Strategy of resource efficiency	
Criteria	**Procedures**
Conservation of raw materials	Use of reusable building materials
	Use of recyclable building materials
	Use of reclaimed building materials
	Use of recycled building materials
	Use of long-lasting building materials
	Rehabilitation and reuse of existing structures and infrastructures
	Development of new eco-innovative building materials
	Optimization of supply chain
	Optimization of material production techniques
Conservation of nonrenewable resources	Increase of use of renewable energy resources
	Reduction of energy consumption in all life cycle stages of buildings
	Use of energy saving electrical installation
	Use of energy saving heating, ventilating, and air conditioning installation

Table 6. Criteria and procedures for strategy of resource efficiency.

Conservation of raw materials: Conservation of resources means achieving more with less [16]. Nowadays, certain resources are becoming extremely rare; that's why the use of remaining stocks should be treated cautiously [61]. The scarcity of raw material stocks results in a threat for the economy. The extraction of raw materials may damage lands; the production, usage, and disposal of materials can have significant environmental impacts; and these processes may be energy intensive, labor intensive, and very costly [60]. In this context, resource efficiency ought to be handled based on life cycle assessment (LCA) methodology, as depletion of abiotic resources is one of the prominent environmental impact indicators of this methodology [62]. Raw materials, which are assigned as abiotic resources, can be conserved by using secondary materials such as reusable, recyclable, reclaimed, recycled building materials. Construction wastes can be also reduced by this way. Improving durability, service life, the technical and economic performance of building materials, reusing existing structures and infrastructures, and developing new eco-innovative building materials are other procedures of conservation of raw materials. Additionally, supply chain and material production techniques should be optimized in order to convert raw materials into final building products with less environmental impacts [63].

Conservation of nonrenewable resources: Energy use in buildings from life cycle perspective is one of the significant economic issues, as buildings are intensive energy consumers. Buildings consume energy at each stage of their life cycles, from cradle to grave. The energy consumed in usage stage of buildings accounts for a considerable part of the total energy. For this reason, minimizing the use of energy in usage stage is a central task in sustainable building [64]. Energy use in usage stage of the buildings includes both operational and embodied energy [65]. Operational energy comes out as a result of heating, ventilating, air conditioning, and hot water use in buildings, while the embodied energy occurs from the choice of building materials used.

Nowadays, energy used in buildings for electricity is supplied from nonrenewable resources, which are fossil fuels such as natural gas, fuel oil, and coal. The reserves of these resources are limited reserves. The entire world, therefore, looks for the means of safe and continuous access to energy [66]. In this sense, using renewable energy resources, reducing the energy consumption of in all life cycle stages of buildings, and using energy saving electrical, heating, ventilating, and air conditioning installations are important tasks to take into consideration.

2.2.2. Criteria and procedures for strategy of cost efficiency

The construction sector can be mentioned as the sector of the economy which plans, designs, constructs, alters, refurbishes, maintains, repairs, and eventually demolishes buildings. The inputs of the sector are obtained from other sectors of the economy, such as manufacturing, financial services, local government, commercial sectors, and industrial sectors supplying materials. Due to these dealings, there have been considerable procedural and structural changes in the construction sector, such as the increased use of design and construct arrangements, integrated project management processes, novation, partnering, benchmarking, re-engineering, management contracting, private finance initiatives, and public and private partnerships. Concordantly, life cycle cost management of building projects has become progressively important in terms of delivering the highest-quality projects in time with accurate budgeting and cost control, ensuring cost efficiency [67]. Through life cycle cost perspective, there are three main costs to be considered at the outset of a building project, being the initial building investment cost, the cost of the building in use, and the cost of building recovery [68]. In this respect, the strategy of cost efficiency focuses on long-term economic performance with minimized initial, operating, and recovery costs providing satisfaction of the actors of the construction sector. The criteria for the strategy of cost efficiency are classified as the *reduction of initial cost*, *reduction of operating cost, reduction of recovery cost*, and *satisfaction of the construction sector actors* in this study. Additionally, related procedures for each criterion are determined and presented in **Table 7**.

Reduction of initial cost: The initial cost, also referred to as acquisition cost or development cost, covers the entire cost of designing and constructing a building. In a broad sense, initial cost comprises land and building acquisition costs, professional consultant fees, the cost of the building materials, and the cost of construction processes. It can be said that the initial cost is the basic and sometimes the only source of concern for many actors in the construction sector [68]. Therefore, initial cost reduction procedures should be considered in sustainable building design process. Recycled, reclaimed, and locally available building materials have to be selected to reduce the cost value of materials and transportation costs. Deconstruction techniques rather than demolition have to be employed to reclaim materials for reuse in other applications on site [69]. Flexible and modular designs and standardized building components, which allow reconfiguration when required, must be preferred [70]. Common and readily available building components should be selected to minimize replacement costs and to reduce stocking of components. Building components that cannot be easily repaired or replaced ought to be selected as durable to minimize replacement and retrofitting [16]. Appropriate storage facilities should be provided on site to maintain the integrity of the materials [69]. Cost saving and proper construction technologies must be implemented for different types of buildings.

Strategy of cost efficiency	
Criteria	**Procedures**
Reduction of initial cost	Use of local building materials to reduce transportation cost
	Use of recycled building materials
	Use of reclaimed building materials
	Reduction of transportation to and from the site
	Utilization of flexible and modular building design
	Use of standardized building components
	Use of common and available building components
	Safe and correct storage of building materials
	Reduction of time for assembly of building materials on site
	Selection of appropriate construction technologies for various building types
	Selection of appropriate suppliers for building materials
	Selection of right labor force for right positions
Reduction of operating cost	Selection of long lasting building materials and components
	Reduction of maintenance and repair cost
	Reduction of regular cleaning cost
	Selection of right location for heating, ventilating, and air conditioning systems
	Use of easy-to-use building automation and control systems
Reduction of recovery cost	Consideration of recycling potential of building materials in design phase
	Consideration of reclaiming potential of building materials in design phase
	Reuse of building materials or components
	Consideration of ease of demolition of building in the design phase
	Reuse of an existing building
Satisfaction of the construction sector actors	Improvement of productivity
	Increase of profitability
	Development of lower-cost projects by increasing cost estimation
	Shortening the completion time of the project

Table 7. Criteria and procedures for strategy of cost efficiency.

Besides these, the right workers for the right works and the right supplier choice are the other issues that need to be carefully considered in order to reduce the initial costs.

Reduction of operating cost: The operating cost, also known as the cost in use or the running cost, is affected by the decisions made during the design and construction phases of the building design process in terms of the choice of materials and the impeccability of the detailing [68]. It involves the costs of heating, ventilating, air conditioning services, building automation and control systems, maintenance and repair, and cleaning fees in the usage stage of the building's life cycle. Only the initial cost was estimated, and operating cost was neglected in the design phase before the life cycle cost methodology has underlined the relationship between design decisions and costs in use [68, 71]. In fact, the lower the life cycle cost, the more economically efficient the building [72]. Therefore, implementing operating cost reduction procedures would contribute reducing the life cycle cost of the buildings. Durable, long-lasting, low-maintenance building materials and components have to be preferred to reduce maintenance and repair costs [73]. The access points of central and major elements of heating, ventilating, and air conditioning systems ought to be located properly for easy maintenance, repair, and cleaning. Simple environmental automation and control systems should be selected, as opposed to complex systems with high maintenance costs [74]. If the required efficiency can be achieved by a simple system, then a complicated one ought to be avoided [16].

Reduction of recovery cost: The recovery cost, which consists of the cost of building demolition and materials recovery, is rarely considered by the actors of the construction sector due to looking for short-term gain with minimum outlay [68]. However, recovery cost is also of great importance from standpoint of the life cycle cost methodology. Therefore, implementing recovery cost reduction procedures would promote reduction of the life cycle cost of the buildings. Recycling and reclaiming potential of building materials have to be evaluated in the design phase in order to provide for maximum recovery of materials by reusing them. Besides, proper demolition techniques of the building should be considered and improved through the design phase. Another procedure for reducing recovery cost is reuse of an existing building to reduce the amounts of construction waste, raw materials, and the energy used for material production processes. When all of these are succeeded within the scope of end-of-life perspective, the allocation of resources at minimal costs would be provided, and the value of the building would be increased [75].

Satisfaction of the construction sector actors: The construction sector involves actors such as designers, users, contractors, stakeholders, suppliers, manufacturers, and several organizational levels that have different tasks. These actors make the construction sector a multilevel entity. Satisfaction of the construction sector actors can be stated as an essential criterion of the future economic success of the sector [76]. Long-term economic performance of buildings can be provided with the satisfaction of the actors by improving the productivity of labor force and enhancing profitability. Profitability could be increased by improving the management of the building project process. Meanwhile, accuracy of cost estimation is of great importance in terms of decreasing the costs of the projects. In addition, flows of information, money, goods, and services move between the construction sector actors during the project process [76]. The longer the project process, the greater the costs. In order to decrease the costs during this process, it is necessary to shorten the completion time of the project.

2.3. Social aspect of sustainable building design

Debates about sustainability do not consider sustainability solely as an environmental and economic concern but also incorporate social dimensions [77]. In this respect, the main goals of sustainable development are defined as environmental stewardship, economic prosperity, and social responsibility. These three goals should be interrelated and supportive of each other in order to execute sustainability strategies [78]. When the construction sector is examined, it is observed that the social aspect of sustainability is usually neglected, despite the anthropocentric focus of sustainability definitions [77]. In the mentioned definitions, sustainability focuses on well-being rather than well-having by sustainable livelihoods and addresses fundamental issues for humanity now and in the future, which constitutes the social aspect of sustainable building design [79]. In order to achieve socially sustainable building design, creating unpolluted and safe environments, protecting human health, improving user productivity, enhancing human comfort conditions, creating esthetically satisfactory indoor and outdoor environments, conserving local heritage and culture, improving communication with the public, and developing regulations are of great importance. In this context, socially sustainable building design criteria can be classified as *health and well-being* and *public awareness*.

2.3.1. Criteria and procedures for strategy of health and well-being

It is imperative to pay attention to enhance the quality of life in buildings that encourage a healthy and safe internal and external built environment for users [8] without exhausting natural resources or causing severe ecological damage. The strategy of health and well-being consists of building design procedures ensuring unpolluted, fire- and natural-hazard-resistant, disabled-friendly environments and good indoor environmental quality to protect the health and comfort of building users. It also addresses increased comfort, health, and safety of building users, visitors, and others within the vicinity. Livable and high-quality indoor environments contribute increasing property value, to improve productivity and to reduce absenteeism [80]. In this context, the criteria for the strategy of health and well-being are classified as the *creation of livable environments* and *creation of appropriate indoor comfort conditions* in this study. Additionally, related procedures for each criterion are determined and presented in **Table 8**.

Creation of livable environments: The concept of livability is directly related to the quality of human life. Livability evolves out of a wealth of existing resources and conditions that promote healthy living like clean air, water, and soil. The provision of healthy and comfortable indoor and outdoor spaces is the key indicators of livability, which is related to the effects of building performance on the quality of living. The environmental aspects typically include the issues of noise, visual, air, water, and soil, which cause significant implications on health and well-being of users [81]. For this reason, solutions have to be produced to prevent above-mentioned pollution in order to create livable environments. Additionally, fire protection is essential for livable environments, and fire safety systems have to be advanced. These systems, such as fire sprinklers, can offer environmental benefits by reducing air and water pollution levels and by lowering water usage and fire damage. The resistance to natural hazards should also be ensured. It is not possible to prevent these hazards, but mitigation measures ought to be taken to overcome. Accessibility of disabled users has to be considered, and accessibility features should be improved to make the environment more livable for them [82]. In addition to all these, preservation of cultural heritage and values is another significant procedure of the related criteria.

Creation of appropriate indoor comfort conditions: In developed countries, people spend more than 90% of their time indoors. Indoor conditions have therefore far-reaching implications for their health, general well-being, and performance [83]. Indoor environmental quality of building has a high-level impact on users' health, comfort, and productivity [84]. Apart from these

Strategy of health and well-being	
Criteria	**Procedures**
Creation of livable environments	Prevention of noise pollution
	Prevention of visual pollution
	Prevention of air pollution
	Prevention of water pollution
	Prevention of soil pollution
	Provision of fire protection
	Provision of resistance to natural hazards
	Consideration of the accessibility of disabled users
	Conservation of local heritage and culture
Creation of appropriate indoor comfort conditions	Provision of sufficient indoor air quality
	Provision of appropriate indoor humidity ratio
	Provision of indoor visual comfort conditions
	Creation of visual connection with the outer environment
	Provision of indoor thermal comfort conditions
	Provision of indoor acoustical comfort conditions
	Provision of operable windows
	Provision of clean fresh air
	Use of low volatile organic compound (VOC) building materials
	Prevention of electromagnetic pollution
	Use of nontoxic and noncarcinogenic building materials
	Use of antibacterial building materials

Table 8. Criteria and procedures for strategy of health and well-being.

features, a sustainable building has appropriate ventilation and moisture control, maximizes daylighting to provide indoor visual comfort conditions, creates visual connection with the outer environment, provides indoor thermal comfort conditions, optimizes acoustic performance, provides operable windows and fresh air, and avoids the use of materials with high-VOC emissions [56]. Except these, electromagnetic pollution has to be prevented to improve the indoor air quality, and nontoxic, noncarcinogenic, and antibacterial building materials have to be used for maximizing the comfort of users.

2.3.2. Criteria and procedures for strategy of public awareness

Ensuring sustainability in construction sector depends not only on achieving environmental and economic aspects of sustainability but also the participation of the public and an understanding of the consequences of individual behaviors. Although sustainable building design is envisaged as a necessity in construction sector, in general it continues not to receive much attention between public [85]. As a matter of fact, there is a need to create greater public awareness of the health impacts of buildings, to increase the focus on sustainability strategies, and to encourage building codes to place increased emphasis on healthier building practices [86]. Strategy of public awareness comprises raising consciousness of public and the actors of the construction sector about the benefits of sustainable buildings, mobilization of sustainable building tools, adoption of procedures for sustainable building management, and development of innovative concepts and services [87]. It focuses on developing financial incentives, improving cooperation between organizations, and developing policies for innovative initiatives and technologies on sustainable design features [88]. In this context, the criteria for the strategy of public awareness are classified as *educating the public* and *development of incentives and policies* in this study. Additionally, related procedures for each criterion are determined and presented in **Table 9**.

Educating the public: Creating public awareness about sustainable buildings could be achieved by educating the public. More symposiums, conferences, educational videos, programs, workshops, seminars, and professional talks have to be held under the theme of sustainable buildings in order to educate the public about the importance of sustainability and to raise the awareness. Competitions on sustainable buildings should be organized to improve ability and know-how of the actors of the construction sector that have been gained from their previous experiences [89]. Additionally, media ought to be used intensely and effectively in creating public awareness and improved understanding of issues [90], and public authorities ought to disseminate plans, programs, and other related relevant materials through media [91]. Apart from these, pilot sustainable buildings can be opened to the public for on-site training. Consequently, the public has to be completely environmental conscious and should be encouraged to prefer sustainable buildings.

Development of incentives and policies: It is very crucial to develop policies and approaches that enable utilization of domestic resources complying with the conditions of the countries and

Strategy of public awareness	
Criteria	**Procedures**
Educating the public	Organization of congresses and conventions on sustainable building design
	Implementation of training programs about sustainable building design
	Preparation of educational videos about sustainable building design
	Organization of competitions on sustainable buildings
	Efficient use of media about sustainable building design
	Educating the public in pilot sustainable buildings
Development of incentives and policies	Provision of financial incentives such as tax and customs' duty exemption
	Improvement of cooperation between public and private organizations
	Implementation of policies for the efficient use of renewable energy technologies
	Implementation of the decisions made in the international meetings on environment

Table 9. Criteria and procedures for strategy of public awareness.

to monitor studies pertaining to energy in the world [66]. Sustainable building design and practices can be only achieved by political decision-making, including several incentives and policies based upon public awareness in this manner [92]. Financial incentives such as taxes, subsidies, tradable permits, and rewards do not usually require as much enforcement as regulations [93], whereas it is a considerable procedure for encouraging the actors of the construction sector to opt for sustainable building design. Furthermore, it can be stated that improving cooperation among public bodies, universities, private enterprises, and nongovernmental organizations can support the generalization of sustainable buildings. Finally, policies for efficient use of renewable energy technologies have to be implemented, wide range of innovative policy instruments ought to be developed, and the decisions made in the international meetings on environment must be complied with.

3. Conclusion

Today's world is facing environmental, economic, and social problems. Many studies and researches in various sectors are being carried out to reduce these problems. Sustainable building design can be considered as a path of minimizing environmental, economic, and social problems in the construction sector. In this context, sustainable building design has to be contextualized properly. When reviewing the most recent interpretations of sustainable building design in the literature, many uncertainties and constraints have been observed because of the inability to integrate the environmental, economic, and social aspects of sustainability. These uncertainties and constraints are tried to be solved in this study by developing a holistic conceptual scheme, which comprehensively contextualizes all the strategies, criteria, and procedures associated with the aspects of environmentally, economically, and socially sustainable building design. By this way, it is envisaged that this study can contribute to the improving literature on sustainable building design in terms of site efficiency, water efficiency, energy efficiency, material efficiency, resource efficiency, cost efficiency, health and well-being, and public awareness. Consequently, this scheme may be adopted as a guideline for the actors of the construction sector and the researchers and can help in promoting sustainable building practices in the construction sector. Furthermore, it is of vital significance to develop new laws and regulations, to improve government incentives, to study on new standards, to carry out scientific researches, and to conduct effective training programs.

Author details

Arzuhan Burcu Gültekin*, Handan Yücel Yıldırım and Harun Tanrıvermiş

*Address all correspondence to: arzuhanburcu@yahoo.com

Department of Real Estate Development and Management, Ankara University,
Ankara, Turkey

References

[1] Say C, Wood A. Sustainability rating systems around the world. CTBUH Review. 2008;**2**:18-29

[2] Smith PF. Architecture in a Climate of Change: A Guidance to Sustainable Design. 2nd ed. Great Britain: Routledge; 2005. 294 p. ISBN-13: 978-0750665445, ISBN-10: 0750665440

[3] Gültekin AB, Farahbakhsh EB. Energy performance of glass building materials. Journal of TÜBAV. 2016;**9**(13):52-65

[4] Gültekin AB, Yavaşbatmaz S. Sustainable design of tall buildings. Journal of the Croatian Association of Civil Engineers – Gradevinar. 2013;**65**(5):449-461, UDK: UDK 72.011.27:504.06

[5] Collins A, Watts S, McAlister M. The economics of sustainable tall buildings. In: Proceedings of the CTBUH 8th World Congress; Mar 3-5, 2008; Dubai. Dubai: CTBUH (Council on Tall Buildings and Urban Habitat); 2008. pp. 175-185

[6] Yıldırım HY, Gültekin AB, Tanrıvermiş H. Evaluation of energy efficient urban planning approach. In: Proceedings of the Smart Metropoles – Integrated Solutions for Sustainable and Smart Buildings & Cities (SBE16 ISTANBUL); Oct 13-15, 2016; İstanbul. İstanbul: İMSAD; 2016. pp.224-235

[7] Akbıyıklı R, Sönmez İ, Dikmen SÜ. Sustainable development in Turkey and sustainability in construction sector. In: Proceedings of the International Sustainable Buildings Symposium (ISBS); May 28-30, 2010; Ankara. Ankara: Başak Publishing; 2010. pp. 422-425 (In Turkish)

[8] BREEAM. Category Issues and Aims [Internet]. 2017. Available from: http://www.breeam.com/ [Accessed: Nov 1, 2017]

[9] Officine Green Building. Integrative Projects for Sustainable Architecture [Internet]. 2017. Available from: http://www.officinegb.com/wp-content/uploads/2016/07/Flyer_OGB_s.pdf [Accessed: Nov 1, 2017]

[10] LEED. U.S. Green Building Council [Internet]. 2017. Available from: https://new.usgbc.org/leed [Accessed: Nov 1, 2017]

[11] Gültekin AB, Alparslan BA. Ecological building design and evaluation in Ankara. Journal of the Croatian Association of Civil Engineers Gradevinar. 2013;**65**(11):1003-1013. UDK: UDK 725/728.001.1:699.87/88(56)

[12] Yavaşbatmaz S. Evaluation of tall buildings in the context of sustainable design criteria [MSc thesis]. Ankara: Gazi University; 2012 (In Turkish)

[13] Alparslan B. Design and evaluation of an example building in ankara in the context of ecological building design criteria [MSc thesis]. Ankara: Gazi University; 2010 (In Turkish)

[14] Çalışkan Ö. Research on prioritized ecological building design criteria for bursa and example design [MSc thesis]. Gebze Institute of Technology: Kocaeli; 2007 (In Turkish)

[15] Çelebi G, Gültekin AB. Scope of sustainable architecture: A view from conceptual framework. Bulletin of Mimaran, Global Warming and Architecture. 2007;**1**(2):30-36 (In Turkish)

[16] Akadiri PO, Chinyio EA, Olomolaiye PO. Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. Buildings. 2012;**2**:126-152. DOI: 10.3390/buildings2020126

[17] Gültekin A B, Yavaşbatmaz S. Sustainable Tall Building Design: Evaluation of LEED Certificated Tall Buildings. 1st ed. Saarbrucken: LAP Lambert Academic Publishing; 2013. 75 p. ISBN: 978-3-659-36665-9

[18] Yılmaz M, Bakış A. Sustainability in construction sector. Procedia – Social and Behavioral Sciences. 2015;**195**:2253-2262. DOI: 10.1016/j.sbspro.2015.06.312 (In Turkish)

[19] Çelebi G, Aydın AB. Architectural responsibilities within the context of sustainability. In: Proceedings of the Livable Environments and Architecture International Congress (Livenarch 2001); July 4-7, 2001; Trabzon. Trabzon: KTÜ Publishing; 2001. pp. 140-146

[20] Kim J-J, Rigdon B. Sustainable Architecture Module: Introduction to Sustainable Design. 1st ed. Michigan: National Pollution Prevention Center for Higher Education; 1998. 28 p

[21] Gültekin AB, Dikmen ÇB. Analysis of ecological design criteria in architectural design process. In: Proceedings of the VI. National Ecology and Environment Congress; Sep 18-21, 2006; Diyarbakır. İzmir: Türkiye Biyologlar Derneği; 2006. pp. 159-167

[22] Ching FDK. Building Construction Illustrated. 5th ed. New Jersey: John Wiley and Sons; 2014. 480 p. ISBN: 978-1-118-45834-1

[23] Keles R. Sustainable urbanization and its policy implications. The case of Turkey. In: Camarda D, Grassini L, editors. Interdependency between Agriculture and Urbanization: Conflicts on Sustainable Use of Soil and Water. Bari: CIHEAM; 2001. p. 119-135

[24] The World Bank. Sustainable Land Management: Challenges, Opportunities, and Trade-Offs. Washington, DC: The World Bank; 2006. 112 p. DOI: 10.1596/978-0-8213-6597-7

[25] Muilerman H, Blonk H. Towards a Sustainable Use of Natural Resources. Stichting Natuur en Milieu: European Commission; 2001. 18 p

[26] Vrscaj B, Poggio L, Marsana FA. A method for soil environmental quality evaluation for management and planning in urban areas. Landscape and Urban Planning. 2008;**88**:81-94

[27] Deakin M, Huovila P, Rao S, Sunikka M, Vreeker R. The assessment of sustainable urban development. Building Research & Information. 2002;**30**(2):95-108. DOI: 10.1080/096132102753436477

[28] Chen Y, Hipel KW, Kilgour MD, Zhu Y. A strategic classification support system for brownfield redevelopment. Environmental Modelling & Software. 2009;**24**(5):647-654. DOI: 10.1016/j.envsoft.2008.10.011

[29] Shiftan Y, Kaplan S, Hakkert S. Scenario building as a tool for planning a sustainable transportation system. Transportation Research Part D. 2003;**8**(5):323-342. DOI: 10.1016/S1361-9209(03)00020-8

[30] United Nations Department of Economic and Social Affairs (UNDESA). Shanghai Manual – A Guide for Sustainable Urban Development in the 21st Century. Shanghai 2010. World Exposition Executive Committee; 2010. 38 p

[31] Yan-ling W, Xin W, Ming-Chun Z. Current situation and analysis of parking problem in Beijing. Procedia Engineering. 2016;**137**:777-785. DOI: 10.1016/j.proeng.2016.01.316

[32] World Road Association (PIARC) Cycle 2012-15 Technical Committee 2.2 Improved Mobility in Urban Areas. Key issues for improving mobility strategies in large urban areas. In: Proceedings of the 25th World Road Congress Seoul; Nov 2-6, 2015; Korea. New York: Curran Associates, Inc.; 2017. pp. 1-90

[33] Steg L, Gifford R. Sustainable transportation and quality of life. Journal of Transport Geography. 2005;**13**(1):59-69. DOI: 10.1016/j.jtrangeo.2004.11.003

[34] Santamouris M. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy. 2014;**103**:682-703

[35] LEED. U.S. Green Building Council [Internet]. 2017. Available from: https://new.usgbc.org/leed [Accessed: Oct 27, 2017]

[36] Feyisa GL, Dons K, Meilby H. Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa. Landscape and Urban Planning. 2014;**123**:87-95. DOI: 10.1016/j.landurbplan.2013.12.008

[37] EPA. The United States Environmental Protection Agency [Internet]. 2017. Available from: https://www.epa.gov/heat-islands/using-trees-and-vegetation-reduce-heat-islands [Accessed: Nov 3, 2017]

[38] Ottelé M, Perini K, Fraaij ALA, Haas EM, Raiteri R. Comparative life cycle analysis for green façades and living wall systems. Energy and Buildings. 2011;**43**(12):3419-3429. DOI: 10.1016/j.enbuild.2011.09.010

[39] Karaca NK, Gültekin AB. Business management in sustainable buildings: Ankara-Turkey case. Materials Science and Engineering. 2017;**245**(062008):1-11. DOI: 10.1088/1757-899X/245/6/062008

[40] Silva-Afonso A, Pimentel-Rodrigues C. The importance of water efficiency in buildings in Mediterranean countries. The Portuguese experience. International Journal of Systems Applications, Engineering & Development. 2011;**5**(1):17-24

[41] Kibert CJ. Sustainable Construction: Green Building Design and Delivery. 4th ed. New Jersey: John Wiley & Sons; 2016. 583 p. ISBN: 9781119055174

[42] Bossink BAG, Brouwers HJH. Construction waste: Quantification and source evaluation. Journal of Construction Engineering and Management. 1996;**122**(1):55-60

[43] Nolde E. Greywater reuse systems for toilet flushing in multi-story buildings – Over ten years experience in Berlin. Urban Water. 2000;**1**(4):275-284. DOI: 10.1016/s1462-0758(00)00023-6

[44] Santos C, Taveira-Pinto F, Cheng CY, Leite D. Development of an experimental system for greywater reuse. Desalination. 2012;**285**:301-305. DOI: 10.1016/j.desal.2011.10.017

[45] Qu X, Brame J, Li Q, Alvarez PJJ. Nanotechnology for a safe and sustainable water supply: Enabling integrated water treatment and reuse. Accounts of Chemical Research. 2013;**46**(3):834-843. DOI: 10.1021/ar300029v

[46] Ministry of Public Works. Commission Report of Spatial Planning System and Institutional Structuring. Ankara: General Secretariat of Ministry of Public Works; 2009. 116 p. (In Turkish)

[47] Chan H, Riffat SB, Zhu J. Review of passive solar heating and cooling technologies. Renewable and Sustainable Energy Reviews. 2010;**14**(2):781-789. DOI: 10.1016/j.rser.2009.10.030

[48] Chena H, Wei P. Utilization of natural daylight in office buildings. International Journal of Smart Grid and Clean Energy. 2013;**2**(2):301-306

[49] Backer NV, Fanchiotti A, Steemers K. Daylighting in Architecture: A European Reference Book. 1st ed. Routledge: Earthscan; 1993. 380 p. ISBN-13: 978-1849713009, ISBN-10: 1849713006

[50] Lyle JT. Regenerative Design for Sustainable Development. Canada: John Wiley & Sons, Inc; 1996. 352 p. ISBN-13: 978-0471178439, ISBN-10: 0471178438

[51] Çelebi G, Gültekin AB, Harputlugil G, Bedir M. Tereci A. Building-Environment Relationships. Istanbul: TMMOB Chamber of Architects Continuing Program Development Centre; 2008. 108 p. ISBN/ ISSN: 978-9944-89-645-0 (In Turkish)

[52] The Institut Bauen und Umwelt e.V. Environmental Product Declarations (EPDs) [Internet]. 2017. Available from: http://ibu-epd.com/en/ [Accessed: Nov 4, 2017]

[53] HPD. Health Product Declaration [Internet]. 2017. Available from: https://www.hpd-collaborative.org/ [Accessed: Nov 4, 2017]

[54] Gültekin AB. Sustainable Cement Sector. CemenTürk (Çimento & Beton Bileşenleri). 2016;**45**:78-85. ISSN: 2146-0833 (In Turkish)

[55] Federle MO. Overview of building construction waste and the potential of materials recycling. Building Research Journal. 1993;**2**(1):31-37

[56] WBDG. Whole Building Design [Internet]. 2017. Available from: https://www.wbdg.org/design-objectives/sustainable/optimize-building-space-material-use [Accessed: Nov 4, 2017]

[57] BD. Online Business Dictionary [Internet]. 2017. Available from: http://www.businessdictionary.com/definition/economic-sustainability.html [Accessed: Nov 5, 2017]

[58] Reddy TL, Thomson RJ. Environmental, social and economic sustainability: implications for actuarial science. In: Actuaries Institute 2015 ASTIN, AFIR/ERM and IACA Colloquia; Aug 23-27, 2015; Sydney. Sydney: Institute of Actuaries of Australia; 2015. p. 1-28

[59] Office of Energy Efficiency & Renewable Energy. The Economic Benefits of Sustainable Design [Internet]. 2017. Available from: https://www1.eere.energy.gov/femp/pdfs/buscase_section2.pdf [Accessed: Nov 6, 2017]

[60] Ruuska A, Hakkinen T. Material efficiency of building construction. Buildings. 2014; **4**:266-294. DOI: 10.3390/buildings4030266

[61] Halliday S. Sustainable Construction. Slovenia: Elsevier, Butterworth-Heinemann; 2008. 394 p. ISBN: 978-0-7506-6394-6

[62] Gültekin AB, Çelebi G. Proposal of a model for assessment of the environmental impacts of construction products within the context of life cycle assessment methodology. Düzce University Journal of Science & Technology – DÜBİTED. 2016;**4**(1):1-36. e-ISSN: 2148-2446 (In Turkish)

[63] Beamon BM. Environmental and sustainability ethics in supply chain management. Science and Engineering Ethics. 2005;**11**(2):221-234

[64] Thormark C. The effect of material choice on the total energy need and recycling potential of a building. Building and Environment. 2006;**41**(8):1019-1026. DOI: 10.1016/j.buildenv.2005.04.026

[65] Dimoudi A, Tompa C. Energy and environmental indicators related to construction of office buildings. Resources Conservation and Recycling. 2008;**53**(1):86-95. DOI: 10.1016/j.resconrec.2008.09.008

[66] Yıldırım HYY, Gültekin AB, Tanrıvermiş H. Evaluation of cities in the context of energy efficient urban planning approach. Materials Science and Engineering. 2017; **245**(072051):1-10. DOI: 10.1088/1757-899X/245/7/072051

[67] Smith J, Jaggar DM, Love P. Building Cost Planning for the Design Team. 3rd ed. Oxon and New York: Routledge; 2016. 388 p. ISBN-13: 978-1138907379, ISBN-10: 1138907375

[68] Emmitt S, Yeomans DT. Specifying Buildings: A Design Management Perspective. 2nd ed. Hungary: Elsevier-Butterworth-Heinemann. 2008. 272 p. ISBN: 978-0-7506-8450-7

[69] Calkins M. Materials for Sustainable Sites: A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials. 1st ed. New Jersey: John Wiley & Sons; 2008. 480 p. ISBN: 978-0-470-13455-9

[70] Kohn EA, Katz P. Building Type Basics for Office Buildings. 1st ed. New York: Wiley; 2002. 312 p. ISBN-13: 978-0471389231, ISBN-10: 0471389234

[71] Woodward DG. Life cycle costing – Theory, information acquisition and application. International Journal of Project Management. 1997;**15**(6):335-344. DOI: 10.1016/S0263-7863(96)00089-0

[72] Iwaro J, Mwasha A. The impact of sustainable building envelope design on building sustainability using integrated performance model. International Journal of Sustainable Built Environment. 2013;**2**(2):153-171. DOI: 10.1016/j.ijsbe.2014.03.002

[73] Lombera JS, Rojo JC. Industrial building design stage based on a system approach to their environmental sustainability. Construction and Building Materials. 2010;**24**(4):438-447. DOI: 10.1016/j.conbuildmat.2009.10.019

[74] Seán Harrington Architects [Internet]. 2017. Available from: http://www.sha.ie/designing-sustainably/ [Accessed: Nov 6, 2017]

[75] Borza M. The connection between efficiency and sustainability – A theoretical approach. Procedia Economics and Finance. 2014;**15**:1355-1363. DOI: 10.1016/S2212-5671(14)00599-1

[76] Kärnä S. Concepts and attributes of customer satisfaction in construction [PhD thesis]. Helsinki: Helsinki University of Technology; 2009

[77] Dempsey N, Bramley G, Power S, Brown C. The social dimension of sustainable development: Defining urban social sustainability. Sustainable Development. 2009;**19**(5):289-300. DOI: 10.1002/sd.417

[78] Placet M, Anderson R, Fowler KM. Strategies for sustainability. Research-Technology Management. 2005;**48**(5):32-41. Print ISSN: 0895-6308 Online ISSN: 1930-0166

[79] Hopwood B, Mellor M, O'Brien G. Sustainable development: Mapping different approaches. Sustainable Development. 2005;**13**(1):38-52. DOI: 10.1002/sd.244

[80] LEED. U.S. Green Building Council [Internet]. 2017. Available from: https://new.usgbc.org/leed-v4 [Accessed: Nov 7, 2017]

[81] Edward NG, Kam-Sing W. Efficiency & liveability: Towards sustainable habitation in Hong Kong. In: Proceedings of Hong Kong Housing Authority Conference; Feb 2-4, 2004; Hong Kong. pp. 1-22

[82] ST/ESA/364 United Nations Department of Economic and Social Affairs. Good Practices of Accessible Urban Development – Making Urban Environments Inclusive and Fully Accessible to All. New York: United Nations Department of Economic and Social Affairs; 2016. 89 p

[83] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. Building and Environment. 2011;**46**(4):922-937. DOI: 10.1016/j.buildenv.2010.10.021

[84] Horr YA, Arif M, Katafygiotou M, Mazroei A, Kaushik A, Elsarrag E. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. International Journal of Sustainable Built Environment. 2016;**5**(1):1-11. DOI: 10.1016/j.ijsbe.2016.03.006

[85] Umar UA, Khamidi MF. Determined the level of green building public awareness: Application and strategies. In: Proceedings of International Conference on Civil, Offshore and Environmental Engineering (Volume: World Engineering, Science & Technology Congress); Malaysia; Jun 12-14, 2012; Kuala Lumpur. Kuala Lumpur: Universiti Teknologi Petronas; 2012. pp. 1-6. DOI: 10.13140/2.1.5095.6480

[86] Croome DC. Sustainable intelligent buildings for people: A review. Intelligent Buildings International. 2011;**3**(2):67-86. DOI: 10.1080/17508975.2011.582313

[87] Hakkinen T, Belloni K. Barriers and drivers for sustainable building. Building Research & Information. 2011;**39**(3):239-255. DOI: 10.1080/09613218.2011.561948

[88] Yılmaz M. Yıldız S. Gültekin AB. Determination of disruptive innovation: Threats and opportunities in sustainable construction sector. Journal of Balıkesir University Institute of Science and Technology – BAUN. 2016;**18**(2):25-36. eISSN: 2536-5142. ISSN: 1301-7985 (In Turkish)

[89] Abidin NZ. Investigating the awareness and application of sustainable construction concept by Malaysian developers. Habitat International. 2010;**34**(4):421-426. DOI: 10.1016/j.habitatint.2009.11.011

[90] McKenzie-Mohr D. Promoting sustainable behavior: An introduction to community-based social marketing. Journal of Social Issues. 2000;**56**(3):543-554. DOI: 10.1111/0022-4537.00183

[91] Energy and Resources Institute. Sustainable Building. Design Manual: Vol. 1: Policy and Regulatory Mechanism. 1st ed. New Delhi: The Energy and Resources Institute (TERI); 2004. 160 p. ISBN-10: 8179930521 ISBN-13: 9788179930526

[92] Alnaser NW, Flanagan R. The need of sustainable buildings construction in the Kingdom of Bahrain. Building and Environment. 2007;**42**(1):495-506. DOI: 10.1016/j.buildenv.2005.08.032

[93] Roseland M. Sustainable community development: ıntegrating environmental, economic, and social objectives. Progress in Planning. 2000;**54**(2):73-132. DOI: 10.1016/S0305-9006(00)00003-9

Chapter 3

Risk Management in Construction

Esin Kasapoğlu

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.76341

Abstract

Construction industry have several different sectors producing heterogeneous products, which are immobile, unique, heavy and large, complex, durable and costly. Site conditions in a construction project can be unpredictable and unexpected natural events can negatively affect construction programs and schedules. Weather conditions constitute the most important and unpredictable handicap for the production process of construction. Construction projects usually executed over a long period and have large budgets. Because of this, demand for a construction project is volatile. Unpredictable site conditions and demand volatility bring high level of risk. Because of this, risk management is very important in construction. Construction insurance, surety bonds, contracts and subcontracting are the main affective solutions for the risk management. This study consists of two main sections. In the first section, characteristics of construction industry defined in detail. Secondly, the importance of risk management evaluated. In the second section, the focus of the study is the evaluation of risk management studies in construction with a broad literature review of previous researches.

Keywords: construction industry, risk management, insurance, surety bond, contract, subcontract

1. Introduction

Construction industry is a sector, which, in many ways, different from all others fields of economic endeavor. Loosely organized firms do non-repetitive work with handcraft methods, and use a contract system involving a serious of subcontractors. The products of the construction industry are immobile, unique, heavy and large, complex, durable and expensive. Characteristics of products changes project to project. Construction products not only takes long time to produce, but also produced and coordinated on-site; and this requires different schedules, programs and temporary solutions for each project.

Since, beginning with unpredictable site conditions and demand volatility, construction process bring high level of risk, a careful management of risks is very important in construction. Risk management is not only important for successfully completing the production process in construction industry, but also for achieving sustainability. Sustainable construction defined as creating a healthy built environment based on ecologically sound principles, and aims to create and operate a healthy built environment based on resource efficiency and ecological design [1]. A careful risk management means an effective using the resources and responsible management of a healthy built environment based on ecologically sound principles. Success lies in the details mean in sustainable construction all details require a careful design and production management.

The objective of this study is emphasizing the importance of risk management and defining affective risk management tools in construction. This study consists of two main sections. In the first section, characteristics of construction industry and construction risks are defined in detail. In the second section, the importance of risk management in building construction and risk management tools are evaluated. In this section, the focus of the study is the evaluation of risk management studies with a broad literature review of previous researches.

2. Construction industry characteristics

Construction has many characteristics common to both service and manufacturing industries. Although, construction is more like a service industry in some ways, because it does not accumulate significant amounts of capital when compared with industries such as steel, mining, transportation and petroleum; there are physical products, and often these are of overwhelming size, cost and complexity as the manufacturing industry. Success or failure in construction industry is by far more dependent on the qualities of its people than it is on technologies protected by patents out by the sheer availability of capital facilities as in service industries [2].

2.1. On-site production

In construction industry, the product is immobile and produced at the point of consumption. Each project is site specific, produced and coordinated on-site, the contractor sets up the factory on-site. Besides, all the complexities inherent in different construction sites. Subsoil conditions, weather, surface topography, transportation, material supply, utilities and services, local subcontractors, available technologies and labor conditions are an innate part of construction. Execution of the project is influenced by social, natural and other locational conditions such as weather, labor supply and local building codes. The anticipation of future requirements is inherently difficult, since the service life of a facility is long. Changes of design plans during construction are uncommon, because of technological complexity and market demands [3, 4]. In a construction project, since site conditions can be unpredictable, unexpected natural events can negatively affect construction programs and schedules. Weather conditions, for the production process of construction, are the most important and unpredictable handicap [5]. One of the two different side effects of weather conditions is unexpected changes in weather might stop, slow down or destroy production. Confining the production process to mild seasons is the other side effect of changes in weather. Construction activities show a trend of seasonality, since it is difficult to execute outdoor activities in winter. Summer is the most active and highest season for all the projects in a contractor's portfolio. Most of the production required to complete before winter, since winter is a problematic season [6].

2.2. Properties of the product

The product is changeable in construction industry. It is one-of-a-kind, large, complex, durable and long lasting. There may be big value differences among the products. Production depends on a project and construction projects typified by the non-standardized nature by their diversity and complexity. The construction process is sometimes subject to the influence of highly variable and unpredictable factors. Nearly every facility requires a long time to complete and custom designed and constructed. To some degree, each construction project is unique and two projects cannot be the same. The vagaries of the construction site and the possibilities for creative and utilitarian variation combine to make each construction project a new and different experience. Both the design and construction of a facility required to satisfy the conditions peculiar to a specific site [3, 4].

2.3. Uncertainty and high level of risk

Construction projects usually executed over a long period and have large budgets. In construction industry, demand is not regular; it is both seasonal and volatile. Construction industry is one of the industries, which is the most effected by the economic crisis. During economic crisis, demand decreases. Because of this, demand for a construction project is volatile. Irregular demand in construction leads construction firms that have difficulty in keeping their overhead down in the case of low demand. In the case of high demand, responding to the load of irregular demand forces the contractor to search for other organizational forms than the traditional forms used in manufacturing [6]. It brings uncertainty in decision-making when different production methods required or the project executed in different parts of the country or the world. Different types of products, such as dam, highway and high-rise building, executed at the same time is a source of uncertainty. Every project requires different design study and production results, which brings both uncertainty and high level of risk.

2.4. Labor specialties

Construction is an industry that involves many different participants from different fields. Owner, design professional, contractor, subcontractors and material suppliers are vital elements of the construction project. A successful project can only achieved if interrelated roles of the participants coordinated effectively. During the life cycle of the project, beginning with the owner's first contemplating a construction project to the completion, there are different types of works, vary in type and intensity, which makes the process complicated. A large number of labor specialties required in construction projects such as electrical installation, sanitary installation or thermal insulation. Cooperation of experts from different fields required, since most of these trades demand the knowledge and experience of experts and it is hard and long way for a contractor to gain this expertise through project experiences. When a problem arises, the solution will be different in a highway project, compared to a solution in a building project. Therefore, outside assistance is needed, such as consultants and subcontractors [6].

2.5. Non-routine production system

Production process in construction industry is less amenable to routinize, because products have diverse characteristics and executed over a long period. A construction firm can execute different types of projects, all of which require different production schedules and systems all at the same time. Hence, this makes the decisions of labor and machinery investments uncertain. Not only coordination of resources among different projects becomes a major problem, but also new schedules and programs are required for each new project. Since the industry requires short-term project objectives and flexibility, construction named a casual industry [6].

3. Method

The specific characteristics of construction industry make the production process risky. Construction projects are time-consuming and intricate undertakings. There are several phases requiring a diverse range of specialized services during a total development of a project. Beginning with the planning phase, the process continues passing typical jobs through successive and distinct stages to project completion. The project demand input from such disparate areas, such as governmental agencies, financial organizations, architects, engineers, lawyers, contractors, material manufacturers and suppliers, insurance and surety companies and building tradesmen [3]. These various parties from different fields have to work together in harmony for successfully completing the project. The high performance green building delivery system requires close collaboration among the parties, much more than in conventional construction delivery system [1].

This study focuses on risk management in construction through the view of sustainability. For this purpose, in the first place a broad literature review of previous studies completed. After evaluation of the previous studies, specific characteristics of construction industry identified. Since, the characteristic of the industry form the basics of risk management in construction industry, risks of construction industry are analyzed. In the last section, the study focuses on the four different tools of risk management in construction.

4. Risks of construction industry

Construction is often a hazardous undertaking work. Risk, as a multi-facet concept [11], is an uncertain event or condition [7] and can defined as the "probability that an adverse event occurs during a stated period of time" [8]. If risk occurs, it has either positive or negative effects on project objectives [7]. In the context of construction industry, according to Faber [9], it could be the likelihood of the occurrence of combination of events/factors or a definite event/factor, which occur during the whole process of construction to the detriment of project. Hertz and Thomas [10] defined construction risks as a lack of predictability about structure outcome or consequences in a decision or planning situation. It is the uncertainty associated with estimates of outcomes—there is a chance that results could be better than expected as well as worse than expected [11]. A risk means, for a construction contractor, an event that will cause costs that were not planned and from which no profit will result [12]. Risk may result substantial cost and time overruns that are detrimental the project objectives, and inherent to any construction project. Arising from delays and additional costs in particular if it comes to public construction projects, not only could project owners [clients], construction contractors but also community at large suffer from losses. Not only the contractor, but also the client's role can be critical to the success of construction projects [13]. Clients do not pay on time or dispute claims for change orders or file for bankruptcy. Contractors cannot or do not reduce fixed overhead fast enough in rough times or their cash runs short. Sometimes, subcontractors do not perform as required, or go broke [14]. It is a common fact among the participants within the construction industry continually faced with a variety of situation, involving many unknown, unexpected, frequently undesirable and often unpredictable factors [15].

The most common and well-known risks embedded in construction are the health and safety issues, delivery scheduling and aspects related to finances. The sector is full of risks that relate to planning, execution, communication and interaction with the surrounding society [16]. A primary classification of construction industry risks are natural and human risks. Natural risks occur outside human agencies or systems, while human risks arise within humanly organized systems. The sub categories of human risks relating to construction and project risks include social, political, economic, financial, legal, health, managerial, technical and cultural risks [8].

4.1. Natural risks of construction

4.1.1. Weather systems

Weather risks covers, adverse weather conditions, the probability of hurricane, typhoon, tornado, flood, tidal wave and lightning strike [8]. If it rains for 2 months while the job is coming out of the ground, meeting the schedules can be impossible [14]. Pollution is a risk factor, because dust, harmful gasses, noise, solid and all of the liquid wastes are harmful to nature and affect final quality of the construction [17].

4.1.2. Geological systems

Geological risks covers, discrepancy in geology and topographic conditions, the probability of earthquake, volcanic eruption and geotechnical fault [8]. Physical risks, such as subsurface conditions, are among the geological system risks of construction. Subsurface condition, different from anticipated, can lead to excavation costs, which is greater than expected [12]. Although, geological investigation reports provide information on the type of soil that contractors can expect to deal with, the contractor still has to rely on experience of the relative occurrences of 'adverse ground conditions' among different soil types, site conditions and site history to make judgments about the risk of adverse ground conditions on any site [18]. Site conditions, particularly subsurface conditions, can create an even greater degree of uncertainty for facilities with heretofore-unknown characteristics during operation [4]. Sometimes it can be possible that non-documented site conditions present themselves mid-project [14].

4.2. Human risks of construction

4.2.1. Social risks

This type of human risks covers criminal acts, such as sabotage and arson, civil torts, such as trespass, damage to fences, unauthorized graffiti and similar acts of vandalism, and substance abuse. While such indices are likely to result in the project proponent appearing as plaintiff or as witnesses for the prosecution, these can also lead to risks of counterclaims by the perpetrators. Social risks in construction industry are becoming a more frequent occurrence on projects vulnerable to militant protest lobbies [8]. According to Chicken [19], social risks are one of the "soft" factors in risk management for major projects, largely because of the difficulty of dealing with them quantitatively.

4.2.2. Political risks

War, civil disorder, industrial relations action are among the political risks of construction. This type of risks can arise from actions of the organization's government against other countries, such as trade embargoes. Another probability of political risks can arise from action within the home country, such as statutory amendments made to industrial relations legislation after a change in government [8]. Disapproval of the required project permits one of the other political and public risks [12]. According to Chicken [19], political risks are the other "soft" factors in risk management for major projects. Political risks are also defined by Ashley and Bonner [20] as foreign government interference with the normal conduct of business, and written mainly in the context of multinational construction firms and developers operating in foreign countries [8].

4.2.3. Economic risks

This type of risks can occur due to unexpected changes in supplying materials and labor, availability of equipment, inflation, tariffs, fiscal policies and exchange rates. Cost escalation is another economic risk of construction [12]. Warszawski [21] considered inflation as a risk factor for cost control, profit planning and other managerial decision-making aspects of construction projects [8]. Economic conditions of the past decade have negative effect on the climate of uncertainty with high inflation and interest rates. The deregulation of financial institutions, related to the financing of construction, can cause unanticipated problems [4]. Inflation is an important risk factor, because the price of construction materials rises with inflation. Sometimes, inaccurate cost estimate, underestimation of construction costs due to lack of information [22], that when many unforeseen factors may occur in construction activities causing the estimated cost to deviate from the real cost is another risk factor. Long-term investment can be a risk factor, especially when the project delivery approach requires the contractor to make large endowments in advance [17].

4.2.4. Financial risks

This type of risks are about funding of the project and national and international impacts [23] can result unexpected changes in interest rates, credit ratings, capital supply, cash flows and rentals. Jaafari et al. [24] concluded at the end of their research that a prudent pre-construction risk evaluation of the project in real life would have revealed its financial feasibility [8]. Sometimes the cost certain materials spikes unexpectedly. Other times, suppliers can cut off credit [14]. Unavailability of funds, which means client's poor management of funding in the development of construction projects, is another risk factor [17].

4.2.5. Legal risks

Risk allocation through the contractual aspect of building procurement covers contract clauses, regulations, code and changed labor's safety laws or regulations. Legal risks, since the processes and remedies of subcontractor default, are widely found in the construction contract literature [8]. Contractual risks, such as risks assigned by contract over which the contractor has no control, are among the legal risks [12]. Amphibious contract, which means when the clauses of the contract are hard to understand because of the loose or awkward way in which they written, is an another important risk factor. Governmental bureaucracy, which means excessive approval procedures in government departments, is another source of risk [17]. Since inability to know what will be required and how long it will take to obtain approval from the regulatory agencies, the environmental protection movement has contributed to the uncertainty for construction. When the problems continue, after re-evaluation of the problems, additional costs can occur. Public safety regulations, which have been most noticeable in the energy field involving nuclear power plants and coal mining, have similar effects. As projects move through the stages of planning to construction, new dimension of uncertainty is added, can make it virtually impossible to schedule and complete work at budgeted cost [4].

4.2.6. Health risks

A construction site is an environment vulnerable to viruses and infectious diseases. Health risks of construction are occurrence and impact of epidemic on construction projects [8]. Construction accidents resulting from operating errors or carelessness [22] and the occurrence of safety failures in construction forms an important health risk. When resulted with accidents, safety failures, may lead to surgeries, which is the other health risk category for construction projects.

4.2.7. Managerial risks

Inefficiency of owner supervisors, productivity of labor, productivity of equipment and labor disputes [23] can lead to problems with the productivity on-site, quality assurance, cost control and human resource management. Labor availability and labor productivity, strikes and safety risks, such as worker injury or an injury to a member of the public, are the other managerial risks of construction [12]. Managerial strategies, which form managerial risks, can affect negatively or positively worker safety behavior and can make important contributions negatively or positively to occupational health and safety knowledge for construction [8]. Deregulation of safety, which means poor safety awareness of project managers and inaccurate safety measures, is an important risk factor. On the other hand, lack of insurance, in other words, if major equipment and employees are not insured, it is another risk factor. Design variations, which may result from issues such as changes by the client or defective designs is another source of risk. Communication is very important for the sake of project, and poor communication, lack of effective communication among project partners can lead important problems. Theft is a risk factor, because employees can steal construction materials and equipment [17]. Organizational relationships are the other source of risk, since strained relationships may develop between various organizations involved in the design/construction process. When the problems occur, although the focus should be on solving the problems, discussions often center on responsibilities rather than project that needs at a time [4].

4.2.8. Technical risks

Late drawing and instructions, defective design, availability of resources, suitability of materials, defective work [23] can result in design failure, equipment and systems failure, estimation error, collision and accident. Faulty design not detected by contractor in tendering process and contraction errors due to faulty design but not checked in time by contractor are among the other technical risks [22]. A project design that is not constructible, construction-related risks such as the inability of a subcontractor to perform, construction vehicle accidents are among the technical risks of construction [12]. Reworking or delay of work, poor workmanship of subcontractor and material overuse by subcontractor with poor technique or working habits are the other technical risks [22]. Lack of high-quality staff is a risk factor that poorly trained laborers may lead to poor quality outcomes for the project. Defective construction materials that do not meet the building requirements are another risk factor [17]. Site location, and access, equipment and system failure, new technology failure, and collisions and accidents are the other technical risks. The risk associated with the introduction of new technology is an important risk factor, particularly with regard to information technology and the building procurement process. Construction technical risks can also be tracked from the bidding phase to the estimating process, and thus, to the planning and scheduling of a project [8]. The machinery break down is one of the essential technical risks inherent in all types of construction projects. The maintenance program, equipment life and haul road condition are the three input factors influence the probability of machinery breakdown. Cost overrun and project delay are the major negative impacts on project objectives are the results of machinery breakdown risk [22].

4.2.9. Cultural risks

This type of risks can occur when there are religion or/and cultural differences. Cultural issues can be relate to the risks of major international projects, but can also be found on home ground [8]. Liu et al. [25] intended to understand project risks as perceived by contractors from a perspective of culture how culture influences contractor's risk management. According to their findings, project risks perceived and managed differently in different national cultures. Risks are extended when the host country cultures differs from a contractor's expectation. International projects are inevitable that contractors could make effective plans to manage project risks, minimize the influences of cultural shock and develop a more realistic way of understanding and managing the differences. Where the host culture is similar to the contractor, risks are fewer and easier to manage than when the host culture is different [25].

The project success usually depends on the combination of all risks, although some of the individual risk factors may be more significant. Respond strategies used to mitigate risks and a company's ability to manage them is fundamental [26]. Sound management of risk is a crucial determinant of the success of a project due to an increased attention to the variations in actual quality, time and cost performance compared to the expected ones, as a consequence of a growing pressure on reducing time and costs. Carborne and Tippett [27] demonstrated that failure to deal with risk is one main cause for exceeding budget, falling behind schedules and missing performance targets.

5. Managing construction risks

Risk is difficult and inherent to deal with, and this requires, both of theoretical and practical meanings a proper management framework [11]. It has demonstrated that failure to deal with risk is one main cause for missing performance targets, exceeding budget and falling behind schedules [27]. According to Guofeng et al. [28] in construction industry, this situation is exacerbated because, project is characterized by long execution processes, huge investments, many resources and stakeholders and unstable economic and political environments bring a high level of complexity [29]. In responding the risks and uncertainty, Ranasinghe [30] showed that the engineering construction industry should not allocate contingency at a predetermined probability of success for global variables such as project cost or duration, but rather at the input level. A suitable predetermined probability of success value to allocate contingency at the input level is about 70% and with at least 70% probability of success for bill items, work package costs and durations, or activity costs and durations, then contingency available for project cost and duration can ensure a high probability of success in successful completion of the project [30].

In the past, claims for damages were regularly presented subject to the precondition that an actual or rather obvious damage or loss at the structure occurred. However, in the meantime the claim increasingly asserted in the case of defects that have not yet led to damage or loss at the structures [31]. In building construction projects, probability of risks is difficult to assess, since each project has unique characteristics. Buildings are too dissimilar and it makes impossible to say what effect any one project will have on the firm providing it. It becomes easier to generalize about probabilities, when a series of building is repetitive [32]. The benefits of risk management are tremendous in construction projects. Risk management can improve the quality of cost estimate and decision-making, help projects completed on time and within budget, lower transaction costs and facilitate better risk allocation [33].

Risk management emphasized and implemented in construction projects, regardless of the project size to assure the achievement of project objectives; however, small projects are prone to more risks. Since, they face more challenges than large projects due to their innate characteristics such as resource constraints, tight project schedule, competition and low profit margin, small projects should managed diligently to prevent schedule and cost overruns. The benefits of risk management in small project and the impact of risk management on project performance are different from those in larger projects. Actually, risk management implementation in small projects would bring about benefits that outweigh the costs in the end [33].

Project complexity, the property of a project which makes it difficult to understand, foresee, and keep under control its overall behavior, even when given reasonably complete information about the project system [34], can contribute toward the failure of projects, in terms of cost and time overruns. Qazi et al. [35] consider the decision problem of identifying critical risks and selecting optimal risk mitigation strategies at the commencement stage of a project, taking into account the utility function of the decision-maker with regard to importance of project objectives and holistic interaction between project complexity and risk [35].

5.1. Construction insurance

Construction is hazardous and the risk is significant, injury to individual workers and damage to property [14]. In any risk management program, insurance forms a major option to shift designated risks to a financially strong party, willing to assume some or all of the financial responsibility for the loss, for an agreed premium amount [2]. In construction industry, both the project owner and the contractor seek to control risk. One way project owners manage their risk requiring contractors to have certain types of insurance. Insurance protects contractors against certain events. Since, builder's risk insurance protects the owner, the general contractor, the subcontractors and the material suppliers against fire, theft and wind, while the facility is under construction; it is an "all risk" policy [12].

An insurance policy is a contract between the two parties and spells out obligations, responsibilities, benefits available and policy exclusions [14]. Purchasing insurance, to cover specific events that would result in a loss if they occur, is the primary way to manage risks. When a key piece of equipment is lost and can cause the contractor additional unplanned costs, insurance can cover the loss. If a contractor who owns and operates only one bulldozer, the loss of the bulldozer would be a risk that would put the contractor out of business. Insuring the bulldozer is a way for the contractor to manage that risk [12].

Odeyinka [36] identified the sources of insurable construction risks perceived to encounter in the Nigerian construction industry, and the types of insurance policy employed in managing them, examined how they managed through insurance premiums and investigated the effectiveness of the use of insurance. If there is any damage to the work, the risk bearing responsibility transferred to the insurance company by the contractor. The results of his study showed that great importance placed on-site security, construction risks, and health and welfare requirements, and the use of an all-risk insurance policy is the most prominent method for managing the identified risks. He found a correlation between insured sum and actual replacement cost when there are losses or damages. All-risk policies cover all the risks in construction except those specified by exclusion clauses. Odeyinka [36] concluded that actual replacement cost had a significant relationship with the claim settled. He concluded also that there was a significant correlation between the actual cost of replacement and the claim settled and the use of insurance was effective in managing construction risks [36].

Song et al. [37] investigated the possibility of using insurance for alternative dispute-resolution implementation and then subjective loss to represent the risk-averse attitude of project participants and quantify the effect of alternative dispute-resolution implementation costs in monetary terms. One approach to reduce the negative influence of uncertain alternative dispute-resolution implementation costs is to structure and price potential financial consequences of the cost losses as an insurance product. Thus, it becomes possible to transfer the risk of unexpectedly high alternative dispute-resolution costs from the project participant to insurance company. The insurance company receives a premium that covers the company's underwriting expenses and targeted profit, in return. However, the risk transfer process does not directly eliminate the possibility that a dispute will occur. Compared to the uneven occurrence of alternative dispute-resolution implementation costs in the traditional self-funded model, periodic payout of premiums helps maintain a stable cash flow and thus makes it easier to budget and plan for insurance expenditures. The risk transfer process reimburses any alternative dispute-resolution implementation costs associated with that dispute [37].

There are a number of the more common and usual types of insurance, of the general interest to owners, contractors, subcontractors, construction managers and design professionals.

5.1.1. Workers' compensation insurance

This type of insurance designed to provide the statutory benefits required by state law to an employee hurt or killed because of employment [2]. This type of insurance protects workers, injured on the job, covering medical and hospitalization expenses, plus a percentage of the hourly wage during the time the employee out of work. The worker's compensation insurance protects contractor by limiting the workers' remedy from the employer to the amount that covered by the worker's compensation law [12]. Employers required by law, maintain statutory worker's compensation insurance for their employees, and in exchange relieve of direct liability for an injured worker's claims [14].

5.1.2. Employer's liability insurance

They are the contractor safety programs that form another example of risk management. If the contraction company has a high accident rate, the company will have a high experience modifier rating. A high experience modifier rating increases the cost of worker's compensation insurance and therefore makes the contractors less competitive. A good contractor works very hard at reducing the occurrence and severity of accidents [12].

5.1.3. Comprehensive general liability insurance

This type of insurance protects against third-party liability claims for property damage or personal injury that arise from the contractors' operations and acts, and the operations of subcontractors or representatives and tailored to protect against other claims [14]. The basic policy endorsed to include coverage for contractor's and owner's protective insurance, products and completed operations, personal injury (libel, slander, etc.) blanket contractual and coverage for liability arising from the insured's automobiles. This type of insurance is against liability imposed by law for negligent acts occurring in the conduct of the business, which result in bodily injury or damage to the property of others [2].

5.1.4. Contractual liability insurance

When the contractor assumes the legal liability of the owner, designer or other designated party, *contractual liability insurance* protects him. Since, the contractor is required to assume the potential liabilities of others, most contracts contain in some form of indemnification clause or hold-harmless provision [2].

5.1.5. Professional liability insurance

This type of insurance protects architects and engineers from liability based upon professional errors or omissions in performing design, construction management or other services [2].

5.1.6. Builder's risk insurance

The aim of this type of insurance is providing protection to the insured party or parties against physical damage. Destruction of the project or temporary buildings on the job site by external causes such as fire and storm, and the insurance should include not only physical damages, but also coverage for materials stored in transit to job site waiting for incorporation into the project [14]. Builder's risk insurance is against the cost of damage of a physical nature to a building or other component of a construction project. This type of insurance covers material and equipment not yet incorporated into the work when located on site or in transit to the site. Generally it include the interests of the owner, the general contractor and material supplies [2].

5.1.7. The equipment floater policy

They protect damages to mobile and stationary construction equipment, which is not generally subject to vehicle registration. It is coverage for damage to the equipment whether located at the job site, in transit, or at the contractor's yard, but not liability and property damage insurance for cars, trucks and other equipment subject to the motor vehicle licensing laws, since they covered under other liability policies [2].

5.1.8. Wrap-up insurance

This type of insurance is established by the owners to cover the owner, contractors, subcontractors, construction managers and the designers. Basic policies generally cover comprehensive general liability insurance, excess general liability, builder's risk, worker's compensation and occasionally errors and omissions insurance. Equipment floaters, and the deductible or self-insured retention and automobile liability insurance normally continue to be the responsibility of the individual injured [2].

5.2. Construction surety bonds

A surety is a company that guaranties for a fee the obligations of one party to another party. When the surety, usually an insurance company, guaranties to a project owner that his contractor will perform as required by the construction contract between the owner and the contractor, this is a bond made in writing. The surety is obliged to the owner to see that the contract completed—up to the face amount of the bond, if the contractor defaults on his obligations under the construction contract [14]. Surety bonding is an effective risk mitigation approach to avoid the possible risk of contractor default, in the construction industry. The surety company carries the risk of contractor pre-qualification and quarantines the project completion according to the contractual obligations, when a surety company agrees to bond a contractor for a construction project. The surety company, through a surety underwriter, conducts an evaluation of the contractor to estimate contractor competency for performing a specific project [38].

A construction owner is under the risk that the general contractor will not be able to complete the project on schedule, within budget, and in compliance with plans and specifications. It is the same for the general contractor; similarly, a general contractor runs the same risk against subcontractors. A surety bond is a financial instrument used to guarantee the completion of an obligation. The oblige turn to the bonding company, step in and, on behalf of the principal, accomplish the work according to contract terms, if the principal fails to perform [39].

Kangari and Bakheed [40] identified and classified quantitative and qualitative risk factors that impact construction bond underwriting, to improve the quality of the evaluation analysis and to reduce the highly unstructured environment and the subjectivity of the bond evaluation in underwriting. The objective of their paper was, based on a set of surveys and interviews with surety companies, to identify major factors impact surety-bond evaluation. The results showed that, contractor's financial strength was the first important factor. The second one was contractors past experience or character attributes such as the quality of contractor's people and their experience, contractors past work, contractor's business plan and trust with agents. Contractor's capacity, work schedule to analyze job's consistency and potential project characteristics; and contractor's continuity that came as the least important factor among the others [40].

There are three types of common and usual construction surety bonds of the general interest to owners, contractors and subcontractors.

5.2.1. Performance bonds

Construction surety bonds, for the performance of construction contract obligations that provide a third-party guarantee. Performance bonds are one of them that guarantee performance of contract obligations to the owner as set forth in the contract, but it is not insurance. The amount of the performance bond guaranteed to make available by the surety to complete the contract in the event of default by the contractor, which represents total contract price. The surety is obligated either complete the work or to arrange with the owner to pay for the cost of completion of the work less, in the event of default [2].

5.2.2. Bid and proposal bonds

They provide guarantee for the contractor's surety that the contractor contracts and provides required bonding if selected. If the bid or proposal is successful, surety remuneration comes from furnishing the performance and payment bonds and the contractor normally does not pay any premium for bid bonds [2].

5.2.3. Labor and material payment bonds

They provide prompt payment to all those furnishing labor and/or materials to the job. Although payment is made to the subcontractor by the general contractor, this type of clause cover unpaid bills to the same subcontractor [2]. This assures the owner that the vendors do not cause to place liens on his property [14].

In some circumstances, utilizing a combination payment and performance bond, under the amount of total contract price, can be preferred [2].

5.3. Construction contract

In the construction business, contracts are the vehicles used for the procurement of everything, both services and goods. A contract is an agreement between two parties that is enforceable by law, and protects parties such as contractors against risks. When the site subsurface conditions might not be exactly what the contractor anticipated or any changes in conditions occur, examining the contract language addressing these changes makes possible to protect against risks [12]. Successful project execution requires a proper contractual foundation and construction contracts have a key role with fair, clear and comprehensive allocation of risks [23]. Construction contract risks are qualitative, based on analyst's knowledge and experience of the risks and the process by which the analyst selects and organizes such knowledge and experiences into meaningful patterns [41]. Contracts for today's extended and interconnected enterprise have growing importance. Contracts are management tools in terms of risk, opportunities for value creation, successful inter-firm collaboration, profitability and competitive advantage. Contracts can help enabling companies to share, minimize and manage risks; preventing problems; and keeping problems from developing into disputes. In a situation where a dispute is unavoidable, contracts provide evidence of what agreed and an effective means to control and resolve dispute [42]. Many countries have develop standardized conditions contract to be used in construction projects. All contracts based on the general conditions of contract that formalize risk allocation in Sweden. They assign liabilities and responsibilities of each contracting party regarding job performance, organization, timeframes, guaranties, insurances, errors and payments [43].

5.3.1. Basic requirements for an effective risk management in the content of contract

Misunderstandings, delays, claims or disputes can be unexpected losses or other negative outcomes of contracts. Including goodwill and reputation a lot is at stake and contract disputes are expensive. If contracts fail, business performance will suffer, in terms of money, management and staff time that used for productive work. Language risks and contract wording is one of the sources of contract risk. The parties seldom concur on the terms of agreement, what those terms mean, when a dispute arises. Perceptions, growing complexity and communication failures are the other sources of contract risks and help to understand the true causes of contract risk. Contracts are a record of what agreed and communicate the deal and its terms clearly, so that future disputes over their meaning avoided. Gaps in the contracting process or lack of contract management are the next contractual risk. When several organizations and supply chain are added, the process becomes more complex and delivering the promises made in documents is not easy [42].

According to Rahman and Kumaraswamy [44], appropriate, clear and equitable conditions of contract are invaluable for successful projects. Appropriate contract conditions are important to meet the specific requirements and objectives of the project. Contract conditions should be clear to define the rights and duties of project participants and unequivocally allocate risks or future uncertainties to the different contracting parties. Contract conditions also expected to be equitable, apart from merely following the often-espoused principle of assigning the risks to those best equipped to deal with them [44].

Since any construction project involves risk, eliminating all the risks associated with a specific project is impossible. Regulating the risk allocated to different parties and then properly managing the risk is all that done. The language of the construction contract can achieve this. Serving as a framework between the parties to establish which one has assumed which risk is one of the objectives of the contract. Risk sharing or risk shifting decisions made within the context of the contracting policy an owner [45]. Construction contracts not only serve as a means of pricing construction, they also structure the allocation of risk to the various parties involved.

5.3.2. Risk management with contract types

In a *lump-sum contract* [*single fixed-price contract*], all risks removed from the owner and assigned to the contractor [4] and the contractor entitled to a fixed amount of payment from the owner. It believed that lump-sum contracts can make the contractor accountable for all cost overruns and thus gives the contractor the strongest incentive to improve efficiency [46]. Under *unit-price contracts*, the contractor, in the absence of changes or impacts unforeseen by either party, takes all of the construction risk [2] and follow a strict sequential planning and design, procurement [tendering or bidding] and construction [23]. The risk of inaccurate estimation of uncertain quantities for some key tasks removed from the contractor in a unit-price contract [4]. Although the contractor may pass on much of the risk to lower tier specialty contractors when feasible, usually bears the economic risk of unusual weather conditions, strikes or other external factors that influence a contractor's cost, but which may not be directly under its control [2]. In a *cost plus fixed percentage contract*, the owner sometimes forced to assume all risks of cost overruns, especially types of construction involving new technology or extremely pressing needs. Under *cost plus fixed fee contract*, the owner assumes the risks of direct job cost overrun, while the contractor may risk the erosion of its profits if the project dragged on beyond the expected time. In *cost plus variable percentage contract*, the contractor takes the risk on its own estimate, agreeing to a penalty if the actual cost exceeds the estimated job cost, or a reward if the actual cost is below the estimated job cost. Cost plus variable percentage contract allocates considerable risk for cost overruns to the owner. Under *guarantied maximum cost contract* the contractor takes all the risks, both in terms of actual project cost and project time [4]. In this types of contracts, although the contractor may bear risks for items not under his control, eliminated the risk inherent in lump sum contracting as a trade-off for a lower guarantied fee [2]. There are possible options for improved contracting methods and better risk allocation processes such as collaborating/alliances, risk sharing/reward systems, incentive-based contracts and others. *Target cost contracts* are one of the construction contracts, often practiced in the projects with a high level of risk [47].

5.3.3. Various dimensions of contract risk management

Since the owners interested in knowing which risk factors will generate significant impacts on the projects, the identification of risks is a significant test for all major contracting parties across all building and civil engineering projects [47]. Risk allocation is the definition and division of responsibility associated with a possible future loss or gain and its objective is seeking to assign responsibility for a variety of hypothetical circumstances, if the project does not proceed as planned. Risk allocation is a part of risk management strategy, through the contractual documents. The owner generally has a tendency to pass the responsibility for most of the risks to the contractor contractually, under traditional procurement processes. A contract indicates willingness of the contractor for undertaking the work and his accepting both the controllable and uncontrollable risks. The principles behind the allocation in the documents of model or standard sets of general conditions have not clearly stated, although model or standard sets of general conditions of contract are available. Any problems can occur using any of the model or standard sets of general conditions of contract, if additional clauses affecting risk applied to them. Moreover, in today's high-risk scenarios and multiparty complex projects, the nature and extend of risks tend to be project specific that adoption of tailor-made contract strategies is more desirable [48]. According to Zaghloul and Hartman [45], with the absence of trust in business relationships, the success of any project or business relationship is always questionable. Their findings identify the relationship between trust and risk allocation practices in construction contracts. How a strong relationship can reduce the final cost of any specific project by improving the risk allocation method between the contracting parties [45].

The aim of the Chang's [46] study is to make a case for the need of incorporating the consequence of contract breakup into risk allocation decisions, and analyzed the modeling of the post-contract hazard. A compelling reason for taking this factor seriously is that contract breakup may result in contracting parties incurring substantial additional costs. Although owners have a larger stake and hence have a stronger incentive to stay in the project; contractors' staying in or leaving the project depend on their risk bearing capacity. Beginning with an analyzation of standard pain-gain sharing arrangement in construction contracts, Chang [46] found that taking no account of contract breakup hazards result in underuse of incentives. When the outturn cost also depends on the contractor's effort high-powered incentives offered to the contractor when cost variations expected to be modest, contractor's distaste for risk taking is low, and contractor's disutility does not rise steeply. According to Chang [46], contract breakup potential is an important factor and incentives more intensively used to harness the contractor's potential in cost reduction because the efficiency savings stimulated by stronger incentives can serve as a buffer for downside risks and thus reduce the expected loss of contract breakup [46].

Contract choice decisions are central to the management of risk and uncertainty. Chapman and Ward [49] indicated that the starting position has to be a best practice approach to risk management in terms of the whole project life cycle. Fully integrating a balanced incentive and risk sharing approach to contracting is of central concern for a successful risk management. A two-dimensional view of risk and uncertainty, a linked risk efficiency view of choices and addressing both expected outcomes and potential departures from expectations, is essential for this integration to work. A concern for all sources of uncertainty, including ambiguity and lack of knowledge and addressing dependence and feedback is essential for an effective contract choice decision. Clients need to choose an appropriate form of contract from available common options and facilitating appropriate choices usefully addressed within a balanced incentive and risk sharing contract framework. According to Chapman and Ward [49], comparative measurement and related comparative assessment of assumptions is the key to effective choices. They indicated that the key overall conclusion is that full integration of contract choice decisions with a best practice approach to risk management is both practical and advantageous [49].

5.4. Subcontracting

Subcontracting is outsourcing a part of the job to another group and it is widely used in construction. Demand volatility, high level of risk and uncertainty are some special conditions of construction industry that causes subcontracting and enables some advantages to general contractor, even if the size of the firm and capacity of work increase. The construction industry traditionally uses the method of subcontracting to fulfill the need for flexibility and short-term project objectives. According to Eccless [5], since bounded rationality of the general contractor in highly uncertain conditions, market contracting is preferred over vertical integration [6]. Subcontracting is another form of risk management. There is a great risk for a company performing in construction industry; a contractor can reduce project risk by hiring qualified subcontractors. The cost may be increased, but an unqualified subcontractor is a greater risk. The return justifies the cost by reducing the constructor's exposure to risk [12].

Unstable market conditions are the overriding reason for general contractors to conduct transactions with subcontractors, since subcontracting out work packages enables general contractors to be flexible in responding to potential market difficulties. The construction industry hosts an unstable and seasonal demand [i.e. market volatility] because construction firms to split into autonomous units and to rely on subcontractors to undertake some of the work packages. As construction firms prefer being flexible, general contractor-subcontractor relationship emerges as a rational response to the instability of demand in construction markets and to problems caused by seasonality. Uncertainty and asset specificity are the two dimensions of general contractor-subcontractor transactions. Uncertainty in general contractor-subcontractor transactions can both stem from the nature of the construction process and from the potential partner's performance during the course of the construction process. One of the sources causing uncertainty in the construction process is that construction operations carried out on sites, which present uncertainties regarding weather and soil conditions. Each project requires a new design and generates new production problems regarding the coordination and integration of the outputs of specialized task groups which carry out interdependent tasks; and the contracting system itself is a recipe for uncertainty since cost estimation is not an exact science are the other ones. General contractors and subcontractors also face difficulties in assessing each other's performance, which means poor performance on the part of either party, can have profound effects on the other one [50].

5.4.1. Importance of subcontracting in construction

Subcontracting is widely used much more extensively on housing and building construction projects than on engineering projects and industrial projects. Regardless of the general contractor's skills, especially building projects, it is common for subcontractors [39] perform 80–90% of the work. In spite of the benefits of subcontracting, there are some inherent risks. Quality is a critical issue and the cost of quality rectification problems is high. The contractor enters into contractual arrangements with the subcontractors in the traditional procurement arrangement option. Coordinating and controlling the works to ensure that the project delivered to time, cost and quality targets are the responsibilities of contractor. It is more risky when the main contractor in managing subcontractors, especially where the value of the subcontractors' work is significant in relation to the main contractor's work. The main contractor's performance and reputation may depend on the performance of the subcontractors. The control and coordination of the subcontractors and their works become problematic, and could result in unsatisfactory project outcomes. In this context, the main contractor becomes a construction manager and need to have sufficient construction management skills [51].

General contractor-subcontractor transactions involve a 'high human asset specific investment' and high human asset specificity is a direct result of the production technology used in the construction process. Interdependence among work groups is high, and its predecessors in the construction process define the workplace of a group. General contractors and subcontractors restrict access to transaction relationships increases the frequency of transactions between existing parties and enables them to learn from one another to overcome problems caused by newness. Learning new roles, coordination problems, developing trust and communication routes are some of these problems [50]. While main contractors do not depend on subcontracting alone, they support construction activities with their own resources, including equipment and labor. When the main contractors use their own resources, main contractors' control of the overall quality of construction is vastly improved. The control will be more affective, when the employment is direct. Contractors may get a better quality job, by having direct control on work. There is a looser relationship between employer and employee in subcontracting, and the client and main contractor have very little control over who carries out the specialist work under a subcontract [52].

5.4.2. Managing construction risks with subcontracting

Subcontracting is another way of managing risks; however, arbitrary passing down risk can create problems, relating to unequal risk allocation. Sometimes, risks not allocated to the party in the best position to manage them. People have less decision power toward the end of the construction supply chain. Increased subcontracting enables the re-distribution of risks between a numbers of subcontractors. In this process, rather than formal quantification and evaluation, perceptions of risk play an important role in determining the allocation of risk between contractual parties [53].

Mbachu [54] analyzed the various ways in which the subcontractor could contribute to the contractor's payment risks and cash flow problems. The results showed that cost management and subcontractor project implementation were the two broad classifications of risk sources. The key issues related to a lack of risk management and administration skills were the results of the evaluation of the various risk factors attributed to the subcontractor have cost management issues. Poor productivity, poor documentation and taking too many jobs at the same time were the three subsets of risk factors under the subcontractor's project implementation role. The major solution overcoming these problems was that using head contractor his/her key skills in risk management, administration and coordination to assist the subcontractor in overcoming these problems [54].

Risk commonly transferred to the subcontractor in the construction industry. According to Arditi and Chotibhongs [39], broad form indemnity, which entirely relieves the general contractor and/or owner from covering losses related to the subcontractor's performance of work, regardless of the cause or type of risk is the least balanced approach for a subcontractor. The additional insured endorsement is another risk, which is independent, but can have the same effect. The owner and/or general contractor named as insured under the subcontractor's commercial general liability policy. The waiver of subrogation is a third method of risk transfer that makes the subcontractor responsible for losses controlled by other parties. Signing a waiver, asked by the general contractor and/or owner, protects the subcontractor's insurance carrier from making any claim to recover funds from the general contractor that the carrier paid out to cover a loss [39].

6. Conclusion

The construction industry has a dynamic, challenging and high risky business environment. Since the characteristics of the industry is specific and resources used for the production are diverse and at a high rate, the process directly related with sustainability. Sustainable development movement has evolved worldwide for almost two decades and caused significant changes in construction delivery systems. Since sustainable development requires an affective and carefully consuming the resources of the earth, an effective risk management is a key for achieving sustainability in construction projects, in particular building projects, not only to secure work, but also to make profit. In construction industry, uncertainty contributes to most of the problems related to contractual, client and commercial issues. Construction projects are prone to more risk and uncertainty than any other industries, such as production or service industries. Sometimes lack of close collaboration among the stakeholders can enough to lead higher levels of risk for success of the project. A collection of different risk factors occurs for risk management consideration by the Construction Company or contractor. Uncertainty may lead to changes in the performance of the task relating to productivity, work method, supply and quality of labor and materials can affect the construction projects' time and/or cost. It is possible that sometimes uncertainty can lead to the inflated prizing or the deflated pricing in the tendering phase. There are different tools to manage risks of construction. A construction company with a well-prepared contract can overcome the difficulties of uncertainty and achieve low cost by optimizing the cost effectiveness of risk allocation. Construction insurance, surety bonds and subcontracting are the other main affective solutions for the risk management in building construction projects.

Author details

Esin Kasapoğlu

Address all correspondence to: ekasapoglu@iku.edu.tr

Faculty of Architecture, Istanbul Kultur University, Istanbul, Turkey

References

[1] Kibert CJ. Sustainable Construction: Green Building Design and Delivery. 2nd ed. New Jersey: John Wiley and Sons; 2008

[2] Barrie DS, Paulson BC. Professional Construction Management. Including C.M., Design-Construct, and General Contracting. 3rd ed. Singapore: McGraw-Hill International Editions; 1992

[3] Sears SK, Sears GA, Clough RH. Construction Project Management: A practical Guide to Field Construction Management. 5th ed. New Jersey: John Wiley & Sons; 2008

[4] Hendricson C. Project Management for Construction: Fundamental Concepts for Owners, Engineers, Architects and Builders [Internet]. 2008. Available from: http://pmbook.ce.cmu.edu [Accessed: 2017-10-19]

[5] Eccles RG. The quasifirm in the construction industry. Journal of Economic Behavior and Organization. 1981;**2**:335-357

[6] Erktin AH. Control, coordination in contractor subcontractor relationships [master thesis]. Istanbul Bogazici University; 1991

[7] Hilson D, Simon P. Practical Project Risk Management. The ATOM Methodology. Vienna: Management Concepts; 2007

[8] Edwards PJ, Bowen PA. Risk and risk management in construction: A review and future directions for research. Engineering Construction & Architectural Management. 1998;**5**(4):339-349

[9] Faber W. Protecting Giant Projects: A Study of Problems and Solutions in the Area of Risk and Insurance. England, Ipswich, UK: Willis Faber; 1979

[10] Hertz DB, Thomas H. Risk Analysis and its Applications. New York: John Willey and Sons Inc; 1983

[11] Wang SQ, Dulami MF, Agar MY. Risk management framework for construction projects in developing countries. Construction Management and Economics. 2004;**22**(3):237-252. DOI: 10.1080/0144619032000124689

[12] Knutsson K, Schexnayder CJ, Fiori C, Mayo R. Construction Management Fundamentals. 2nd ed. New York: McGraw-Hill Higher Education; 2009

[13] Wibowo A, Taufic J. Developing a self-assessment model of risk management maturity for client organizations of public construction projects: Indonesian context. Procedia Engineering. 2017;**171**:274-281. DOI: 10.16/j.proeng.2017.01.335

[14] Ganaway NB. Construction Business Management. 1st ed. USA: Butterworth-Heinemann/Elsevier; 2006

[15] Akintoye AS, MacLeod MJ. Risk analysis and management in construction. International Journal of Project Management. 1997;**15**(1):31-38

[16] Abderisak A, Lindahl G. Take a chance on me? Construction client's perspectives on risk management. Procedia Economics and Finance. 2015;**21**:548-554. DOI: 10.1016/S2212-5671[15]00211-7

[17] Lu S, Yan H. A comparative study of the measurements of perceived risk among constructors in China. International Journal of Project Management. 2013;**31**:307-312. DOI: 10.1016/j.ijproman.2012.06.001

[18] Adams FK. Expert elicitation and Bayesian analysis of construction contract risks: An investigation. Construction Management and Economics. 2006;**24**:81-96. DOI: 10.1080/014446190500310254

[19] Chicken J. Managing Risks and Decisions in Major Projects. 1st ed. London: Chapman and Hall; 1994

[20] Ashley DB, Bonner JJ. Political risk in international construction. Journal of Construction Engineering and Management, ASCE. 1987;**9**:447-467

[21] Warszavski A. Construction cost control under inflation. Journal of the Construction Division, ASCE. 1981;**107**:248-257

[22] Nasirzadeh F, Afshar A, Khanzadi M, Howick S. Integrating system dynamics and fuzzy logic modeling for construction risk management. Construction Management and Economics. 2008;**26**(11):1197-1212. DOI: 10.1080/01446190802459924

[23] Charoenngam C, Yeh C-Y. Contractual risk and liability sharing in hydropower construction. International Journal of Project Management. 1999;**17**(1):29-37

[24] Jaafari A, Coles J, Anderson R. Risk assessment on development projects, the case of lost opportunities. Australian Institute of Building Papers. 1995;**6**:21-36

[25] Liu J, Meng F, Fellows R. An exploratory study of understanding project risk management from the perspective of national culture. International Journal of Project Management. 2015;**33**:564-575. DOI: 10.1016/j.ijproman.2014.08.004

[26] Dikmen I, Birgonul MT, Han S. Using fuzzy risk assessment to rate cost overrun risk in international construction projects. International Journal of Project Management. 2007;**25**:494-505. DOI: 10.1016/j.ijproman.2006.12.002

[27] Carbone TA, Tippett DD. Project risk management using the project risk FMEA. Engineering Management Journal. 2004;**16**(4):28-35

[28] Guofeng W, Min W, Weiwei Z. Study on the existing problems and counter measures of project risk management in China. Energy Procedia. 2011;**13**:2726-2733

[29] Cagliano AC, Grimaldi S, Rafele C. Choosing project risk management techniques. A theoretical framework. Journal of Risk Research. 2015;**18**(2):232-248. DOI: 10.1080/01 3669877.2014.896398

[30] Ranasinghe M. Risk management in the insurance industry: Insights for the engineering construction industry. Construction Management and Economics. 1998;**16**(1):31-39. DOI: 10.1080/014461998372565

[31] Schieg M. Risk management in construction project management. Journal of Business Economics and Management. 2006;**7**(2):77-83. DOI: 10.1080/16111699.2006.9636126

[32] Gruneberg S, Hughes W, Ancell D. Risk under performance-based contracting in the UK construction sector. Construction Management and Economics. 2007;**25**(7):691-699. DOI: 10.1080/01446190601164097

[33] Hwang BG, Zhao X, Toh LP. Risk management in small construction projects in Singapore: Status, barriers and impact. International Journal of Project Management. 2014;**32**:116-124. DOI: 10.1016/j.ijproman.2013.01.007

[34] Vidal LA, Marle F. Understanding project complexity: Implications on project management. Cybernates. 2008;**37**(8):1094-1110

[35] Qazi A, Quigley J, Dickson A, Kirytopoulos K. Project complexity and risk management [ProCRiM]: Towards modelling project complexity driven risk paths in construction projects. International Journal of Project Management. 2016;**34**:1183-1198. DOI: 10.1016/j.ijproman.2016.05.008

[36] Odeyinka HA. An evaluation of the use of insurance in managing construction risks. Construction Management and Economics. 2000;**18**(5):519-524. DOI: 10.1080/014461900407329

[37] Song X, Pena-Mora F, Menassa CC. Insurance as a risk management tool for ADR implementation in construction disputes. Journal of Construction Engineering and Management. 2012;**138**(1):14-21. DOI: 10.1061[ASCE]CO.1943-7862.0000401

[38] Awad A, Fayek AR. Adaptive learning of contractor default prediction model for surety bonding. Journal of Construction Engineering and Management. 2013;**139**(6):694-704. DOI: 10.1061[ASCE]CO.1943-7862.0000639

[39] Arditi D, Chotibhongs R. Issues in subcontracting practice. Journal of Construction Engineering and Management. 2005;**131**(8):866-876. DOI: 10.1061/[ASCE]0733-9364[2005]131:8[866]

[40] Kangari R, Bakheet M. Construction surety bonding. Journal of Construction Engineering and Management. 2001;**127**(3):232-238

[41] Adams FK. Risk perception and Bayesian analysis of international construction contract risks: The case of payment delays in a developing economy. International Journal of Project Management. 2008;**26**:138-148. DOI: 10.1016/j.ijproman.2007.05.007

[42] Haapio H, Siedel GJ. A Short Guide to Contract Risk. 2nd ed. New York: Routhledge; 2016

[43] Osipova E, Erikson PE. How procurement options influence risk management in construction projects. Construction Management and Economics. 2011;**29**(11):1149-1158. DOI: 10.1080/01446193.2011.639379

[44] Rahman MM, Kumaraswamy MM. Joint risk management through transactionally efficient relational contracting. Construction Management and Economics. 2002;**20**(1):45-54. DOI: 10.1080/01446190110089682

[45] Zaghloul R, Hartman F. Construction contracts: The cost of mistrust. International Journal of Project Management. 2003;**21**:419-424. DOI: 10.1016/S0263.7863[02]00082.0

[46] Chang C-Y. Principal-agent model of risk allocation in construction contracts and its critique. Journal of Construction Engineering and Management. 2013;**140**(1):04013032. DOI: 10.1061/[ASCE]CO.1943-7862.0000779

[47] Chan DWM, Chan APC, Lam PTI, Yeung JFY, Chan JHL. Risk ranking and analysis in target cost contracts: Empirical evidence from the construction industry. International Journal of Project Management. 2011;**29**:751-763. DOI: 10.1016/j.ijproman.2010.08.003

[48] Lam KC, Wang D, Lee PTK, Tsang YT. Modelling risk allocation decision in construction contracts. International Journal of Project Management. 2007;**25**:485-493. DOI: 10.1016/j.ijproman.2006.11.005

[49] Chapman C, Ward S. Developing and implementing a balanced incentive and risk sharing contract. Construction Management and Economics. 2008;**26**(6):659-669. DOI: 10.1080/01446190802014760

[50] Kale S, Ardith D. General contractors' relationships with subcontractors: A strategic asset. Construction Management and Economics. 2001;**19**(5):541-549

[51] Macho J. Conceptual framework for the assessment of subcontractors' eligibility and performance in the construction industry. Construction Management and Economics. 2008;**26**(5):471-484

[52] Ulubeyli S, Manisalı E, Kazaz A. Subcontractor selection practices in international construction projects. Journal of Civil Engineering and Management. 2010;**16**(1):47-56

[53] Perez D, Gray J, Skitmore M. Perceptions of risk allocation methods and equitable risk distribution: A study of medium to large Southeast Queensland commercial construction projects. International Journal of Construction Management. 2017;**17**(2):132-141. DOI: 10.1080/15623599.2016/1233087

[54] Mbachu J. Sources of contractor's payment risks and cash flow problems in the New Zealand construction industry: Project team's perceptions of the risks and mitigation measures. Construction Management and Economics. 2011;**29**(10):1027-1041. DOI: 10.1080/01446193.2011.623708

Chapter 4

Optimization of Building Facade Voids Design, Facade Voids Position and Ratios - Wind Condition Relation

Enes Yasa

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72697

Abstract

The air flow between building interior and the courtyard to form via natural convection in hot-dry climatic regions are achieved with the help of wind pressure in other warm-humid and hot-humid climatic areas. Therefore, it is necessary to take into consideration and to humid other openings of the building which might change the effectiveness of the air movement to form due to wind effect in courtyard buildings. Therefore, wind tunnel experimental ways were developed and examined first in this study for the purpose of gaining knowledge on the effect of the wind on the cooling load of the atrium and courtyard buildings, and information to allow pre-estimation of the air flow to take place at the surface openings of such structures. Since numerical methods would not be enough alone in particular with regard to the wind, the planned study on the models was realized via the experimental method in a wind tunnel; and also Computational Fluid Dynamics numerical analyses were realized. This is a wind tunnel experimental study for the investigation of various architectural solutions for better cooling and ventilation through examination of the air flow passing through the surface openings of courtyard structures and for revelation of the effects of those results on the cooling and ventilation load. In this context, a courtyard building model was made to experiment on. Example courtyard building models were acquired by modifying various parameters (courtyard and gap area rates) to assess the test data from the boundary layer wind tunnel of wind-supported natural ventilation event of the example model courtyard structure used in the study.

Keywords: air movement, building openings, building with courtyards, natural ventilation, passive cooling, wind effects, wind velocity, wind tunnel, building facade design, building facade voids position, numerical analysis, computational fluid dynamics

1. Introduction

Architects and city planners are in general held liable for production of the plan and for coordination of the project and some vital inputs are acquired from consultants of other disciplines [1]. Planners and designers have, for centuries, considered wind or air flow as innate data for construction of components at several levels which involve cities, regions and countries [2]. Miscellaneous passive or natural air-conditioning methods taking advantage of the wind are used by architects and city planners in order to reduce the costs of cooling in territories with high temperatures [3]. As a passive air-conditioning medium, the moving air may be precious for provision of ventilation within buildings, particularly when it comes to hot and humid climates. The traditional courtyard building form entailed by climates which are hot and dry ensures that air flow is due to wind pressure variations leading to some natural ventilation [4–7].

Therefore, other openings of buildings which may cause a change on the efficacy of air movements resulting from the wind effect in courtyard buildings should be a subject for thorough study. There have been several studies, either numerical or experimental on the angle of insulation for buildings with courtyards. Nevertheless, wind effects have served as subject to a limited number of studies only. For instance, the wind attitude is to either flow over or circle in the courtyard if buildings are adjacent forming an open courtyard in a settlement area. Area of and openings position in courtyards in view of the wind (as well as openings width or total width) constitute variables that influence qualitative and quantitative wind character in courtyards [8, 9]. Outdoor layout and outdoor position have their effects on discomfort parameters for pedestrian spaces. The discomfort parameter is at its highest degree in areas subject to wind and at a medium degree in areas that are fully closed or subject to wind from a single direction [10–12]. Wind directions influence ventilation performance of buildings with courtyards and weaken if those courtyards are located in perpendicular to the wind [13]. In case buildings contain openings, openings in wind direction will cause highest speed of air flows as a number of parallel experiments have confirmed [14]. Studies demonstrate in the courtyards that maximum outdoor temperature is observed at noon time in summer of hot climates and minimum outdoor temperature is experienced prior to sunrise.

Courtyard depth is an effective variable for control of those parameters in buildings without openings [15–17]. The openings of buildings with courtyards on perpendicular areas, nevertheless, gain high significance particularly in hot/humid and moderate temperature/humid climatic territories, a parameter that is not true in hot/dry climate areas. In this study we tried to expound the effects of openings in the architecture of buildings with courtyards on airflow velocity in those courtyards. The outcomes depend on not only scale tests in the wind tunnel but also CFD numerical analysis.

2. Limitations and assumptions of the case study

2.1. Experimental process of the research project

Experimental studies have been made on 17 separate opening configurations on the façade of a building not having (BSL-SUZ) openings on its mass that surrounds the courtyards preferred as reference building. The building has been evaluated as two stories as its original scale, whereby each storey has a height of 3.00 m, the external dimensions of the building are 14.00 × 14.00 × 6.00 m but courtyard dimensions are 6.00 × 6.00 × 6.00 m. 36 separate points of measurement have been determined on X and Y dimensions in the model courtyard; and measuring profiles with 36 measurement points have been found on Z dimension at each point of measurement.

The building model in relation to the courtyard is modular to allow observation of the ventilation effects caused by the openings on the courtyard building. A reference model was made of empty Plexiglas material with dimensions of 4.00 × 4.00 × 4.00 cm to allow 17 separate configurations for courtyards. The model dimensions are 28.00 × 28.00 × 12.00 cm and dimensions for the internal courtyard are 12.00 × 12.00 × 12.00 cm.

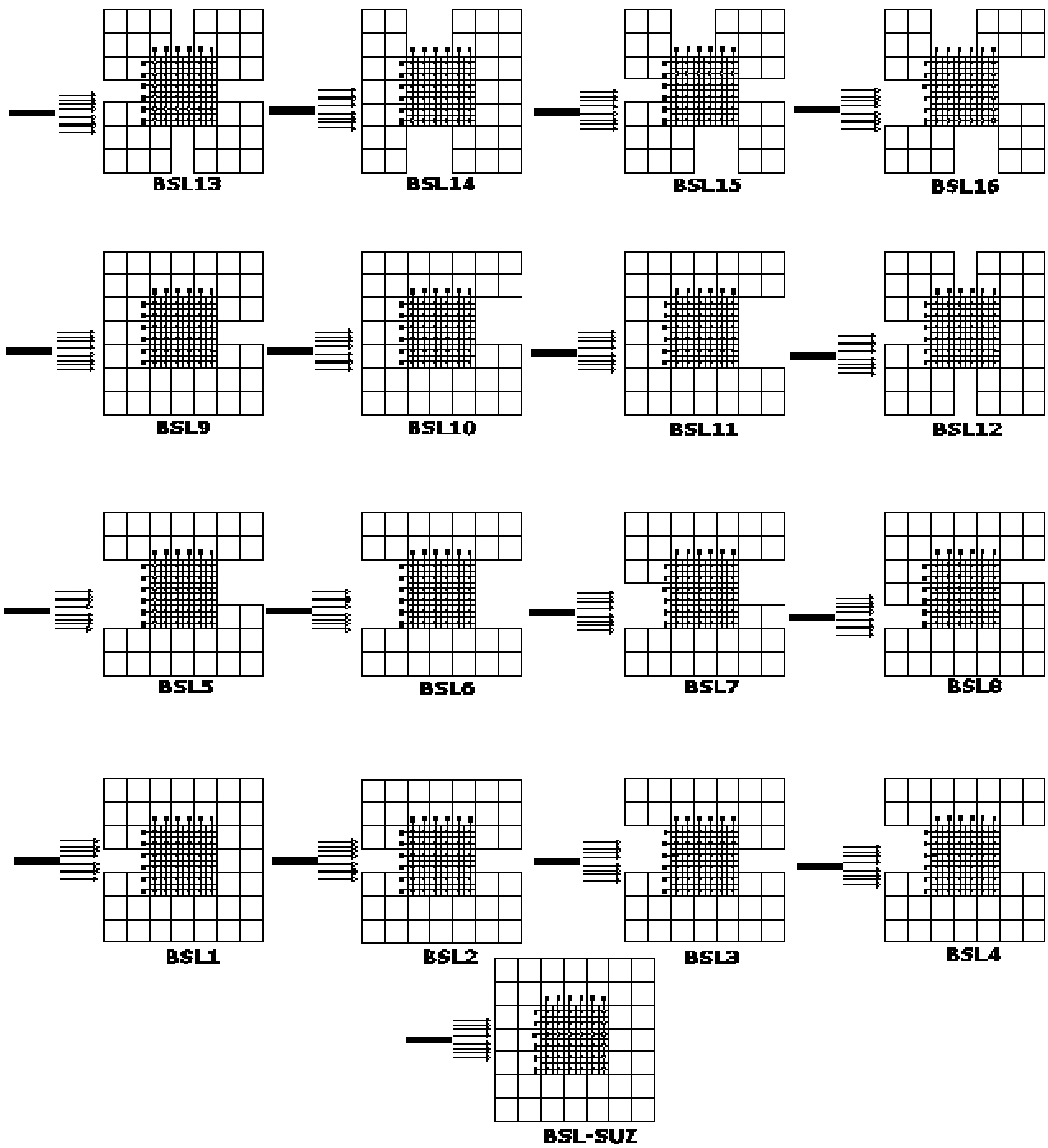


Figure 1. Appearance at ground floor plan level of the configuration for the courtyard with 17 different openings experimented [10].

The measuring axis perpendicular to the wind tunnel observation section "AB, B, C, D, E, F" lateral surface was in the wind direction. The points of measurement "1, 2, 3, 4, 5, 6" were placed on the axis perpendicular to the direction of the wind. At the courtyard, 36 points of measurement in total have been set with distances of 2.00 cm between directions of the X and Y axis. As to the points of measurement in dimension Z, profiles with 34 points of measurement have been placed at differing intervals in a way to be closer to the ground, to the roof and the opening edges that are to be organized on the model courtyard surfaces (**Figures 1–3**). At each measurement profile, nine points of measurement from 0 to 4 cm have been set at 0.5 cm intervals; 6 of them were placed at 1.00 cm intervals in the section as far as the following 10.00 cm; 14 have been placed at 0.5 cm intervals through the area between 10.00 and 17.00 cm; and another out-of-the-model 5 between 17.00 and 22.00 cm.

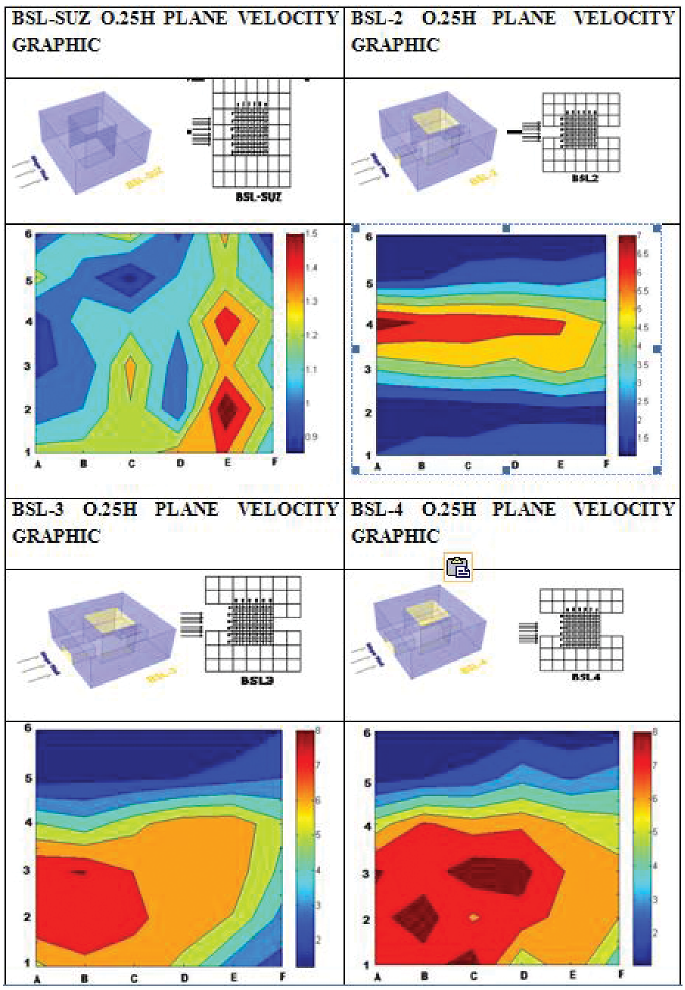


Figure 2. The wind velocity and air flow characteristics of courtyard options between BSL-SUZ-BSL-4 at 0.25H plane.

http://dx.doi.org/10.5772/intechopen.72697

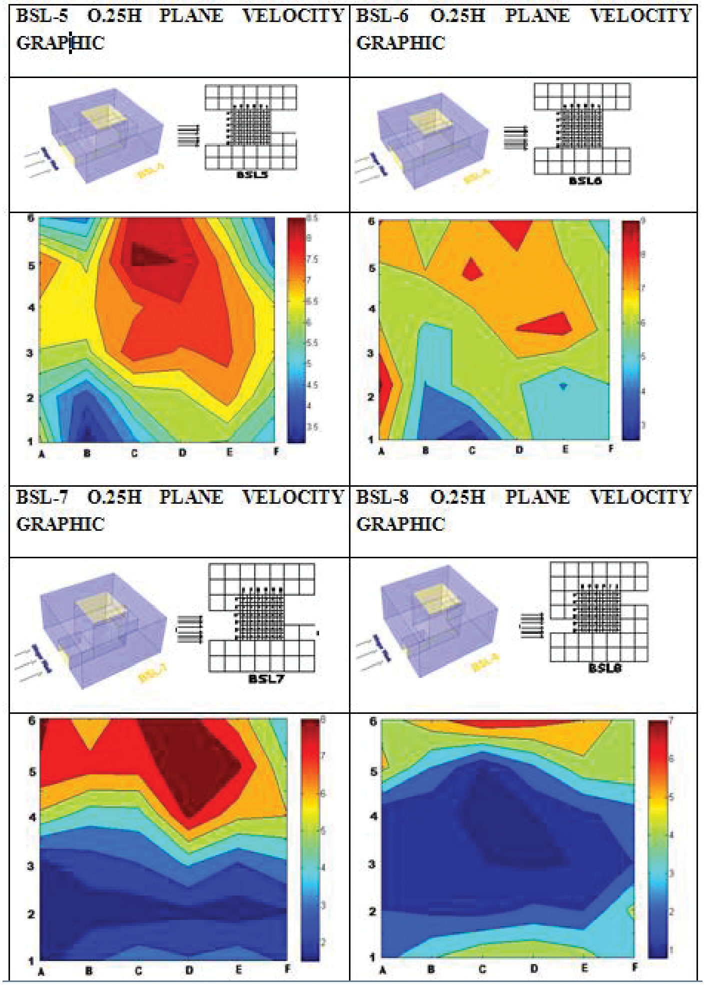


Figure 3. The wind velocity and air flow at 0.25H level for courtyard options between BSL-5-BSL-8.

2.2. Modeling and simulation in numerical analysis

Computational Fluid Dynamics have been utilized in prediction of the transfer of convective heat on the exterior of building surfaces [13–15]. The main advantages of CFD in this practice has been that: (1) it allows for analysis of a specific and complex building or building configuration; (2) it provides high data on spatial resolution; (3) it makes consideration of high Reynolds number flows for atmospheric conditions possible and (4) it makes information on the flow as well as the thermal areas available in detail.

Those former studies made possible the analysis in detail of: the Correlation over building surfaces of the distribution of the Heat Transfer Factor; the effect of turbulence in addition to the wind direction; correlation with various reference wind velocities; the thermal boundary layer, etc. Nevertheless, we need to highlight some important limitations of the numerical models applied, taking into consideration the building shell in assessment of thermal comfort and energy performance of buildings with a courtyard, as also studied in CFD. The wall section is made of several layers in various thicknesses and with miscellaneous physical properties. The external surface is subject to solar radiation (Is), convection heat transfer (qc,o) and an exchange of radiation from the sky (qr,o). The internal surface is affected by a combination of convection and radiation heat transfer (qi) in turn being relevant directly to the air-conditioning load necessary to preserve the inside design temperature (Tf,i). The following assumptions have been utilized in formulating the mathematical model:

i. Lack of heat generation.

ii. Fine contact of layers, resulting in interface resistance being negligible.

iii. Negligible variation of thermal properties.

iv. Relatively small thickness of composite roof in comparison to other dimensions. One-dimensional temperature variation has been thus assumed.

v. Constant convection factor based on the heat flow direction and daily average of wind velocity.

Taking as a basis the aforementioned assumptions,

Reynolds number:

Air intensity $\rho = 1225\ kg/m^3$

Wind speed (average) V = 30 m/s

Dynamic viscosity $\mu = 1.7894e\text{-}05\ kg/(m\cdot s)$

Building Length D = 14 m

Reynolds number has been found $28{,}75.10^6$ in view of the reference values. The flow has turbulence since the value is greater than 106.

Mach number:

$$M=\frac{V}{c} \tag{1}$$

Sound velocity $c \approx 340$ m/s

Wind velocity (average) V = 30 m/s

Mach number has been found as 0.09 in view of the reference values. Because the value is smaller than 0.3, the flow has been deemed incompressible.

Furthermore, because the properties at any point within the flow do not vary in time, the flow is defined as perpetual. According to those results, the flow is:

- incompressible,
- with turbulence

http://dx.doi.org/10.5772/intechopen.72697

- perpetual
- realized in 3 dimensions (x,y,z cartesian coordinate system).

Preservation equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) = 0 \tag{2}$$

Perpetuity equation: (for perpetual flow)(for incompressible flow)

$$\nabla \cdot \left(\rho \vec{V}\right) = 0 \tag{3}$$

$$\nabla \cdot \vec{V} = 0 \tag{4}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{5}$$

Momentum Equation:

$$\rho \cdot g - \nabla P + \nabla \tau_{ij} = \rho \frac{dV}{dT} \tag{6}$$

in case of constant intensity and viscosity in Newtonian flow (because the air is Newton type fluid): the flow is perpetual and gravity acts in negative z direction turning the equation into:

$$\begin{aligned} -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = 0 \\ -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = 0 \\ \rho \cdot g_z - \frac{\partial P}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = 0 \end{aligned} \tag{7}$$

2.3. Boundary conditions

Entering right boundary conditions in CFD is highly important to solve equations correctly. Those conditions having being determined, necessary surfaces should be designated before the analysis process to read them for analysis and post-analysis. Fluids contacting to the solid surface adheres to the surface due to viscose effect, and velocity is zero on the surfaces. Consequently, those surfaces should, for correct solution, be determined in our model.

The ground on which the fluid moves and the surfaces of the courtyard buildings being set as Wall, non-slippery condition will be applied on those surfaces. Because the flow takes place outdoors, Symmetry boundary condition will be selected for upper and lateral boundaries.

2.4. Modeling of courtyard configurations

Separate geometries were formed for each of the 17 different courtyard configurations in Fluent Design Modeler. In choosing the control volume to be calculated, attention was paid to selection of a domain where all necessary geometric and flow properties can be captured. Sensitivity was paid at a few important points for mesh and analysis in forming those geometries.

The first one of those is to make independent from the control volume the analysis in the solution area to be formed around the building. Recommendations from some resources were used to this end. It is generally recommended that if the height of the building is H and width is W, then the control volume should be at least 5H in height and 10W in width, and 2H for upward flow and 10H for the downward flow of the building. [Tutorials: Fluent Introduction - Cell Zone and Boundary Conditions] Another recommendation suggests that the upward flow value should be at least 5H and the downward flow value at least 15H [18].

An average interval was elected among those recommended values and the height of the building which was designed in dimensions of 28.00 × 28.00 × 12.00 cm at the scale of 1/200 (H = 12 cm, W = 28 cm), was set 100 cm in height, 200 cm in width, 100 cm in upward flow and 200 cm in downward flow.

The second important point is that the geometry was divided into as many parts as possible to increase the number of structural meshes in the mesh procedure. Although a structural mesh is easier to approach a solution, they still are hard to shape in complex geometries. Therefore, the geometry may require elimination of unnecessary details and division into an adequate number of smooth parts. In our model, the geometry was divided into an adequate number of parts in view of the same. Furthermore, “form new part” option was used to define under a single form to allow mesh element nodes capturing each other among respective parts.

3. Evaluation of the experimental and numerical simulation data

Surroundings suitable for people’s comfort conditions may vary in view of the environmental conditions within and outside of the building as well as user’s age, gender, metabolism level and clothing. Human body not only can produce heat through the metabolism but also consumes the heat it has produced as a result of its actions. Creation of environments suitable for all kinds of climatic comfort conditions should considered as an objective in architectural designs in view of all these conditions. Openings at different ratios and locations on the building surface have been considered for comfortable ventilation and cooling in buildings with a courtyard, an indispensable architectural feature particularly for hot-dry climatic zones, if used in other climatic zones. And drawing from that central idea of this study, which was first to experimentally investigate to what extent such openings are effective in terms of climatic

http://dx.doi.org/10.5772/intechopen.72697

comfort and then to serve as a background for a more comfortable environment through comparison of achieved findings; the information from the measurements in the existing wind tunnel and the data from the analyses with CFD were examined and interpreted in detail.

With the experimental study; it was aimed to find out the effect on velocity profiles of the rates of opening placed on the building surface, the effects of the flow types on turbulence, and the comfort conditions that can be deducted from human-climate data. The results of the measurements were compared via charts to the average velocity and turbulence values gained from measurements at heights of 0.00H–0.25H–0.50H–0.75H–1.00H–1.25H–1.50H–1.75H at 36 different pre-set points within the courtyard in the pre-set courtyard building configuration with 17 different openings. All openings were opened at ground floor level and the BSL-SUZ configuration accepted as reference building consists of a total of 40 4.00*4.00*4.00 cm boxes on ground floor level.

The opening rates on the courtyard building models with experimented 17 different openings are as follows. Openings were formed at a rate of 1/20 of the total ground floor area for BSL1, at a rate of 1/10 of the total ground floor area for BSL2, at a rate of 3/20 of the total ground floor area for BSL3, at a rate of 1/5 of the total ground floor area for BSL4, at a rate of 1/4 of the total ground floor area for BSL5, at a rate of 3/20 of the total ground floor area for BSL6, at a rate of 1/5 of the total ground floor area for BSL7, at a rate of 1/10 of the total ground floor area for BSL8, at a rate of 1/20 of the total ground floor area for BSL9, at a rate of 1/10 of the total ground floor area for BSL10, at a rate of 3/20 of the total ground floor area for BSL11, at a rate of 3/20 of the total ground floor area for BSL12, at a rate of 1/5 of the total ground floor area for BSL13, at a rate of 1/5 of the total ground floor area for BSL14, at a rate of 3/10 of the total ground floor area for BSL15, at a rate of 2/5 of the total ground floor area for BSL16 (**Figure 1**).

Although the opening rates of some courtyard building configurations are of the same value, the air velocity and turbulence values within the courtyard were found at different levels. The reason why different values have been found is the position to the wind and opening dimensions rather than same opening rates.

In BSL-SUZ courtyard building configuration, the average wind speed in the courtyard is 1.50 m/s. While turbulence values were between approximately 50 and 60% as far as 1.25H level, they have showed a decrease after 1.25H level. Although turbulence values exhibit an unstable appearance going up and down at 0.25H level, high turbulence values have been reached at other levels.

The opening rate at BSL-1-BSL-9 courtyard building configurations is 1/20. It has been seen upon comparison of the velocity values in BSL1 configuration and the values in the configuration of BSL-SUZ, the reference building, that velocity values in the courtyard show an increase. The average velocity in reference building courtyard H height is 1.50 m/s compared to BS1, which rises to 2.50 m/s. As to the windward points with opening, that rate reaches values of 4.50–5.00 m/s. Laminar flow type has been observed considering the flow values at 0.00H- and 0.50H levels. Turbulence air flow type has been observed at other levels. BSL9 configuration shows similarity in terms of lack of windward opening, yet measurements in the courtyard came out differently. The average wind velocity in courtyard at the side of the windward area without opening is the same as between 1.50 and 2.00 m/s, in contrast to the average wind velocity at the side of the windward area with the opening, which has been between 3.50 and 4.00 m/s. Consequently, the average courtyard wind velocities at the side of openings for courtyard building models BSL-1-BSL-9 with openings are almost the same, as about 3.50–4.00 m/s. The average wind velocities at sides without opening in both configurations are 1.50–2.00 m/s, the same level as the reference building.

Other courtyard building models with equal opening rates are BSL-2-BSL-8-BSL-10. Opening rate is 1/10. A comparison of BSL2 with the previous building and BSL-1 buildings show us that the wind speed within the courtyard shows quite an increase. While the average velocity value in BSL1 was 2.50 m/s at H height, it rose to values of 4.50–5.00 m/s in BSL-2. The peripheral air flow to occur in gaps left oppositely will be quite high. The openings in BSL2-BSL-4-BSL-6 configurations were left oppositely at different rates. The reason why in the three configurations, wind velocities show an increase with the opening height within the courtyard at points with opening is due to the "Venturi Effect."

BSL-8 configuration essentially shows similar features to BSL-7 configuration. The only difference of BSL-8 configuration from BSL-7 configuration is the openings widths at windward and leeward regions. The openings widths at BSL8 are less. That has increased the wind velocity at windward and leeward areas with openings.

Average wind velocities as far as H height within the courtyard are about 3.50–4.00 m/s in BSL-2 and BSL-8 model. The wind velocities along the H height within courtyard are found close to wind velocities within the reference building except in general for the points with openings within BSL-8 model (**Figure 3**).

The BSL-10 building with courtyard configuration is highly similar with the BSL-9 building model with courtyard. The only difference of BSL10 configuration from BSL-9 configuration is the openings widths at windward and leeward regions. Openings width in BSL-10 configuration is 2H/3. Consequently, measured velocities and turbulence values are almost the same. Wind velocity as far as 1.25H level is average 3.00 m/s.

Courtyard building configurations BSL-12-BSL-13-BSL-14-BSL-15-BSL-16 are different compared to other configurations. While the openings of other model buildings were at windward and/or leeward area, openings were left in both windward and leeward area and in lateral areas in those models. The air flow within the courtyard is not from the windward and leeward area only but also from lateral areas. The openings at the lateral areas of the courtyard ensure a sudden change in direction after the air flow heads toward the courtyard, and limits toward the air outlet openings on the side wall. Thus, the high rate of air flow and velocity within the courtyard will have been prevented.

The openings rates at BSL-4-BSL-13-BSL-14 building configurations are 1/5. There are quite high values at BSL-4 openings points. The average wind velocity between 0.00H and 0.50H is 7.00–7.20 m/s. Between 0.50H and 1.25H, however, it showed a sudden decrease to fall to 2.00 m/s wind velocity values (**Figure 4**).

http://dx.doi.org/10.5772/intechopen.72697

The wind velocity at average courtyard H height in BSL-13 is 3.50 m/s. The speed values at points with openings on 3-4 axis at windward region on ground level are quite high compared to other points without openings.

Since the openings left at BSL-14 configuration is only from lateral areas, the wind does not enter the building courtyard from the windward area, resulting in a fall in the courtyard wind velocity values. A comparison of the BSL-14 measurements to the measurements of the reference building, BSL-SUZ courtyard building model, showed that the air velocity values up to 1.25H and turbulence values in the courtyard were almost the same. Average wind velocity is 1.50 m/s. At that level, no speed over 2.00 m/s wind velocity value was encountered up to almost 1.25H level. A comparison of the turbulence values showed that BSL14 had higher turbulence values.

The openings rates at BSL-3-BSL-11-BSL-12 building configurations are 3/20. Although the speed values on 1-2-3-4 axes with openings in BSL3 are about 5.50–6.00 m/s, quite high up to 0.50H height, the wind speed at points on 5-6 axes without openings turned out to be about 1.50 m/s. The width at the windward area constituting the entry area with the openings is greater compared to the width at the leeward area, which constitutes the exit area. Consequently, thanks to the effect called "channel-funnel effect" at leeward area, the speed values particularly at leeward exit area are quite high (**Figures 4** and **5**).

The speed value is average 2.50–3.00 m/s at openings points within the courtyard in BSL-11 configuration. Openings were left only from the leeward area.

BSL-12 configuration differs from the other configurations examined until now. This is because openings were formed at windward and leeward areas only in the others in contrast to this one where openings were formed laterally in addition to those areas.

As a consequence, the air flow within the courtyard is not from the windward and leeward area only but also from lateral areas. The air entry openings placed in the middle of the courtyard and the openings in the middle of the lateral area ensure a sudden change in direction after the air flow heads toward the courtyard, and limits toward the air outlet openings on the side wall. Thus, a high rate of air flow and velocity within the courtyard will have been sent out before they may even occur. Average wind velocities up to 1.25H height at points within the courtyard are about 3.00–3.50 m/s. Turbulence values are high here particularly at points in the leeward area.

The openings rates at BSL-6-BSL-15 building configurations are 3/10. In BSL6, velocities of laminar flow type at very high levels between 0.00H and 0.50H such as 7.00–7.50 m/s have been achieved. Considering the flow values at 0.50H and 1.25H levels, wind velocity fell to values between 1.50 and 2.00, and velocities of turbulence flow type were achieved (**Figure 4**).

The BSL-15 building with courtyard configuration is similar to the BSL13 building model with courtyard. Consequently, courtyard and extra-courtyard measurements came out almost similar. While the openings widths at lateral areas were 2H/3, the openings widths of windward and leeward areas were at H/3 rate, and heights of the same at H/3 rate. The average wind velocity within the courtyard up to 1.25H height is about 2.50 m/s.

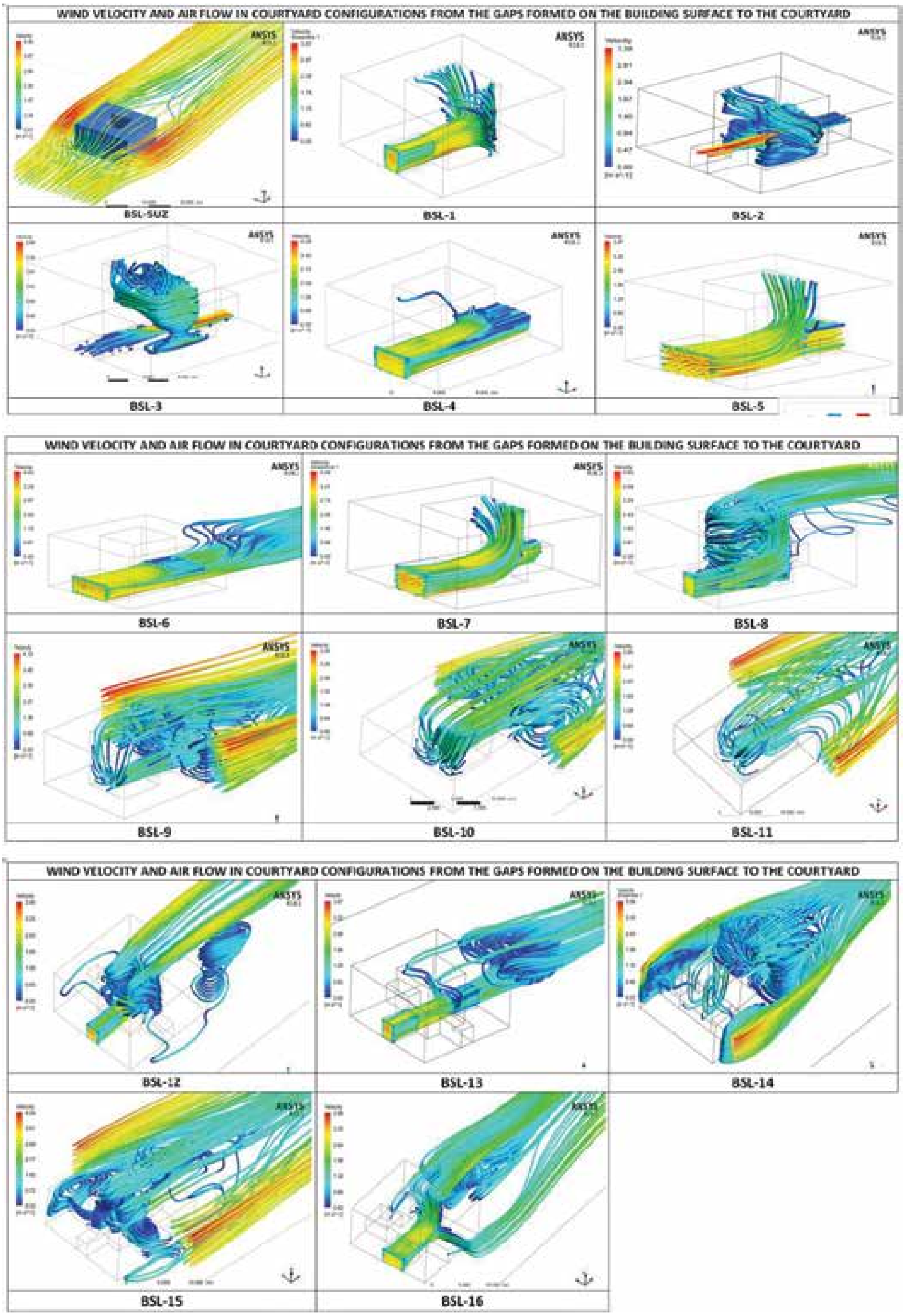


Figure 4. Wind velocity and air flow in courtyard configurations from the gaps formed on the building surface to the courtyard.

http://dx.doi.org/10.5772/intechopen.72697

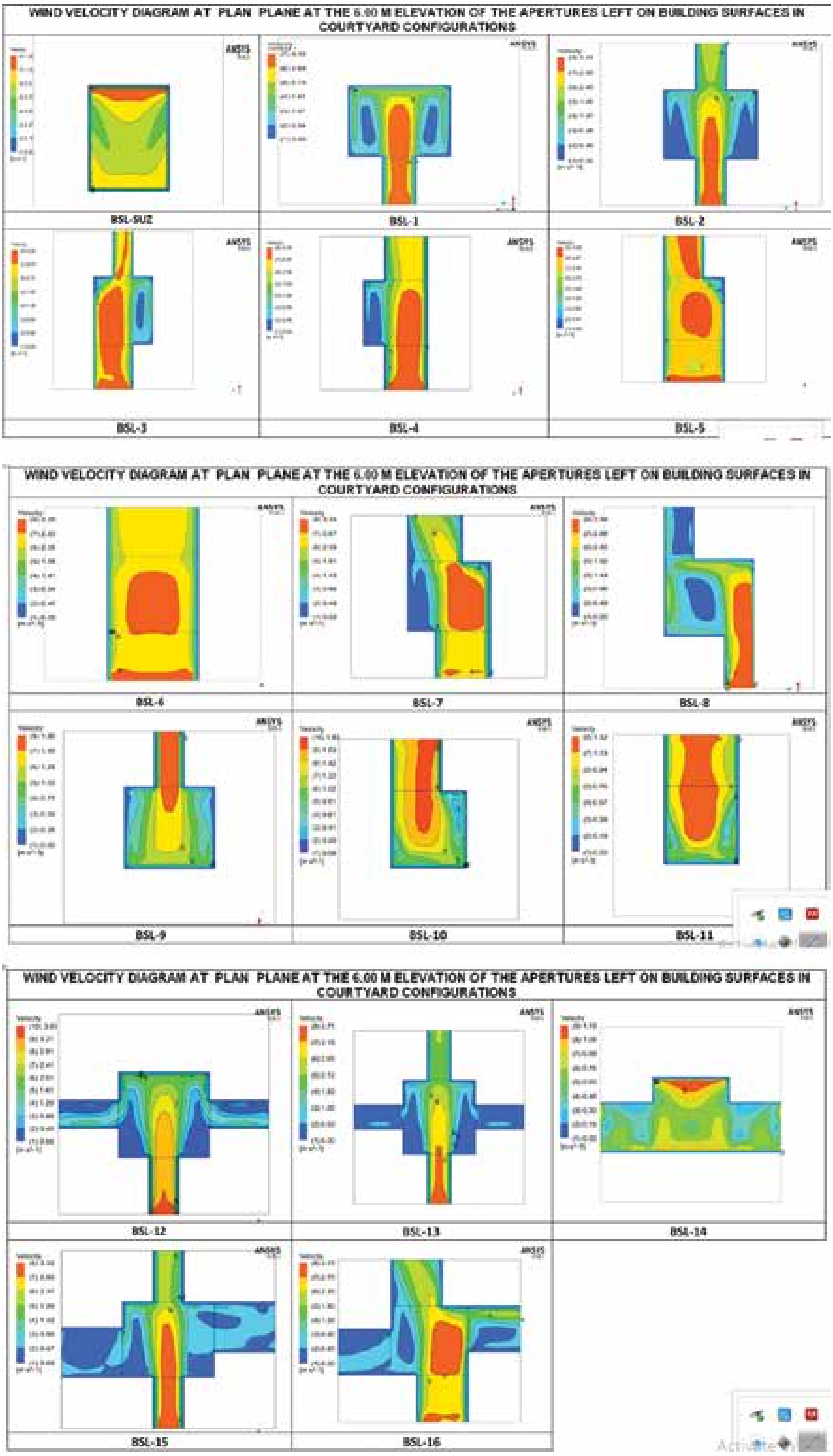


Figure 5. Wind velocity diagram at plan plane at the elevation of the openings left on building surfaces in courtyard configurations.

The BSL16 building with courtyard configuration is in fact a different version of BSL13-BSL15 models of building with courtyard. Consequently, courtyard and extra-courtyard measurements came out almost similar. The average wind velocity at points of 3-4-5-6 axes with openings is about 5.50–6.00 m/s. As to the points on windward 1-2 axes without openings, the increase of the wind velocity fell considerably to an average of 2.00 m/s. The wind velocity average between 0.50H and 1.50H is about 2.50–3.00 m/s (**Figures 4** and **5**).

As a result, the reference building model BSL-SUZ has a wind velocity of 1.50 m/s when assessed in view of average wind velocities in its region at H level area within the courtyard. There are two different velocity values within the courtyard in building configurations BSL1-BSL2-BSL3-BSL4-BSL5-BSL6. These are; while the average wind velocity is found out at high values up to 0.00H-0.50H level, the openings height at points with openings, a sudden fall occurs in locations without openings in the wind velocity values between 0.50H and 1.25H.

Wind velocities of 4.50–5.00 m/s were found for BSL1 up to openings level 0.00H-0.50H and of 2.00–2.50 m/s above openings level or at points between 0.50H and 1.25H without openings; of 5.50–6.00 m/s for BSL2 up to openings points level and of 3.50–4.00 m/s above openings level or at points without openings; of 5.50–6.00 m/s for BSL3 up to openings points level and of 1.50 m/s above openings level or at points without openings; of 7.00–7.20 m/s for BSL4 up to openings points level and of 2.00 m/s above openings level or at points without openings; of 6.50–7.00 m/s for BSL5 up to openings points level or of 2.50–3.00 m/s above openings level or at points without openings; of 7.00–7.50 m/s for BSL6 up to openings points level or of 1.50–2.00 m/s above openings level or at points without openings. There are average wind velocity values for other building configurations up to courtyard H height. Those are average velocity values of 2.00–3.00 m/s for BSL7, 3.50–4.00 m/s for BSL8, 1.50–2.00 m/s for BSL9, 3.00 m/s for BSL10, 2.50–3.00 m/s for BSL11, 3.00–3.50 m/s for BSL12; 3.50 m/s for BSL13, 1.50 m/s for BSL14, 2.50–3.00 m/s for BSL15, 2.50–3.00 m/s for BSL16.

4. Conclusions

As a result of the experimental study made; it is an experimental study aimed at presenting preliminary information for studies to be held thereafter and form a base for the designated data about exactly how much cooling and ventilation would occur within a courtyard building using numerical methods for the air flow values acquired within the courtyard. The results of this study can be summarized as follows. Courtyards of surrounded courtyard without openings (BSL-SUZ) type have minimal air velocity.

Although openings rates are same, the position of the openings becomes increasingly significant. Proportional velocity increases occur as the openings rate grows on windward and leeward opposite surfaces. In the event of different openings rates on windward and leeward opposite surfaces, velocity increases become considerable as the openings on the windward surface grows.

Very different wind velocity and ventilation characteristics are observed due to differentiation of the positions with openings in courtyard options with same openings rates. In the event of unilateral openings arrangement, the openings on the windward surface are effective at the highest level and those on the leeward surface at the lowest level. While there might be decreases in the average air movement velocity due to the relative positions and area rates of openings, points where it increases at spatial distribution may also be formed.

With this study, several experimental measurements and numerical studies will be held in relation with the building form and surface openings in courtyard buildings at different configurations and at different dimensions. As a result, it will constitute a very good reference to all studies to be held hereafter with regard to the reliability and availability of all measurements conducted and results found, and constitute a base to the design data in various conditions.

Author details

Enes Yasa

Address all correspondence to: enesyasa@yahoo.com

Faculty of Architecture, Department of Architecture, Ankara Yıldırım Beyazıt University, Turkey

References

[1] Erell E, Pearlmutter D, Williamson T. Urban climate: Designing Spaces Between Buildings. London: Earthscan/James & James Science Publishers; 2010. 266 p

[2] Ansley RM, Melbourne W, Vickery BJ. Architectural Aerodynamics. London: Applied Science Pub; 1977

[3] Awbi HB. Design consideration for naturally ventilated buildings. Renewable Energy. 1994;**5**(5):1081-1090

[4] Ratti C, Raydan D, Steemers K. Building form and environmental performance: archetypes, analysis and an arid climate. Energy and Buildings. January 2003;**35**(1):49-59

[5] Al-Mumin AA. Suitability of sunken courtyards in the desert climate of Kuwait. Energy and Buildings. January 2001;**33**(2):103-111

[6] Al-Hemiddi NA, Al-Saud KAM. The effect of a ventilated interior courtyard on the thermal performance of a house in a hot–dry region. Renewable Energy. November 2001; **24**(3–4):581-595

[7] Rajapaksha I, Nagai H, Okumiya M. A ventilated courtyard as a passive cooling strategy in the warm humid tropics. Renewable Energy. September 2003;**28**(11):1755-1778

[8] Lawson TV. Wind Effects on Buildings – Vol. 1, Design Applications. London: Applied Science Publishers; 1980

[9] Gandemer J, Guyot A. Integration du Phenomene Vent Dans La Conception du Millieu Bati. Paris, France: Premier Ministre Groupe Central deş Villes Nouvelles Secretariat General; 1976

[10] Yasa E. An experimental study on the effect of the surface openings on the air flows by the wind effect on natural ventilation and cooling [Master of Science thesis]. Institute of Science and Technology, Istanbul Technical University; February 2005

[11] Ok V et al. Yerleşme dokusu dizayn değişkenlerinin Açık mekanlardaki rüzgar hızına ve Akım tipine etkilerinin incelenmesi, TÜBİTAK Proje No. İNTAG-214, Istanbul: Istanbul Teknik Universitesi; 1996. pp. 3-4

[12] Ok V, Yasa E, Ozgunler M. An experimental study of the effects of surface openings on air flow caused by wind in courtyard buildings. Architectural Science Review. 2008;**51**(3): 263-268

[13] Sharples S, Bensalem R. Airflow in the courtyard and atrium buildings in the urban environment: A wind tunnel study. Solar Energy. 2001;**70**(3):237-244

[14] Ünal B. Bina Biçimlenmesinde Boşlukların Yakın Çevredeki Hava Hareketi Üzerine Etkilerinin İncelenmesi [Y.Lisans Tezi]. Istanbul, Turkiye: Istanbul Teknik Universitesi; 1995

[15] Grigs PF, Sexton DE. Experimental techniques for wind tunnel tests on model buildings. Energy and Buildings. 1974. CP 43/74, 11, Seiten, BRS, Garston, England

[16] Reynolds SJ. Courtyards, Aesthetic, Social and Thermal Delight. New York: John Wiley & Sons Inc.; 2001

[17] Harrouni K. Thermal Comfort in Courtyard Housing Model in Morocco. A Case Study of a Traditional House Model in the Medina of Rabat. Architecture, Energy & Environment. HDM, Lund University, Sweden; 2002

[18] Daeung Kim. The Application of CFD to Building Analysis and Design: A Combined Approach of an Immersive Case Study and Wind Tunnel Testing. Architecture and Design Research. Blacksburg, Virginia; December 11, 2013

Section 3

Energy Efficiency upon Sustainable Building Design

Advanced Control Strategies with Simulations for a Typical District Heating System to Approaching Energy Efficiency Buildings

Li Lian Zhong

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72290

Abstract

District heating systems (DHSs) are very common and important in cold areas in the world not only because of the huge energy consumption including kinds of fuel, electricity and water but also due to thermal comfort of all customers. To increase the energy efficiency and improve heating quality within the operational period, suitable and optimal control strategy should be applied for the DHSs. Thus, in this chapter, a typical DHS is designed. Based on the DHS information, a dynamic model is developed by using thermodynamic principles and corrected according to the measured operational data from real systems. The DHS properties are simulated by utilizing the open-loop tests (OLTs) of the developed actual dynamic model. System performance of operation, energy consumption and zone air temperature are addressed for several control strategies. Based on the energy consumed and indoor air temperature response, average water temperature set point corrected by equivalent outside air temperature (Case 4) and indoor air temperature control directly (Case 5) are considered, which are the best cases of optimal operation in the DHS.

Keywords: district heating system, dynamic modeling, control strategy, simulation, estimation, energy efficiency

1. General information of typical district heating systems

1.1. Introduction of DHSs

Indoor environment of living and work in cold areas in the world must satisfy certain conditions in cold period. For instance, in some Nordic countries, if people feel cold with in zone air temperature, they could run the heating system to maintain the air temperature warmer due to the DHS operated yearly. Another example is that, in China, following the heating guide, if average outside air temperature lowers than 5°C within 3 days continuously, heating systems should be run from that time (adjusted a few days actually). The space heating systems have been developed from decentralized heating to district heating, which are sometime called as central heating systems, usually with huge served heating floor area.

When the DHSs are operated from the beginning to the end, the systems have been expectedly running in an optimal way to improve their performance, increase their energy efficiency, reduce the pollutant emissions and maintain accepted indoor air temperature as well. Consequently, energy efficiency of buildings has been approached. DHS performance is related to operational data collection, status estimation, alarm, data analysis, control settings and control strategies. Energy efficiency should consider the heat transfer from the heat source to the end users, which could be separated by efficiency of heat source, pipe network and substation, respectively. Although zone air temperature is normally kept in constant, but the set points could be reasonably changed such as to increase the human body adaptability with a little bit zone air temperature fluctuation.

From energy-saving point of view, how to reduce energy consumption including fuel, electricity and water is always a hot topic, a question and a great challenge. These reasons behind are that currently DHSs integrated not only have been become larger and larger but also require strong and various technologies to assist the activity. For example, Beijing Heating Group has the biggest DHSs in the world, around 2.55 Mm^2 in 2016–2017 heating period with powerful SCADA system to support the operation.

One way to increase system energy and served building efficiency is to investigate the system properties using collected operational data and apply the results to the real system operation. However, this is time-consuming and cannot test all kinds of situations, which are expected because of potential risks. Therefore, what the efficient way could be utilized has been considered by the researchers and HVAC engineers in this field. Currently, this methodology is entitled as dynamic simulation based on mathematical modeling, which basically could be used to obtain system characteristics, study control strategies and predict energy consumption and dynamic responses of system operation.

1.2. The advantages and disadvantages of dynamic modeling

System modeling has two types of methods: one is steady-state modeling, and the other is dynamic modeling [1, 2]. The thermal capacities of DHSs are not considered in steady-state modeling process, but those have been calculated in dynamic modeling. This is because thermal capacities have profound influence in actual system dynamic responses and process control. To investigate the system responses closely to the real world, the system modeling and simulations in this chapter always refer to the dynamics. The properties of modeling can be described as follows.

1.2.1. The advantages of modeling

(1) An ideal model of an overall DHS can be developed by the first law of thermodynamics and corrected by operational data, which has been changed to the actual model.

http://dx.doi.org/10.5772/intechopen.72290

(2) Quick dynamic responses and characteristics could be gathered in the simulation with acceptable accuracy by simulating the actual model.

(3) The results could be obtained in simulation environment without any risks.

(4) The boundary conditions could be changed very efficiently by inputting different parameters and could be utilized while they are modified.

(5) Both greater efficiency and time-saving of R&D could be achieved by programming with friendly user interface.

(6) Almost all consideration and simulation could be fulfilled by using dynamic modeling to attain optimal results.

(7) The system responses such as the performance of system, energy efficiency and zone air temperature could be observed and analyzed.

(8) By using simulation method, the optimal parameters of system operation could be found and applied for real system to improve energy efficiency of buildings as well as overall DHSs.

1.2.2. The disadvantages of modeling

(1) It is relatively difficult to develop an overall dynamic model of a DHS with correction.

(2) Programming based on mathematics, control theory, optimization method and computer skills is required for various dynamic simulations.

(3) Simulations for fast dynamic system, water mass flow rate and pressure, for instance, could consume more time to get results.

(4) Very powerful computers could be required for more accurate simulation with bigger and more complex DHS system.

1.3. Methods of dynamic modeling and simulation

1.3.1. Dynamic modeling method

Any closed system must obey certain laws including energy, momentum and mass conservation [3–5]. According to the properties of DHSs, the dynamic responses mainly depend on slow response system (temperature dynamics) rather than fast response system (mass and pressure dynamics). To this end, the dynamics of fast response systems could be replaced by using steady-state method without affecting the major dynamic properties of DHSs. Energy and mass conversion are applied for the development of an overall DHS that is addressed in the following section below.

1.3.2. Dynamic simulation method

Recently, simulation methods of DHSs have played more important rule than ever followed by the progress of science and technology. The computer, algorithm, programming and software become very powerful as simulation tools. Many businesses or academic software such as BLAST, EnergyPlus, DeST, DOE-2, RNSYS, PKPM-CHEC, eQuest, VisualDOE, ESP-r, Ecotect, IES, etc. [6] can be easily obtained from various channels. However, if considering inside of the software, most of them were developed based on steady-state approach. In research area, dynamics is normally applied to equipment or partial system simulations. Few researchers are working in the dynamic simulation field for developing entire DHS modeling and try to utilize the models for system-level improvement [7–12].

1.4. Major focus on this chapter

In this chapter, a typical hot water DHS is considered and designed. Then, a dynamic mathematical model is developed based on the physical model and thermal dynamic principles. An actual model is developed by correcting an ideal model of the DHS. Following that, the characteristics of the DHS could be collected by using open-loop test (OLT) method. Finally, five types of control strategies are simulated and compared with the analysis of dynamic response, energy consumption and zone air temperature responses.

2. Design of a typical DHS

2.1. A typical DHS diagram

Due to the heated floor area of DHSs which become very larger, indirect DHSs are commonly formed in practice for major district heating field with substations. A typical DHS diagram is shown in **Figure 1**, and the meaning of symbols in it is given in the nomenclature.

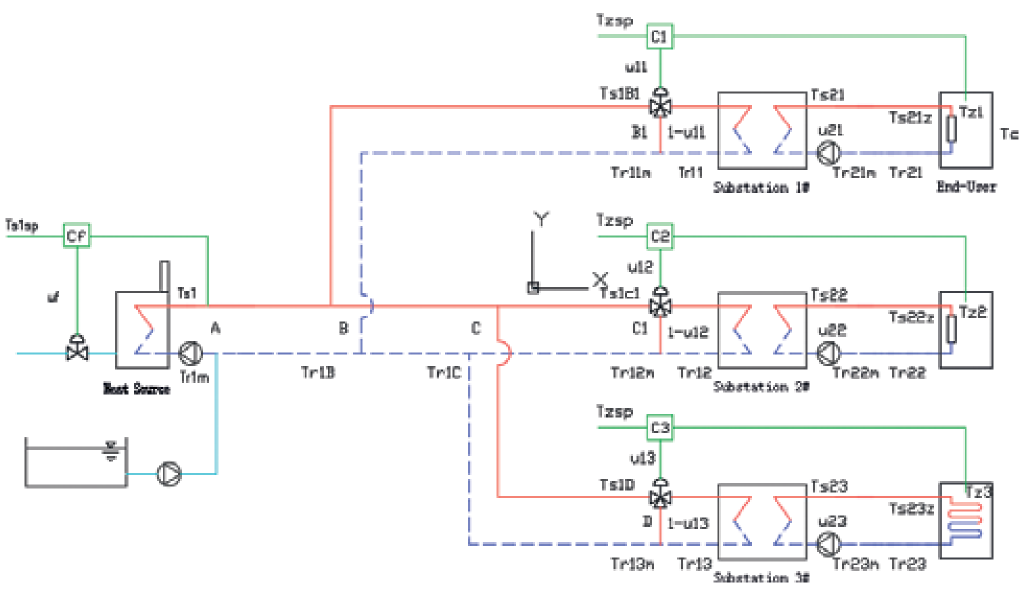


Figure 1. A typical DHS diagram with control principle.

http://dx.doi.org/10.5772/intechopen.72290

The hot water with high-level temperature (usually less than 150°C in design condition) is supplied from the boiler (sometimes from CHPs) in the heat source and transfers heat to the substations; then the heat is released to the secondary side in the substation, and the temperature of the return water in the primary side is decreased. The radiators at the end-users receive transferred heat from the substations and then are emitted to the indoor air for space heating. The supplied heat should be continuously gained to maintain suitable zone air temperature due to the heat balance between the indoor and the outdoor environments. The three-way control valves installed in the primary side of the substations are utilized to regulate the water mass flow into the heat exchangers and to balance the heat supplied to the secondary systems. Note that the makeup water systems in the secondary side are same as it is in the primary side (drawing ignored).

2.2. Subsystem of the DHS

From **Figure 1**, it is realized that the structure of the indirect DHS includes the following subsystem such as heat source, pipe network in the primary side, substation, pipe network in the secondary side, heat emit system from terminal, indoor air and outside environment.

3. Mathematical model development

3.1. Physical model

To obtain the mathematical model of the DHS, it is required to design the heating system illustrated in **Figure 1**. The design parameters are given in **Table 1**. The DHS is designed based on these parameters, which could be utilized to develop mathematical model and simulations.

3.2. Assumption of model development

The designed DHSs are a very complex system from mathematic modeling point of view because of the multiple connections among the subsystems. To simplify the dynamic model development process, several assumptions are listed below without affecting major properties of the DHSs [13]:

(1) Some parameters such as comprehensive heat transfer coefficient of buildings and heated floor area of buildings are integrated.

(2) The water leakage from the pipe network is assumed taking place in the primary pipe network of the substation and in the end-user of the secondary side, and it is divided into half in supply and half in return pipes, respectively.

(3) Transportation delay of pipe network is not considered in the system dynamics.

(4) Fast response system is expressed as steady-state condition.

(5) The solar radiation is considered from south side windows in the outside wall only.

(6) The water mass flow rate remains constant in the secondary system in each substation.

No.	Name	Unit	Data	Remark
1	Outside air temperature	°C	−20	
2	Supply water temperature in the primary system	°C	120	
3	Return water temperature in the primary system	°C	60	
4	Heat capacity in the heat source	MW	7	
5	Natural gas-fired boiler	%	92	
6	Water volume in the boiler body	T	3	
7	Supply water temperature in the secondary system	°C	75	Radiator
8	Return water temperature in the secondary system	°C	50	Radiator
9	Supply water temperature in the secondary system	°C	50	Floor heating
10	Return water temperature in the secondary system	°C	40	Floor heating
11	Indoor air temperature	°C	20	Radiator terminal
12	Indoor air temperature	°C	18	Floor heating terminal
13	Heated floor area in Substation #1	m^2	50,000	
14	Heating load index in Substation #1	W/m^2	55	
15	Water volume in the radiator of Substation #1	T	75	
16	Factor of the heat transfer coefficient test in Substation #1		0.35	
17	Heated floor area in Substation #2	m^2	35,000	
18	Heating load index in Substation #2	W/m^2	42	
19	Water volume in the radiator of Substation #2	T	38	
20	Factor of the heat transfer coefficient test in Substation #2		0.28	
21	Heated floor area in Substation #3	m^2	40,000	
22	Heating load index in Substation #3	W/m^2	35	
23	Water volume in the radiator of Substation #3	T	38	
24	Factor related to heat transfer coefficient simulation in Substation #3		0.04	
25	Heating load in Substation #1	MW	2.75	
26	Heating load in Substation #2	MW	1.47	
27	Heating load in Substation #3	MW	1.40	

Table 1. Design parameters of the DHS.

3.3. Dynamic modeling

By applying for the first law of thermodynamics and mass conservation principle, each subsystem dynamic model is shown and described briefly below:

3.3.1. Boiler model

$$C_b \frac{dT_{s1}}{dt} = u_f G_{fd} HV \eta_b - c_w (u_{11} G_{11d} + u_{12} G_{12d} + u_{13} G_{13d})(T_{s1} - T_{r1m}) \quad (1)$$

In Eq. (1), the net heat stored in the water of the boiler body is computed with the difference between the heat from the gas combustion and the heat transferred to the circulation water in the primary system. Note that the boiler efficiency is calculated according to measured operational data.

3.3.2. Substation model

$$C_{ex11}\frac{dT_{r11}}{dt} = c_w(u_{11}G_{11d} - 0.5G_{mk11})(T_{s1B1} - T_{r11}) - f_{ex1}U_{ex1}LMTD_1 \tag{2}$$

$$C_{ex12}\frac{dT_{r12}}{dt} = c_w(u_{12}G_{11d} - 0.5G_{mk12})(T_{s1c1} - T_{r12}) - f_{ex2}U_{ex2}LMTD_2 \tag{3}$$

$$C_{ex13}\frac{dT_{r13}}{dt} = c_w(u_{13}G_{13d} - 0.5G_{mk13})(T_{s1D} - T_{r13}) - f_{ex3}U_{ex3}LMTD_3 \tag{4}$$

The return water temperatures from each substation in the primary system are given in Eqs. (2)–(4). The net heat stored in the heat exchanger (primary side) is computed between the heat from the pipe network to the substation and the heat transferred in the substation:

$$C_{ex21}\frac{dT_{s21}}{dt} = f_{ex1}U_{ex1}LMTD_1 - c_w u_{21}G_{21d}(T_{s21} - T_{r21m}) \tag{5}$$

$$C_{ex22}\frac{dT_{s22}}{dt} = f_{ex2}U_{ex2}LMTD_2 - c_w u_{22}G_{22d}(T_{s22} - T_{r22m}) \tag{6}$$

$$C_{ex23}\frac{dT_{s23}}{dt} = f_{ex3}U_{ex3}LMTD_3 - c_w u_{23}G_{23d}(T_{s23} - T_{r23m}) \tag{7}$$

The supply water temperature from the substation in the secondary system is presented in Eqs. (5)–(7). The net heat stored in the heat exchanger in the secondary side is related to the heat transferred in the substation and the heat taken from the substation to the secondary system. Note that the logarithmic mean temperature difference (LMTD) is calculated in Eq. (8). Note that it refers to each substation from 1 to 3. Letter i denotes to 1–3, which is the number of substation:

$$LMTD_i = [(T_{s1in} - T_{s2zi}) - (T_{r1i} - T_{r2im})]\left[\ln\left(\frac{T_{s1in} - T_{s2zi}}{T_{r1i} - T_{r2im}}\right)\right]^{-1} \tag{8}$$

3.3.3. Radiator model

$$C_{ht1}\frac{dT_{r21}}{dt} = c_w(u_{21}G_{21d} - 0.5G_{mk21})(T_{s21z} - T_{r21}) - f_{ht1}U_{ht1}[0.5(T_{s21z} + T_{r21}) - T_{z1}]^{(1+k1)} \tag{9}$$

$$C_{ht2}\frac{dT_{r22}}{dt} = c_w(u_{22}G_{22d} - 0.5G_{mk22})(T_{s22z} - T_{r22}) - f_{ht2}U_{ht2}[0.5(T_{s22z} + T_{r22}) - T_{z2}]^{(1+k2)} \tag{10}$$

$$C_{rf}\frac{dT_{r23}}{dt} = c_w(u_{23}G_{23d} - 0.5G_{mk23})(T_{s23z} - T_{r23}) - f_{rf}U_{rf}[0.5(T_{s23z} + T_{r23}) - T_{z3}]^{(1+k3)} \tag{11}$$

The return water temperature from the end-user (radiator and radiant floor heating) is addressed in Eqs. (9)–(11). The net heat stored in the terminal equals to the heat difference between the heat gathered from the circulation water and emitted to the indoor air.

3.3.4. Indoor air model

$$C_{z1}\frac{dT_{z1}}{dt} = c_w(u_{21}G_{21d} - 0.5G_{mk21})(T_{s21z} - T_{r21}) + q_{sols}F_{s1} + q_{\text{int}}F_1 - U_{en1}(T_{z1} - T_o) \tag{12}$$

$$C_{z2}\frac{dT_{z2}}{dt} = c_w(u_{22}G_{22d} - 0.5G_{mk22})(T_{s22z} - T_{r22}) + q_{sols}F_{s2} + q_{\text{int}}F_2 - U_{en2}(T_{z2} - T_o) \tag{13}$$

$$(C_{z3} + C_c)\frac{dT_{z3}}{dt} = c_w(u_{23}G_{23d} - 0.5G_{mk23})(T_{s23z} - T_{r23}) + q_{sols}F_{s3} + q_{\text{int}}F_3 - U_{en3}(T_{z3} - T_o) \tag{14}$$

Zone air temperature dynamic responses can be represented in Eqs. (12)–(14). The net heat stored is related to the heat obtained from the circulation water in the secondary system, the solar radiation from south side windows, the internal heat gains and the heat transferred to the outside environment. Note that the thermal capacity in the terminal of floor heating is considered by accumulating the influence of the concrete structure.

3.3.5. Pipe segment in the primary and secondary systems

$$C_{segj}\frac{dT_{segoutj}}{dt} = c_w G_{seginj}T_{seginj} - c_w G_{segoutj}T_{segoutj} - Q_{mksegj} - Q_{hlsegj} \tag{15}$$

The schematic diagram of a pipe segment is shown in **Figure 2**. The makeup water and the heat loss from the pipe insulation are considered to gather the water temperature left from the pipe segment. The supply water temperature from the pipe segment is related to the heat loss from the pipe segment, while the return water temperature has been considered in the heat losses from pipe insulation and makeup water. In Eq. (15), the net heat stored in the pipe segment equals to the heat received from the entrance minus the heat outlet from the exit and the heat losses from both makeup water leakage and pipe segment. Note that supply pipe segments do not consider the water leakage by the assumption. Letter j represents each pipe segment.

In summary, 29 dynamic equations are used to address the overall DHS mathematical model. The developed model is utilized to obtain system properties, simulate various dynamic responses of control strategies and compare with system energy consumption.

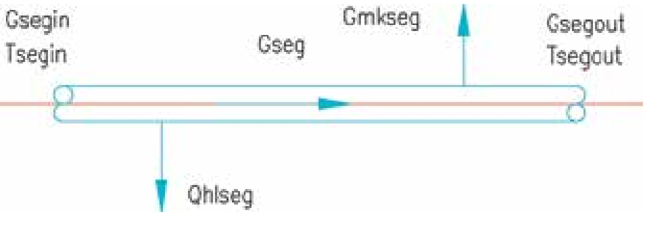


Figure 2. Schematic diagram of a pipe segment.

4. Actual dynamic model corrected by using open-loop test

4.1. The purposes of OLT

The purposes of doing OLT based on the developed dynamic model are stated hereby. Firstly, the mathematical model should be checked out with ideal condition to ensure the accuracy. Then, by applying the experience and operational data, the ideal dynamic model could be corrected to seek the characteristics of the DHS and various simulations.

4.2. Ideal model of the DHS

The ideal conditions represent that outside and indoor air temperature and water mass flow rate in primary and secondary system are same as their design values. The affluent factors of both heat transfer area of each substation and terminal equal to 1. No solar radiation and internal heat gains exist in the ideal dynamic system. The heat losses from both water leakage and pipe network are ignored.

With these situations, the dynamic responses of the ideal model with the fuel control signal by 0.798 are shown in **Figure 3**. In addition to the zone air temperature in Substation #3, which is equal to 17.9°C due to the huge thermal capacity of the floor heating structure, the supply and return temperatures from the heat source and substations are identical to the design conditions. Steady-state time of the water temperatures and zone air temperatures except for the zone air temperature in Substation #3 (48 h) reaches 15 h similarly.

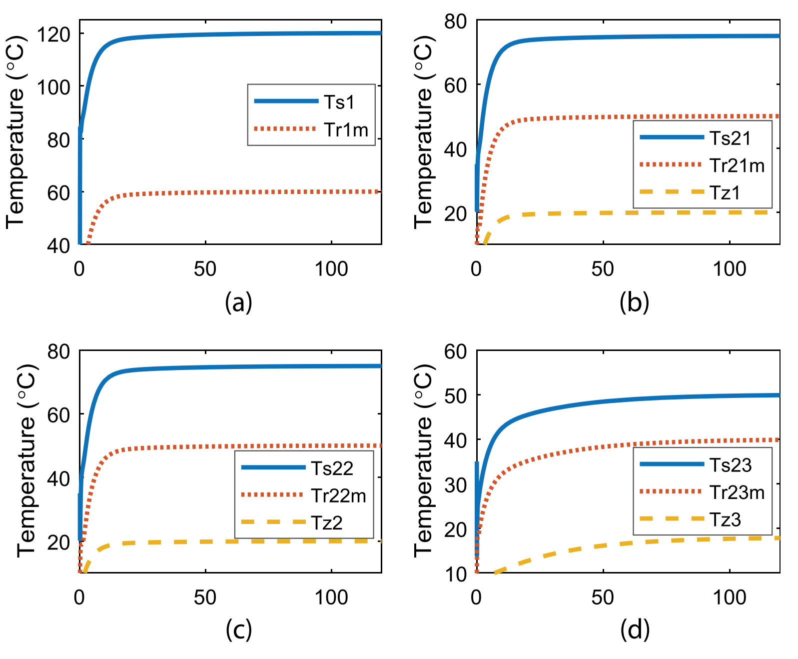


Figure 3. Dynamic responses of ideal model (a) Time(h), (b) Time(h), (c) Time(h), (d) Time(h).

4.3. Actual model of the DHS

In practice, the affluent factors of both heat transfer area of each substation and terminal are greater than 1 because of the safety consideration from designers. The circulation water flow rate could be adjusted rather than design values. With these situations, the ideal dynamic model should be modified to simulate the real DHS, which is entitled as actual dynamic model. Regarding the experience and operational data of typical DHSs in China, the affluent factors of each heat transfer area and terminal in Substations #1–#3 are provided as [1.4, 1.4, 1.4, 1.5, 1.35, 1.4], respectively.

While outside and indoor air temperature and water mass flow rate in primary and secondary system are identical to their design values, no solar radiation and internal gains exist, the water leakage and heat losses from pipe segments are considered, the control signal of fuel equals to 0.854 and the dynamic responses of the temperatures from actual model are shown in **Figure 4**. In this figure, the steady-state values of the supply and return water temperatures from the heat source and Substations #1–#3 are 97.5, 33.2, 57.6, 31.6, 58.6, 33.6, 38.4 and 28.1°C, while the zone air temperatures equal to 20.8, 19.6 and 18.8°C, respectively. From the values, the supply water temperature from the heat source is not necessary to satisfy its design value (120°C), while outside air temperature is −16.9°C. Meanwhile, the zone air temperatures are not same as the design values. The reason behind is that the affluent factors of the heat transfer area affect the operation very much in the DHS. It is also hinted that the zone air temperature should be controlled separately because they cannot approach its design value simultaneously.

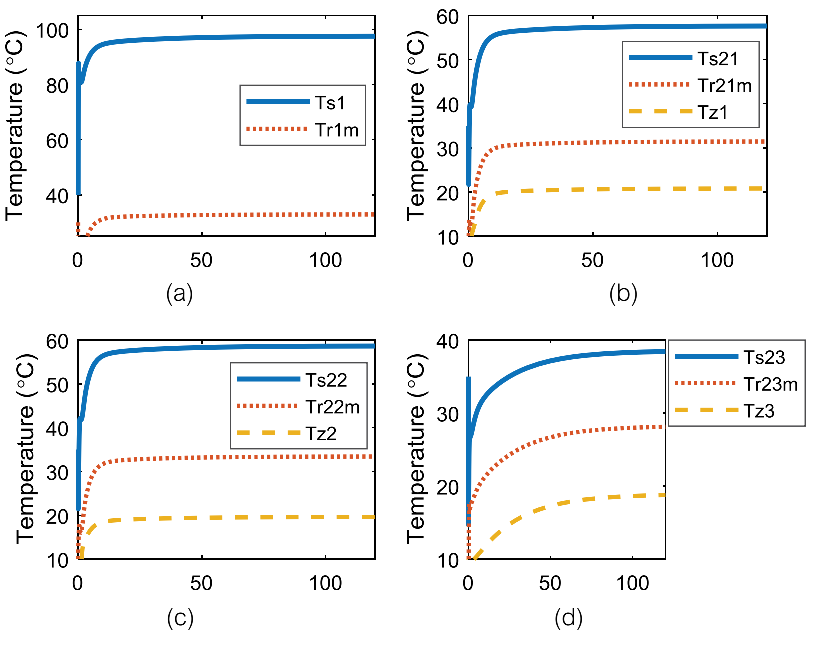


Figure 4. Dynamic responses of actual model (a) Time(h), (b) Time(h), (c) Time(h), (d) Time(h).

5. Advanced control strategies and simulations

5.1. System disturbance

Usually, the disturbances taking place in DHSs include outdoor air temperature, solar radiation and internal heat gains, while outdoor air temperature plays the biggest rule in system operation. On the other hand, when the comprehensive heat transfer coefficient (U_{en} value) of the buildings is getting smaller and smaller, the additional heat gains (solar radiation and internal gains) should be considered in the simulation and in real system operation. In this chapter, outdoor air temperature, solar radiation and internal heat gains are drawn into actual model with the range from 8.2 to 13.1°C, from 0 to 45 W/m^2 and from 0.9 to 6.8 W/m^2, respectively, for all simulations of the cases.

5.2. Control signals

In many circumstances, DHSs are operated with experience; likely, the supply water temperature from the heat source has been controlled depending on the experience of operators. Nevertheless, the disturbances described above change based on time. It means that the heating supply from the heat source and the heat consumption (heating load) should be tracked and balanced. Thus, the DHS must be regulated accordingly. Otherwise, the zone air temperature could fluctuate in larger range, which influences thermal comfort of end-user. By simulating the dynamic responses of actual model with different conditions (change outdoor air temperature, indoor air temperature as similar as design value, design water mass flow rate in the pipe network, constant water leakage rate, considered pipe insulation heat loss, no solar radiation and internal gains), the simulated stable results from OLTs are listed in **Table 2** as set points for related parameters used in control strategies.

5.3. Control strategies

Five cases are selected for dynamic simulations (given in **Table 3**) to study the system responses, the energy consumption (heat consumed in the cases) and the thermal comfort of the end-user [14–17]. Note that typical PI algorithm is used to all controllers to gather output signals [18].

5.4. Case study based on dynamic simulation

5.4.1. Case 1

Many operators run DHSs according to their experience if they cannot realize the set points of supply water temperature from the boiler. In this case with 5 days consciously, the dynamic

T_o, °C	15	10	5	0	−5	−10	−16.9	−20
T_{s1}, °C	37.5	49.1	54.2	70.6	81.1	91.4	104.2	111.8
T_{w2arg1}, °C	24.5	28.5	29.2	35.3	38.4	41.3	44.5	46.9
T_{w2arg2}, °C	25.1	29.3	30.2	36.6	39.8	43.0	46.5	49.0
T_{w2arg3}, °C	20.4	22.7	21.8	26.5	28.3	29.9	31.6	33.2

Table 2. Set points used in control strategies.

responses of the DHS are presented in **Figure 5**. From this figure, the supply water temperature from the boiler changes depending on the outside air temperature (**Figure 5(a)**). The average water temperature responses of the secondary side in Substations #1 and #2 are almost similar and higher than that in Substation #3 due to the difference between the radiator and the floor heating terminals (**Figure 5(b)**). The difference of indoor air temperature dynamic responses shown in **Figure 5(c)** is mainly resulted from the structure of terminals. By

Case	Control strategy	Description	Used controller
1	Experienced T_{s1} control	Supply water temperature from the heat source controlled based on experience	C_f
2	Tuned T_{s1} control	Supply water temperature from the heat source controlled based on tuned set points	C_f
3	Tuned T_{s1} and T_{w2arg} control	Supply water temperature from the heat source and average water temperature in the secondary system of each substation controlled based on tuned set points	C_f, C_1, C_2, C_3
4	Tuned T_{s1} controlled based on T_o and T_{w2arg} controlled based on T_{oe}	Supply water temperature from the heat source controlled based on T_o and average water temperature in the secondary system of each substation controlled based on equivalent T_o (T_{oe})	C_f, C_1, C_2, C_3
5	Tuned T_{s1} controlled based on T_o and zone air temperature controlled based on T_z	Supply water temperature from the heat source controlled based on T_o and zone air temperature in each substation controlled based on T_z	C_f, C_1, C_2, C_3

Table 3. Control strategies used in the cases.

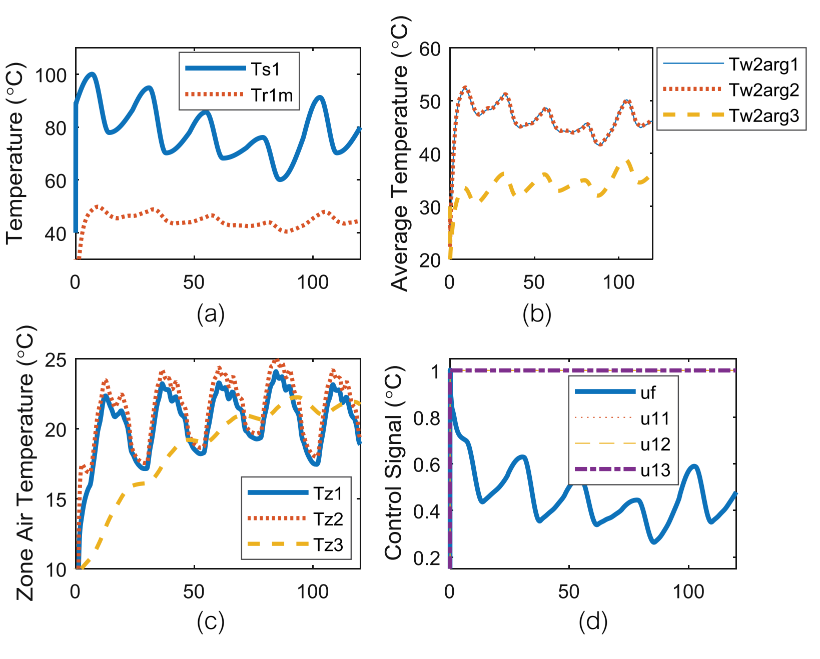


Figure 5. Dynamic responses in case 1 (a) Time(h), (b) Time(h), (c) Time(h), (d) Time(h).

considering the responses of the last 2 days rather than the influences of the initial parameter settings, the average and the range of the zone air temperatures in Substations #1–#3 are 20.2, 17.4–24.1, 20.9, 18.1–25.2, 21.1 and 20.7–22.2°C, respectively. The control signal of fuel in the heat source is changed based on the heating load (**Figure 5(d)**). The water mass flow rate in the pipe network is set to be the design values.

5.4.2. Case 2

From the simulation by using experience of the supply water temperature from the heat source, the average zone air temperatures excess their design values with bigger fluctuation. This situation should be improved by utilizing tuned supply water temperature set points (T_{s1sp}). With T_{s1sp} given in **Table 2**, the simulation results are shown in **Figure 6**. With the tuned setting value, the average zone air temperatures in Substations #1–#3 are given as 19.7, 20.2 and 20.1°C, meaning that average zone air temperatures are reduced comparing with those in Case 1.

5.4.3. Case 3

From Cases 1 and 2, the average and the fluctuation of zone air temperatures are still larger than the expected results. Because the heat properties of the substations are different, indoor air temperatures should be controlled separately to balance their heat supply and requirement. In this situation, the simulation is made and shown in **Figure 7** for zone air temperature responses only, and considering the time-consuming simulation, the time span is decreased to

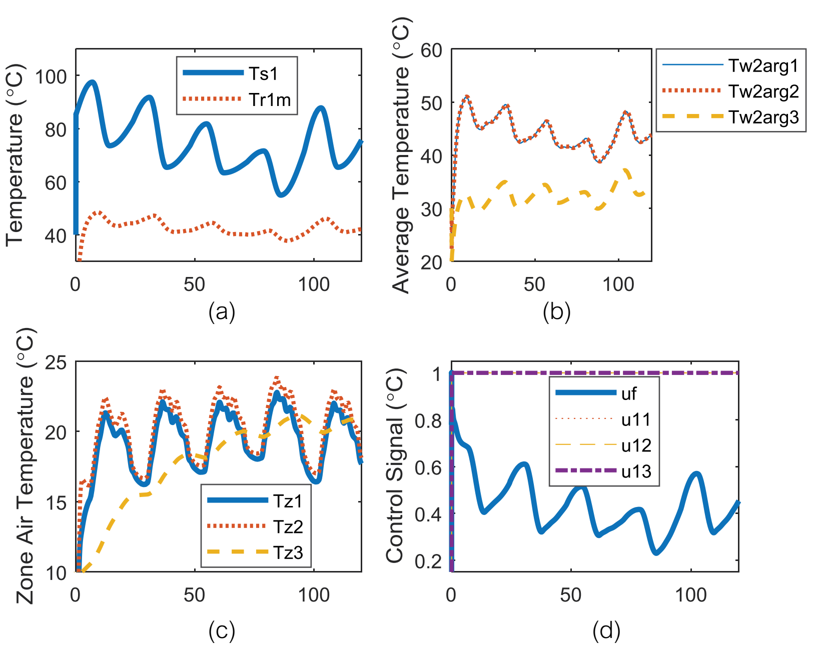


Figure 6. Dynamic responses in case 2 (a) Time(h), (b) Time(h), (c) Time(h), (d) Time(h).

2 days continuously. The results illustrate that the fluctuation of zone air temperatures is reduced significantly, but average zone air temperatures are still high compared with their design values.

5.4.4. Case 4

The meaning behind average zone air temperatures excessed the deign values is that the disturbances are never considered in the control algorithm. Consequently, a concept of an

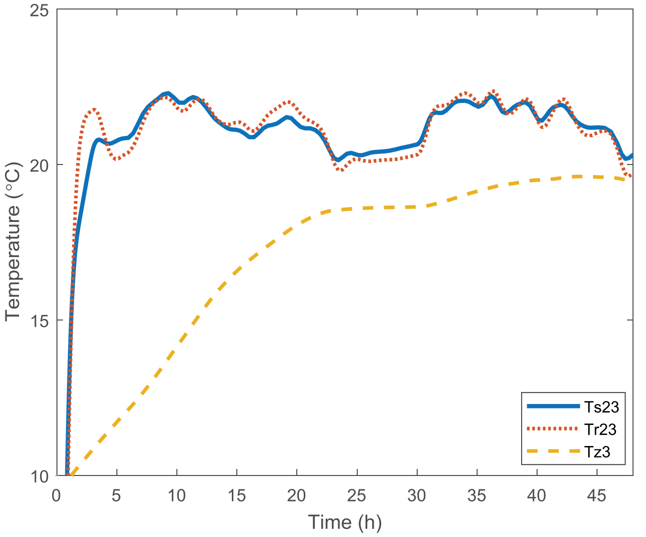


Figure 7. Dynamic responses in case 3.

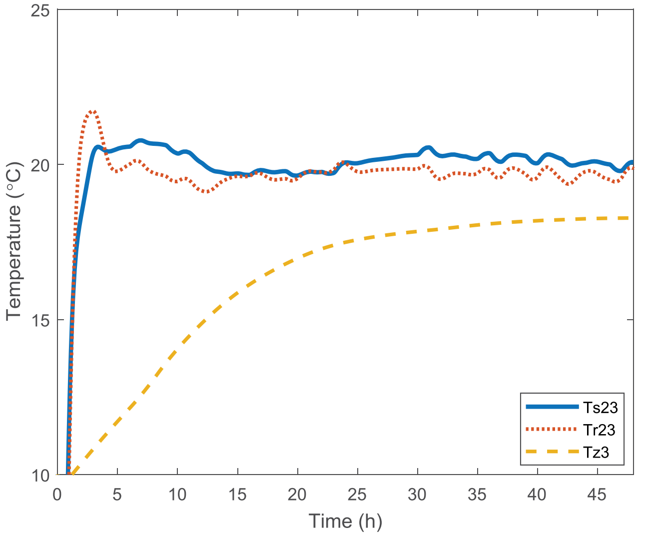


Figure 8. Dynamic responses in case 4.

equivalent outside air temperature is introduced to reset the original average water temperature set points and improve the stability and decrease zone air temperature swing. The equivalent outside air temperature is calculated in Eq. (16). This case is simulated and addressed in **Figure 8**. Compared with **Figure 7**, the purpose of decreasing zone air temperature fluctuation is realized perfectly:

$$T_{oei} = T_o + \left(q_{sols}F_{si} + q_{\text{int}}F_i\right)U_{eni}^{-1} \tag{16}$$

5.4.5. Case 5

As known that, average water temperature in a terminal is related to the zone air temperature indirectly, and the return water temperature from the terminal is delayed due to the thermal capacity of the terminal. If the zone air temperature is measured and applied for the control strategy, it would be better to elevate the thermal comfort of indoor environment. To this end, the simulation is made and shown in **Figure 9**. The dynamic responses of zone air temperatures in Substations #1–#2 are improved very much. Because of the huge thermal capacity of the radiant floor heating structure, the zone air temperature in Substation #3 although approaches 18°C still needs more advanced control strategy such as predictive control or two-temperature control to improve the dynamic response of zone air temperature.

5.5. Comparison with energy consumption

Due to relevant smaller parts of electricity and water consumption in DHSs, the heat consuming is considered only for energy comparison. The simulated results in the fuel control signal responses are presented in **Figure 10**. From this figure, the fuel consumption in Case 2 has the lowest value but with larger zone air temperature fluctuation. By observation with all cases,

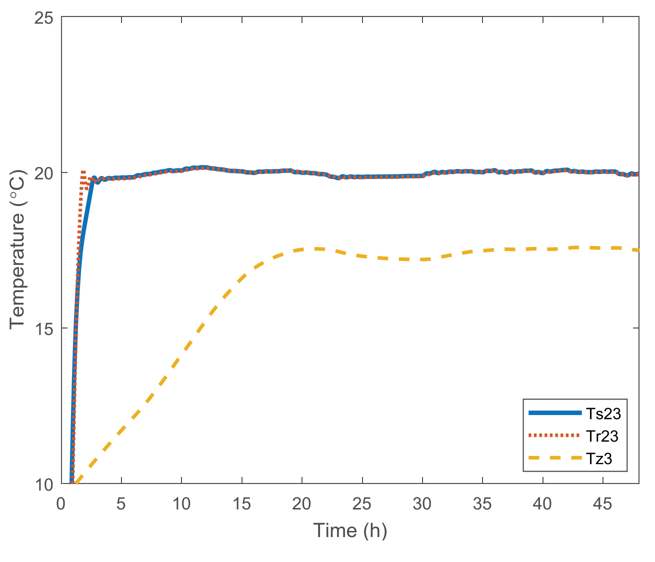


Figure 9. Dynamic responses in case 5.

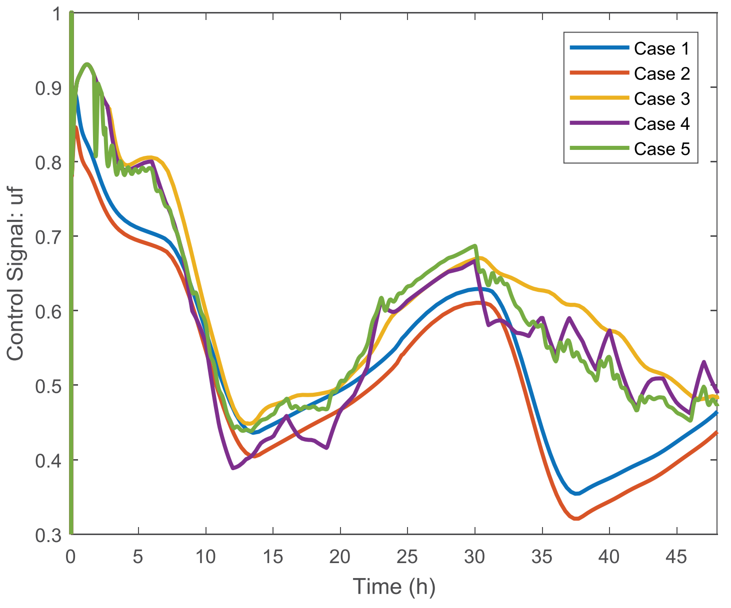


Figure 10. Comparison with fuel consumption.

Case 5 is the best control strategy based on both dynamic responses of zone air temperature and the fuel consumption. Without measuring zone air temperature for compensation, Case 4 is the best one for optimal operation of the DHS.

6. Conclusions

6.1 The first law of thermodynamics and mass conservation principle can be utilized to develop dynamic mathematical models of DHSs.

6.2 The developed ideal dynamic model must be corrected to obtain actual model, which can be applied for various simulations, analysis and compression.

6.3 DHSs must be controlled due to the disturbances from outside air temperature, solar radiation and internal heat gains to reduce the influence of zone air temperature.

6.4 By dealing with the disturbances in Cases 4 and 5, the thermal comfort level has been improved significantly because of the compensation of disturbances.

6.5 Instead of the limitation of measuring zone air temperature in buildings, the equivalent outside air temperature method could be utilized to compensate the disturbances.

6.6 The best thermal comfort can be approached with the lowest energy consumption (Case 5) by utilizing zone air temperature control strategy directly to regulate average water temperature in the secondary system.

Nomenclature

c	specific heat (J/kg°C)
C	thermal capacity (J/°C) or controller
f	factor
F	heated floor area (m^2)
G	water mass flow rate (kg/s)
HV	heating valve of fuel (J/kg)
LMTD	logarithmic mean temperature difference (°C)
q	heating load per m^2 (W/m^2)
Q	heating load (W)
t	time (s)
T	temperature (°C)
u	control signal
U	heat transfer rate (W/°C)
Subscripts	
1, 2	number of substation or primary/secondary system
3	number of substation
arg	average
b	boiler
d	design
en	enclosure of building
ex	heat exchanger
f	fuel
hl	heat loss from pipe segment
ht	heater-radiator
i	1–3
in	inlet
int	internal
j	refer to pipe segment j

k	factor related to heater transfer coefficient test
m	mix
mk	makeup water
o	outside air
oe	equivalent outside air
out	outlet
r	return
rf	radiant floor
s	supply
seg	segment of pipe network
sol	solar radiation
sp	set point
w	water
z	zone air
Alphabet	
η	efficiency

Author details

Li Lian Zhong

Address all correspondence to: lilianzhong@danfoss.com

Danfoss Automatic Controls Management (Shanghai) Co., Ltd, Anshan, China

References

[1] Zaheeruddin M, Monastiriakos P. Hydronic heating systems: Transient modeling, validation and load matching control. International Journal of Energy Research. 1998

[2] Lianzhong L, Zaheeruddin M, Cho SH, Jung SH. Steady state and dynamic modelling of an indirect district heating system. International Journal of Air-Conditioning and Refrigeration. 2010;**18**(1):61-75

[3] Riederer P, Marchio D, Visier JC, Husaunndee A, Lahrech R. Room thermal modelling adapted to the test of HVAC control systems. Building and Environment. 2002;**37**(8-9):777-790

[4] Itzhak M, Reddy TA. Literature review of artificial intelligence and knowledge-based expert systems in building and HVAC system design. ASHRAE Transactions. 2003;**109**:12-26

[5] McQuiston FC, Parker JD. Heating, Ventilating, and Air Conditioning Analysis and Design. 6th ed. Hoboken, New Jersey, US: John Wiley & Sons Inc.; 2005

[6] BLAST. Blast 3.0: Building Loads Analysis and System Thermodynamics Program. User Manual. Urbara-Champaign: Support Office, Department of Mechanical and Industrial Engineering, University of Illinois; 1979

[7] Astrom KJ, Wittenmark B. Advanced Control. Boston, Massachusetts, US: Addison-Wesley Publication Company; 1989

[8] Kanarachos A, Geramanis K. Multivariable control of single zone hydronic heating systems with neural networks. Energy Conversion and Management. 1998;**39**(13):1317-1336

[9] Singh G, Zaheeruddin M, Patel RV. Adaptive control of multivariate thermal processes in HVAC systems. Energy Conversion & Management. 2000;**41**(15):1671-1685

[10] Zoltan M, Robert P. Energy saving of district heated flats from the recommendation of the heating system in Hungary. ASHRAE Transactions. 2002;**108**(2):575-588

[11] Nielsen HA, Madsen H. Modeling the heat consumption in district heating systems using a grey-box approach. Energy and Buildings. 2006;**38**(1):63-71

[12] Lianzhong L, Zaheeruddin M, Cho S-H, Hong S-K. Simulated performance of a combined radiant floor heating and domestic hot water supply system under different control strategies. International Journal of Air-Conditioning and Refrigeration. 2013;**21**(2)

[13] Lianzhong L, Zaheeruddin M. A control strategy for energy optimal operation of a direct district heating system. International Journal of Energy Research. 2004;**28**:597-612

[14] Kitamori T. A design method for control system based upon partial knowledge about controlled processes. Transactions of the Society of Instrument and Control Engineers. 1979;**15**(4):549-555

[15] Jacimovic B, Zivkovic B, Genie S, Zekonja P. Supply water temperature regulation problems in district heating network with both direct and indirect connection. Energy and Buildings. 1998;**28**(3):317-322

[16] Kamimura K, Hashimoto Y, Yamazaki T, Kurosu S. A comparison of controller tuning methods from a design viewpoint of the potential for energy savings. ASHRAE Transactions. 2002;**108**(2):155-165

[17] Liao Z, Dexter AL. An inferential control scheme for optimizing the operation of boilers in multi-zone heating systems. Building Services Engineering Research & Technology. 2003;**24**(4):245-256

[18] Kasahara M, Matsuba T, Kuzuu Y, Yamazaki T. Design and tuning of robust PID controller for HVAC systems. ASHRAE Transactions. 1999;105-116

Section 4

Sustainability in Building Materials Proprieties "Study Cases"

Chapter 6

Development of Sustainable High-Strength Self-Consolidating Concrete Utilising Fly Ash, Shale Ash and Microsilica

Pui-Lam Ng, Žymantas Rudžionis,
Ivan Yu-Ting Ng and Albert Kwok-Hung Kwan

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.75508

Abstract

With high flowability and passing ability, self-consolidating concrete (SCC) does not require compaction during casting and can improve constructability. The favourable properties of SCC have enabled its widespread adoption in many parts of the world. However, there are two major issues associated with the SCC mixes commonly used in practice. First, the cement content is usually at the high side. Since the production of cement involves calcination at high temperature and is an energy-intensive process, the high cement content imparts high embodied energy and carbon footprint to the SCC mixes. Besides, the exothermic reaction of cement hydration would cause high heat generation and early thermal cracking problem that would impair structural integrity and necessitate repair. Second, the strength is usually limited to around grade 60, which is considered as medium strength in nowadays achievable norm. With a view to develop sustainable high-strength self-consolidating concrete (HS-SCC), experimental research utilising fly ash (FA), shale ash (SA), and microsilica (MS) in the production of SCC has been conducted, as reported herein.

Keywords: embodied carbon, embodied energy, fly ash, high-strength self-consolidating concrete, microsilica, shale ash, supplementary binder materials, sustainability

1. Introduction

Self-consolidating concrete (SCC) was first developed in Japan [1, 2] with greatly enhanced flowability and passing ability compared to conventional concrete. With high flowability and passing ability, SCC possesses superior capability to deform and flow, fills up constricted spaces and far-reaching corners, passes through small clearance between objects including reinforcing bars, and achieves proper consolidation without compaction applied [3]. These allow proper placement of concrete even at locations of congested reinforcement and sophisticated formwork shape. At the same time, the concreting operations would be much quieter without the noise generated from concrete compaction, and part of the labour input for concreting can be saved [4]. The production of SCC was mainly enabled by the advent of superplasticising admixtures. With the adoption of appropriate dosage of superplasticiser and water to binder ratio, the workability of concrete can be dramatically improved while the strength can be maintained at the desired level or even increased. The favourable properties of SCC have enabled its widespread adoption in many parts of the world [5]. In recent years, guidelines and specifications of SCC have been developed in Japan [6], Europe [7], USA [8], China [9] and many parts of the world.

Nevertheless, there are two major issues associated with the SCC mixes commonly used in practice. The first issue is that the cement content is usually at the high side, and the adverse effects of high cement content are twofold. Since the production of cement involves calcination at high temperature which is an energy-intensive process [10], the high cement content imparts high embodied energy (EE) and carbon footprint to the SCC mixes [11]. Besides, since the hydration of cement is an exothermic chemical reaction, the high cement content would generate a large amount of heat during concrete hardening and increase the temperature [12]. When the temperature drops to the ambient subsequently and if the thermal contraction is constrained, early thermal cracking would result and that would impair structural integrity and necessitate repair [13].

The second issue is that the strength of concrete is usually limited in practical applications to around grade 60, which is considered as medium strength in nowadays achievable norm [14]. It is well known that the strength of concrete can be increased by decreasing the water to cementitious materials (W/CM) ratio. In the past, the practical limit of W/CM below which the concrete would be insufficiently workable was rather high. That was due to the limited efficiency of the then plasticisers or superplasticisers (SP) available. With the advancement of superplasticising technology over the past decades, lower W/CM ratio could be achieved while the concrete could remain highly workable, and this can be translated to high-strength performance. However, though different high-strength SCC mixes had been developed in laboratories [15, 16], the same range of strength has not yet been commonplace in practice. One of the main reasons of limited strength is that the W/CM ratio has not been minimised by effective utilisation of SP. As will be illustrated later in this chapter, with the increasing usage of cementitious materials with high fineness, instead of the conventional way of dosing the superplasticiser (SP) based on the mass content of cementitious materials, the SP can be more effectively utilised with its dosage being set based on the specific surface area of cementitious materials.

To address the above two issues, the authors have conducted research on improving the sustainable performance and mechanical strength of SCC, as reported in this chapter. With respect to the first issue, the cement consumption is reduced with the incorporation of sustainable binder materials including fly ash (FA), shale ash (SA) and microsilica (MS). With respect to the second issue, the compressive strength of SCC was improved by lowering the W/CM ratio through rational mix design and use of polycarboxylate-ether-based SP. The objective of the study is to develop sustainable high-strength self-consolidating concrete (HS-SCC). A series of 12 SCC mixes incorporating FA, SA and MS were produced for laboratory testing. In the study, the sustainability performance is quantitatively represented by the embodied energy (EE) and the embodied carbon (EC) per cubic metre of concrete, the workability and flowability is measured by the slump and slump flow values from standardised tests, the segregation stability is determined by the visual observation of signs of segregation and the strength is measured by the 7-day and 28-day cube compressive strength values.

2. Use of sustainable binder materials

Supplementary cementitious or binder materials have been increasingly used in recent years to yield various beneficial effects on the performance of concrete [17]. For such materials which are naturally occurring or are industrial by-products, their embodied energy and carbon emission are usually much lower than those of silicate cement. The use of these materials as part of the binder to reduce cement consumption can promote the sustainability of concrete, and for this reason they are referred to as sustainable binder materials herein. The different physical properties and chemical reactivity of sustainable binder materials would affect the performance of SCC in different manners. From chemistry viewpoint, common supplementary binder materials can be broadly classified into three types. The first type is silica dominated (mainly single composition of SiO_2), as exemplified by MS, recycled glass powder, perlite and quartz powder [18]. The second type is alumino-silicate dominated (mainly binary composition of Al_2O_3-SiO_2), as exemplified by activated clays and metakaolin [19]. The third type is calcium-alumino-silicate dominated (mainly ternary composition of CaO-Al_2O_3-SiO_2), as exemplified by FA and slags such as ground granulated blast-furnace slag (GGBS) [20]. While the chemical composition of supplementary binder materials determines their pozzolanic reactivity in reacting with calcium hydroxide formed during cement hydration to produce extra cementitious products, the physical characteristics, mainly the granulometry, strongly influence the rate of pozzolanic reaction and various performance attributes of the concrete.

In this study, FA, SA and MS were employed and their effects on SCC are discussed in the following. FA is produced mainly from power stations during the burning of pulverised coal. The ash particles are predominantly spherical in shape and their fineness resembles that of cement. Depending on the source and classification, the silica content of FA would be in the range of 50–70%. Due to its rounded shape, the workability of SCC would not be adversely affected by adding FA. The strength development of concrete with FA is slower than cement concrete, and longer curing period is necessary. The benefits of FA in concrete production are rather established [21, 22]. Particularly, it is very effective in reducing the heat generation of mass concrete during curing to prevent the early thermal cracking problem.

SA is produced by the combustion process of oil shale that contains fossil energy. It is yielded from the solid residue (known as spent shale) resulted from the burning of oil shale [23]. The disposal of SA has been an environmental problem faced by countries that produce shale oil [24]. Though SA may be ground to similar size as cement grains and utilised in the manufacturing of bricks [25], its use in the production of SCC has been much less explored [26]. Due to the minerology of shale, SA contains relatively high content of calcium oxide, usually in the range of 10–40%. The pozzolanicity of SA is similar to that of GGBS, and it has a silica content of 30–40%. In terms of chemical composition, SA can be classified as calcium-alumino-silicate dominated, with a subtle content of aluminium oxide. The addition of SA in concrete had been reported to increase the concrete strength, reduce the permeability and improve frost resistance [27]. However, the alkali content in SA is generally at the high side, and the content of SA in concrete should be limited to prevent expansive alkali-silicate reaction [28].

MS (also called condensed silica fume) is a by-product of the smelting process used to produce silicon metal and ferrosilicon alloys. MS is characterised by the high content of reactive silica of over 85% and the extremely fine particle size in the order of 0.2 μ. The high fineness of MS allows it to fill the voids between larger cement particles and increases packing density. The displaced water becomes excess water to lubricate the solid particles. From mix design perspective, the water demand for packing is greatly reduced and a lower W/CM can be used for achieving higher strength. The high fineness and large specific surface area risk of MS also mitigate the plastic settlement and segregation problems. The use of MS in concrete production is rather established, and it is among the common constituent materials for making high-strength concrete [29, 30]. The use of MS as well as the combined use of MS and FA in producing SCC had been investigated and confirmed to be effective by the authors [31, 32].

3. Use of superplasticising admixtures

Plasticising and superplasticising admixtures have taken an indispensable role in advancing the concrete technology and development of SCC. Before the 1960s, workability improving admixtures based on hydroxycarboxylic acids or lignosulphonates had been developed. They were usually known as plasticisers or water reducers, and they would allow the W/CM ratio to be reduced by 5–10% without adversely affecting the workability of concrete. In the 1960s–1970s, a newer generation of workability improving admixtures based on sulphonated formaldehyde condensates of melamine or naphthalene was developed. These admixtures are generally named superplasticisers (SP) or high-range water reducers because of their superior performance compared to their predecessors. Such SP could allow the W/CM ratio to be reduced by as much as 20–30% without affecting the workability [33]. Terminologically, SPs derived from sulphonated melamine formaldehyde condensates are sub-classified as melamine-based superplasticisers (abbreviated as SMF), while SPs derived from sulphonated naphthalene formaldehyde condensates are sub-classified as naphthalene-based superplasticisers (abbreviated as SNF). SMF and SNF have similar performance and may be blended together in usage [34].

In the 1980s, manufacturers started works to develop polycarboxylate-ether-based SP (abbreviated as PCE), but initially there were serious problems of severe retardation and excessive air entrainment [35]. It was only until around the turn of century, PCE became available in the market and these products were dubbed the third-generation superplasticisers or hyperplasticisers. The PCE remarkably outperformed the existing SP. Their use would allow the W/CM ratio to be reduced by up to 40% without adversely affecting the workability of concrete. The molecular structure of PCE is characterised by an active-monomer (such as polymethacrylate acid, or abbreviated as PMAA) formed main chain, attached with numerous graft copolymers (such as polyethylene glycol, or abbreviated as PEG) formed long side chains. Such long side chains are absent in SMF and SNF molecules.

PCE improve the workability of concrete mixes by dual effects, namely the dispersion effect and steric hindrance or steric repulsion effect. This is in contrast to SMF and SNF which improve the workability of concrete mixes only by dispersion effect. The dispersion effect is explained as follows. There are four main types of minerals in ordinary Portland cement, namely belite (C_2S), alite (C_3S), aluminate (C_3A) and ferrite (C_4AF) [36]. Belite and alite are negatively charged, while aluminate and ferrite are positively charged. Because of the opposite electrostatic potentials, the cement grains tend to coagulate together, making it less readily to thoroughly mix with water to form a uniform paste [37]. With the addition of SP, the SP molecules are adsorbed onto the surfaces of cement grains, and they impart negative charges to all the cement grains. The electrostatic repulsion derived from the negative charges disperses the cement grains apart. For PCE, it is the main chain of PCE molecule that is adsorbed and imparts negative charges to cement grains, whereas the side chains act as physical barriers to separate the cement grains further apart [38]. Such steric hindrance further promotes dispersion and prolongs workability retention [39, 40].

In determining the SP dosage to concrete, attention should be paid to the quantities of SP demand for given levels of workability, the saturation SP dosage beyond which further addition of SP would yield no return, and the maximum SP dosage beyond which further addition of SP would cause segregation. Conventionally, the SP demand, saturation dosage and maximum dosage are expressed in percentage by mass of cementitious materials. However, as SP is a surfactant adsorbed onto the surface of cementitious materials, its effectiveness should be dependent on the amount of SP per surface area of cementitious materials [41]. Therefore, the SP demand, saturation dosage and maximum dosage should be controlled by the fineness and the content of each cementitious material. This forms the basis to rationalise the usage of SP.

4. Method

4.1. Materials employed

A total of 12 concrete mixes were produced for testing. The materials employed were as follows. The cement used was an ordinary Portland cement that complied with the requirements in European Standard EN 197. It has a solid density of 3.1 and a specific surface of 350 m^2/kg. The fly ash (FA) used was produced from coal-fired power station and the properties complied with the requirements in European Standard EN 450. The shale ash (SA) used was produced from shale oil fuelled power plant and the properties have been investigated in this research. To show the morphology of SA particles, **Figure 1** depicts the scanning electron

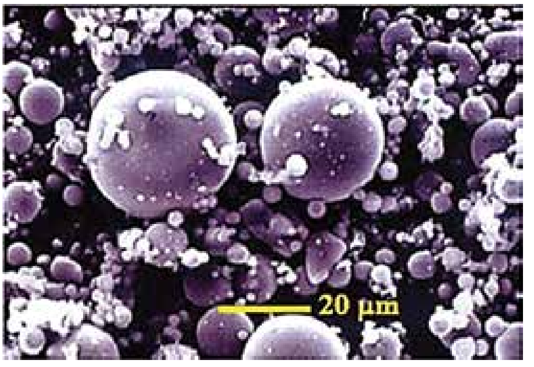


Figure 1. Morphology of SA.

microscopy image of the SA. The microsilica (MS) used was produced from ferrosilicon plant and the properties complied with the requirements in European Standard EN 13263. **Table 1** lists the chemical compositions in percentage of the cement, FA, SA and MS. Regarding the physical properties, the cement, FA, SA and MS had specific surface areas of 595, 415, 570 and 20,000 m^2/kg, and had specific gravities of 3150, 2110, 2800 and 2200 kg/m^3.

The coarse aggregate was crushed granitic rock with a maximum size of 10 mm, while the fine aggregate used was crushed granitic rock fine with a maximum size of 5 mm. The properties and grading of the fine and coarse aggregates have been tested to comply with European Standard EN 12620. The SP used was polycarboxylate-ether-based complying with European Standard EN 934. It is a white-colour milky liquid that can be added into the mixing water or directly to the wet concrete. The recommended SP dosage by the manufacturer was typically 0.5–3.0% by mass of the cementitious materials content. Such polycarboxylate-ether-based SP is very effective and it allows adoption of low W/CM ratios.

4.2. Experimental programme

The experimental programme encompassed 12 SCC mixes. For all concrete mixes, the W/CM ratio by mass was ranging from 0.28 to 0.33, and the paste volume was ranging from 0.32 to 0.35. The fine to total aggregate (F/T) ratio was fixed at approximately 0.4 for the majority of concrete mixes, except for one of the mixes with W/CM ratio of 0.33 the F/T ratio was raised to 0.5. The contents of supplementary binder materials in mass percentage of the total binder were as follows: the FA content varied among 0 and 25%, the SA content varied among 0, 15, 30 and 45%, and the MS content varied among 0, 5 and 10%. One of the SCC mixes was cement concrete and did not contain any supplementary binder materials, six mixes featured binary blending of FA or SA, and five mixes featured ternary blending of FA and MS. **Table 2** summarises the mix parameters of the experimental programme. The SP dosage of the majority of mixes was 3.0%, except the dosage was lowered to 1.5% by mass for the mixes with SA due to the higher inherent workability of those mixes. It should be noted that the dosage was adjusted based on the surface area of the solid particles present in the concrete and the actual achieved workability compared to the target workability. The mix proportions are listed in **Table 3**.

Minerals	Cement	Fly ash (FA)	Shale ash (SA)	Microsilica (MS)
SiO_2	18.8	48.8	24.8	92.1
Al_2O_3	3.9	25.2	5.9	1.2
CaO	62.1	2.4	50.5	1.1
Fe_2O_3	2.8	5.3	4.6	1.2
MgO	2.6	2.4	6.5	0.8
Na_2O	0.2	0.9	0.1	1.1
K_2O	1.1	3.6	2.1	0.7
SO_3	0.8	0.5	4.4	1.3

Table 1. Chemical compositions (in %) of cement and supplementary binder materials.

Mix no.	W/CM ratio	Paste volume	F/T ratio	FA content (%)	SA content (%)	MS content (%)
1	0.30	0.32	0.39	0	0	0
2	0.26	0.35	0.40	25	0	0
3	0.28	0.35	0.40	25	0	0
4	0.30	0.35	0.40	25	0	0
5	0.32	0.34	0.39	0	15	0
6	0.32	0.34	0.39	0	30	0
7	0.32	0.34	0.39	0	45	0
8	0.28	0.35	0.40	25	0	5
9	0.28	0.35	0.40	25	0	10
10	0.30	0.35	0.40	25	0	5
11	0.30	0.35	0.40	25	0	10
12	0.33	0.35	0.50	25	0	5

Note: The FA, SA and MS contents are expressed in percentage by mass of total binder.

Table 2. Concrete mix parameters.

4.3. Embodied energy and carbon

To study the embodied energy (EE) and carbon emission of the SCC mixes, the data in the literature: Embodied Carbon: The Inventory of Carbon and Energy [42] were referred to. **Table 4** lists the embodied energy (*EE*) and embodied carbon (*EC*) of the constituent materials. Here, the embodied energy is expressed in terms of MJ/kg of material, and the embodied carbon is expressed in terms of $kgCO_2/kg$ of material. It can be seen that the tabulated values for cement are generally one to two orders higher than those of FA, SA and MS, which originate from industrial by-products. Therefore, blending with supplementary binder materials to reduce the cement consumption is an effective means to enhance the sustainability of concrete.

Mix no.	Mass content (kg/m^3)					
	Cement	FA	SA	MS	Water	SP
1	492	0	0	0	150	7.4
2	421	140	0	0	146	17.7
3	408	136	0	0	152	17.1
4	395	132	0	0	158	16.6
5	452	0	80	0	152	7.2
6	380	0	163	0	146	5.7
7	320	0	262	0	150	6.3
8	376	134	0	27	150	16.9
9	345	133	0	53	149	16.5
10	365	130	0	26	156	16.4
11	335	129	0	52	155	16.2
12	342	117	0	23	161	14.7

Table 3. Concrete mix proportions.

Based on the listed values in **Table 4**, the embodied energy and embodied carbon of the SCC mixes may be computed as follows, where *EE* is in MJ/m^3, *EC* is in $kgCO_2/m^3$ and *W*, *C*, *FA*, *SA*, *MS* and *A* are the contents of water, cement, FA, SA, MS and aggregate, respectively, in kg/m^3.

$$EE = 0.010\,W + 4.500C + 0.100FA + 0.030SA + 0.850MS + 0.083A \quad (1)$$

$$EC = 0.001\,W + 0.730C + 0.008FA + 0.002SA + 0.020MS + 0.005A \quad (2)$$

4.4. Test procedures

Laboratory pan-type mixer was employed to mix the concrete, with a total duration of mixing of not less than 5 minutes for each mix. The workability of the fresh SCC mixes was measured

Material	Embodied energy (MJ/kg)	Embodied carbon ($kgCO_2/kg$)
Water	0.010	0.001
Cement	4.500	0.730
FA	0.100	0.008
SA	0.030	0.002
MS	0.850	0.020
Rock aggregate	0.083	0.005

Table 4. Embodied energy and embodied carbon of constituent materials.

by the slump and flow tests as stipulated in European Standard EN 12350: Part 2 and Part 8. The same equipment was used for the slump and flow tests. The slump cone had a base diameter of 200 mm, a top diameter of 100 mm and a height of 300 mm. A smooth steel plate of size 1× 1 m was placed on level ground for carrying out the test. The size of steel plate was sufficiently large to cater for the extent of flow of concrete. Concrete was first filled into the slump cone without tamping. When the slump cone was full, the top surface of concrete was trowelled flat and the slump cone was lifted steadily to allow the concrete to flow under its own weight to form a patty. After the flow had ceased, the slump of concrete was measured as the difference between the height of slump cone and the highest point of the patty. Besides, the slump flow (or flow in short) of concrete was measured as the average diameter of the patty in two orthogonal directions. The slump and flow values were measured and reported to the nearest 5 mm. In addition, any sign of segregation instability was observed by visual inspection particularly around the rim of the slumped patty.

The compressive strength of the SCC mixes was measured in accordance with European Standard EN 12390: Part 3 and Part 4. Cubes of size 100 mm were cast from the fresh SCC mixes and then covered to protect against loss of moisture by evaporation. One day after casting, the cubes were demoulded and were cured by immersing in lime-saturated water curing tank at a temperature of 27 ± 2°C. Until the required age of testing at 7 days or 28 days, the cubes were taken out from the curing tank, wiped dry and underwent the compressive strength test. The mean compressive strength was obtained by averaging the test results of a set of three cubes. If there was any individual cube strength deviating from the average cube strength by more than 10%, the individual result would be discarded and the average cube strength would be taken as the average of the remaining two cubes. All strength results presented in this chapter are the mean compressive strength so evaluated.

5. Results and discussions

5.1. Workability and flowability

The experimental results of workability and strength of the SCC mixes are presented in **Table 5**. It is noted that the slump values fell in the range from 220 to 260 mm, and the flow values were within the range from 620 to 775 mm. No sign of segregation instability was observed for all the SCC mixes. Basically, all the concrete mixes achieved the required workability and flowability of being self-consolidating. Such workability and flowability regime also offers potential applications for tremie concrete mixes and pumped mixes. According to the relevant European guidelines [7], SCC are classified into three flow classes, namely class SF1 for flow value between 550 and 650 mm, class SF2 for flow value between 660 and 750 mm and class SF3 for flow value between 760 and 850 mm. The flow classification of each SCC mix is indicated in **Table 5**. It is worthwhile to note that for the SA concrete (Mixes 5, 6 and 7), the workability and flowability at the presence of SA were favourable such that the SP dosage was set at a low level (circa 1.5% by mass of the cementitious materials content). Therefore, the use of SA can economise the material cost of SCC by consuming less amount of SP.

Mix no.	Slump (mm)	Flow (mm)	Flow class	7-day mean cube strength (MPa)	28-day mean cube strength (MPa)	28-day to 7-day strength ratio
1	230	660	SF2	67.4	80.2	1.19
2	220	620	SF1	78.2	98.0	1.25
3	235	665	SF2	74.6	96.1	1.29
4	225	670	SF2	63.3	81.6	1.29
5	250	700	SF2	72.7	86.7	1.19
6	225	650	SF1	73.7	91.8	1.25
7	255	730	SF2	75.2	83.4	1.11
8	250	660	SF2	74.6	101.4	1.36
9	225	620	SF1	81.4	108.5	1.33
10	235	660	SF2	77.1	102.7	1.33
11	225	620	SF1	73.1	104.8	1.43
12	260	775	SF3	72.5	89.8	1.24

Table 5. Workability and strength results.

To reveal the relation between slump and flow, the variation of these two quantities is plotted in **Figure 2**. For ease of visualisation, the data points are divided into four groups, namely "Cement SCC" for Mix 1, "FA SCC" for Mixes 2–4, "SA SCC" for Mixes 5–7, and "FA + MS" SCC for Mixes 8–12. Besides, horizontal lines at flow levels of 550, 650 and 750 mm corresponding to the boundary values of flow classes are drawn. It can be seen from **Figure 2** that the slump and flow are positively correlated. Nevertheless, at a workability level of higher than 200 mm slump, the slump is less sensitive to the change in workability as compared to the flow. Hence, the flow value serves as a better measurement of the self-consolidating ability.

5.2. Compressive strength

The 7-day and 28-day mean cube compressive strength results are listed in **Table 5**. It can be seen that all 7-day strength results were higher than 60 MPa, and all 28-day strength results were higher than 80 MPa. Therefore, the SCC mixes do satisfy the requirement of high strength. The 7-day strength was ranging from 63.3 to 81.4 MPa. Mix 4 with W/CM ratio of 0.3 and with 25% FA content had the lowest 7-day strength, due to the relative slow strength development of FA concrete as expected. The 28-day strength was ranging from 80.2 to 108.5 MPa. Mix 1 without supplementary binder materials had the lowest 28-day strength, which demonstrated the more effective strength development at a later age of blended SCC mixes. Mix 9 with W/CM ratio of 0.28 and with 25% FA content and 10% MS content had the highest 7-day and 28-day strengths, which proved the beneficial effect of MS on strength enhancement. In particular, the use of SA up to even a high volume allowed the achievement of very high strength. At 30% SA content, the 28-day strength of Mix 6 was 91.8 MPa; where at 45% SA content, the 28-day strength of Mix 7 was 83.4 MPa. The 7-day compressive strength is plotted versus the 28-day compressive strength in **Figure 3**. In the figure, the line of

http://dx.doi.org/10.5772/intechopen.75508

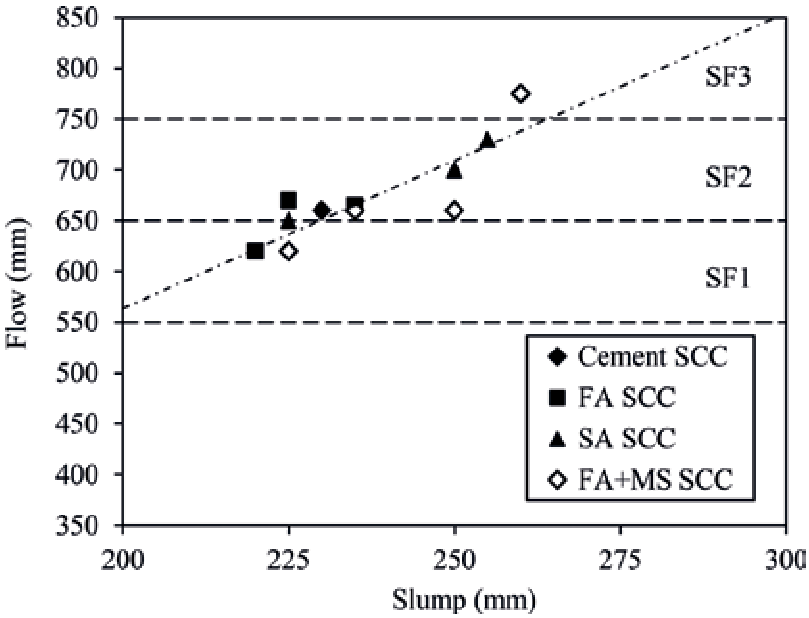


Figure 2. Plot of flow versus slump.

unity, the line of gradient of 1.2 and the trend line of data points are drawn for ease of visualisation. For each SCC mix, the ratio of 28-day strength to 7-day strength is computed and is listed in the last column of **Table 5**. The ratio ranged from 1.11 for Mix 7 with 45% SA content to 1.43 for Mix 11 with 25% FA content and 10% MS content.

It is evident from the strength results that the SCC mixes produced in the current experimental programme are suitable for adoption as high-strength SCC, or HS-SCC mixes. From the authors' experience in concrete production and testing, rational grade designation for Mixes 1–12 is assigned with reasonable allowance of standard deviations in strength results to account for the difference between the mean strength and the characteristic strength (grade strength). The grade designation based on concrete cube strength is listed in the second column of **Table 6**, where Mixes 1, 4 and 7 are designated as C70, Mix 5 is designated as C75, Mixes 6 and 12 are designated as C80, Mixes 2, 3, 8 and 10 are designated as C85, and Mixes 9 and 11 are designated as C90. These concrete grades are significantly higher than the grades of common SCC mixes employed in construction projects. It should be noted that the standard deviation of strength results can be established with a higher confidence level upon the availability of data from a larger sample population. Therefore, the grade designation herein would subject to alteration after further trial mixing and production.

5.3. Sustainability performance

The sustainability performance of the SCC mixes, evaluated through the *EE* and *EC* as per Eq. (1) and Eq. (2), is shown in **Table 6**. The *EE* was ranging from 1590 to 2359 MJ/m^3, whereas the *EC* was ranging from 243 to 368 kgCO_2/m^3. The cement SCC Mix 1 without supplementary binder materials gave rise to the highest *EE* and *EC* values. By blending with FA, SA and MS,

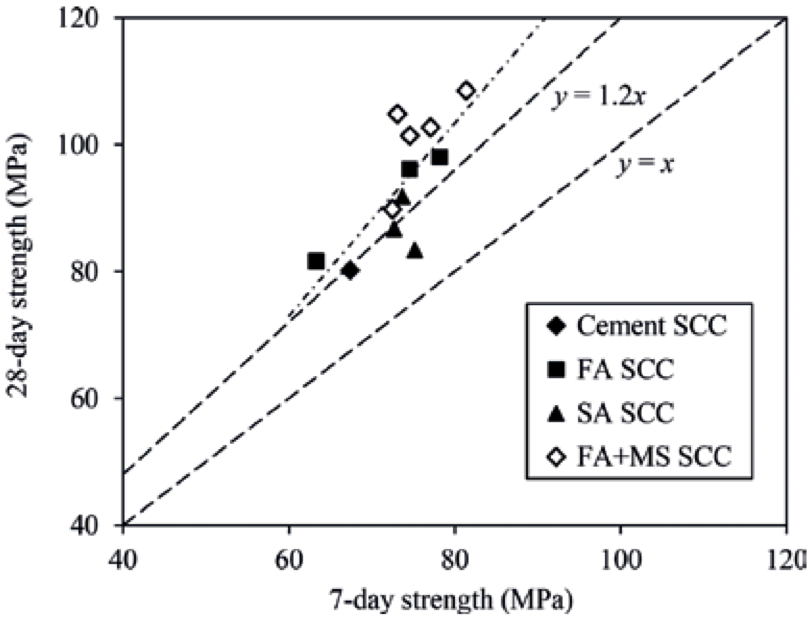


Figure 3. Plot of 28-day strength versus 7-day strength.

the *EE* and *EC* could be remarkably reduced, with the percentage decrease for each mix relative to Mix 1 listed in brackets in columns 3 and 4 of **Table 6** after the respective *EE* and *EC* values. As noted in the above, SA can be used at a high volume while capable of achieving high strength, consequently, the largest decrease in *EE* and *EC* was attained by Mix 7, which had the highest SA content of 45% by mass of binder. The corresponding reduction in *EE* and *EC* was as large as 32.6 and 34.0%, respectively. The variation of *EE* with the 28-day strength

Mix no.	Grade designation	Embodied energy (MJ/m^3)	Embodied carbon (kgCO$_2$/m^3)	*EE* per strength (MJ/m^3/MPa)	*EC* per strength (kgCO$_2$/m^3/MPa)
1	C70	2359 (±0%)	368 (±0%)	29.4 (±0%)	4.6 (±0%)
2	C85	2050 (−13.1%)	317 (−13.9%)	20.9 (−28.9%)	3.2 (−30.4%)
3	C85	1991 (−15.6%)	308 (−16.3%)	20.7 (−29.6%)	3.2 (−30.4%)
4	C70	1932 (−18.1%)	298 (−19.0%)	23.7 (−19.4%)	3.7 (−19.6%)
5	C75	2182 (−7.5%)	339 (−7.9%)	25.2 (−14.3%)	3.9 (−15.2%)
6	C80	1855 (−21.4%)	286 (−22.3%)	20.2 (−31.3%)	3.1 (−32.6%)
7	C70	1590 (−32.6%)	243 (−34.0%)	19.1 (−35.0%)	2.9 (−37.0%)
8	C85	1870 (−20.7%)	285 (−22.6%)	18.4 (−37.4%)	2.8 (−39.1%)
9	C90	1752 (−25.7%)	263 (−28.5%)	16.1 (−45.2%)	2.4 (−47.8%)
10	C85	1819 (−22.9%)	277 (−24.7%)	17.7 (−39.8%)	2.7 (−41.3%)
11	C90	1706 (−27.7%)	255 (−30.7%)	16.3 (−44.6%)	2.4 (−47.8%)
12	C80	1712 (−27.4%)	260 (−29.3%)	19.1 (−35.0%)	2.9 (−37.0%)

Table 6. Sustainability performance results.

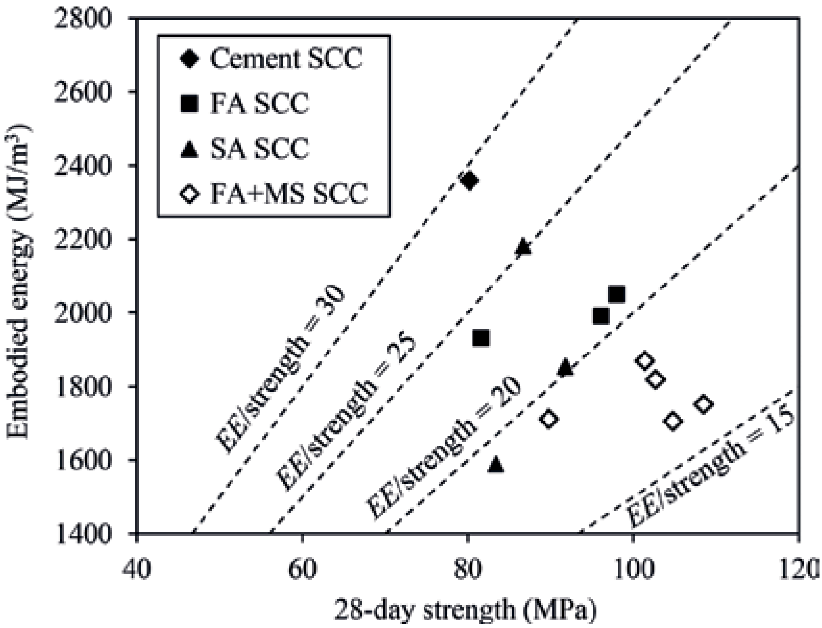


Figure 4. Plot of embodied energy versus 28-day compressive strength.

and the variation of *EC* with the 28-day strength are plotted in **Figures 4** and **5**, respectively. In these figures, moving vertically downwards and towards the right-hand side would indicate a more sustainable and higher strength concrete. It can be observed that Mix 1 performed the worst among all mixes in terms of both strength and sustainability, while the ternary blended (cement + FA + MS) mixes generally performed superior, as reflected by the group of data points close to the bottom right corner in the figures. The good overall performance is due to the effectiveness of FA in lowering the *EE* and *EC*, as well as the effectiveness of MS in improving the strength.

For comparison on an equal-strength basis, the *EE* per strength and the *EC* per strength at age of 28-days are evaluated and listed in the last two columns of **Table 6**. It is seen that the *EE* per strength was ranging from 16.1 to 29.4 (MJ/m^3)/MPa, whereas the *EC* per strength was ranging from 2.4 to 4.6 (kgCO$_2$/m^3)/MPa. Similar to the foregoing, the percentage decrease in *EE* and *EC* per strength relative to Mix 1 is listed in brackets in the last two columns of **Table 6**. This can reflect the concurrent improvement in strength and sustainability by blending with FA, SA and MS. The largest percentage reductions in *EE* and *EC* per strength were attained by Mixes 9 and 11, which contained 25% FA content and 10% MS content. To facilitate visualising the concurrent effects on strength and sustainability, family of straight lines of constant *EE*/strength ratio at equal intervals and family of straight lines of constant *EC*/strength ratio at equal intervals are plotted in **Figures 4** and **5**, respectively.

5.4. Additional investigation of rational SP dosage

To investigate the rationalisation of SP dosage, one of the SCC mixes, additional trial of Mix 2 was carried out with varied SP dosage while maintaining the proportions of other mix ingredients

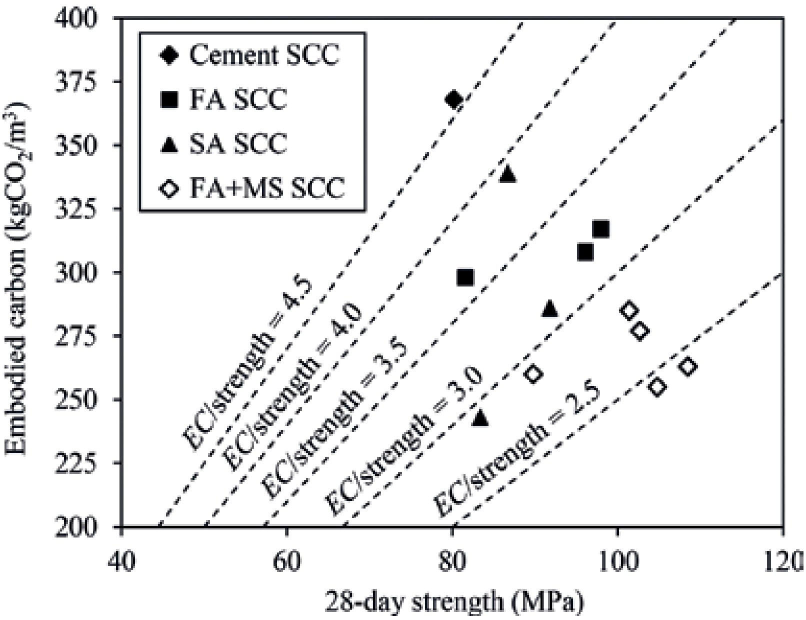


Figure 5. Plot of embodied carbon versus 28-day compressive strength.

unchanged. From the specific surface areas reported in Section 4.1, the SP dosage of Mix 2 in terms of liquid mass per surface area of cementitious materials was evaluated to be 57 × 10^{-6} kg/m^2. Two trial mixes, labelled as Mix 2a and Mix 2b, were conducted with the respective SP dosage set at 76 × 10^{-6} kg/m^2 and 96 × 10^{-6} kg/m^2 area of cementitious materials (approximately correspond to 4% and 5% by mass of cementitious materials, respectively). The slump and flow results of Mix 2a were 255 and 725 mm, respectively, while the slump and flow results of Mix 2b were 240 and 770 mm, respectively. No sign of segregation was observed. It should be noted that when determining the SP dosage of SCC mixes containing materials of high fineness such as MS, the SP dosage should better be set based on the specific surface area of cementitious materials, so as to more effectively utilised the SP. In any case, the above additional investigation indicated possibility of further increasing the flowability at constant W/CM ratio, or conversely, possibility of further reducing the W/CM ratio for achieving even higher strength while maintaining the flowability. Therefore, it should be viable to develop HS-SCC beyond grade C90 by rationalising the SP usage and further mix optimisation, and research along this direction is recommended.

6. Conclusions

With the aim to develop sustainable high-strength self-consolidating concrete (HS-SCC) mixes, the authors have conducted research on improving the sustainable performance and mechanical strength of self-consolidating concrete (SCC) mixes. Reduction in embodied energy and carbon emission of SCC mixes has been achieved by reducing the cement consumption with the incorporation of fly ash (FA), shale ash (SA) and microsilica (MS) as supplementary binder materials. High compressive strength of SCC mixes has been achieved by adopting low W/CM ratios through the use of polycarboxylate-ether-based superplasticiser (SP). A series of 12 SCC mixes incorporating FA, SA and MS have been produced for laboratory testing. From the experimental results, all the concrete mixes have attained the required workability and flowability of self-consolidating. The flow values have satisfied the respective ranges of slump-flow classes SF1, SF2 or SF3 according to the European guidelines for SCC, and there has been no problem of segregation instability as revealed from visual observations. The mean 28-day compressive cube strengths of the SCC mixes were within the range from 80.2 to 108.5 MPa, which could be designated as grade C70 to C90. Depending on the contents of respective supplementary binder materials, the use of FA, SA and MS has significantly lowered the embodied energy (EE) and embodied carbon (EC) of the SCC mixes by up to 32.6% and 34.0%, respectively. In particular, SA can be used at a high volume while capable of achieving high strength, thereby enabling great enhancement in sustainability performance. For comparison on an equal-strength basis, the EE per strength and the EC per strength at 28-day age have been evaluated. By so doing, the concurrent improvement in strength and sustainability by blending with FA, SA and MS has been clearly demonstrated, where reductions in EE per strength and EC per strength by up to more than 45% have been achieved. Overall speaking, the results have concluded successful development of sustainable HS-SCC with superior performance compared to the conventional SCC mixes. The mix design contained in this chapter may be adopted as reference HS-SCC mixes for practical use. Moreover, from additional studies, the authors have suggested rationalising the SP dosage based on the specific surface area of cementitious materials, instead of the conventional practice of dosing the SP based on the mass content of cementitious materials.

Acknowledgements

The financial support from the Marie Skłodowska-Curie Actions of the European Commission (Project no. 751461) is gratefully acknowledged.

Conflict of interest

The authors declare that there is no conflict of interest.

Author details

Pui-Lam Ng[1,2]*, Žymantas Rudžionis[3], Ivan Yu-Ting Ng[2] and Albert Kwok-Hung Kwan[2]

*Address all correspondence to: irdngpl@gmail.com

1 Faculty of Civil Engineering, Vilnius Gediminas Technical University, Lithuania

2 Department of Civil Engineering, The University of Hong Kong, Hong Kong, China

3 Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Lithuania

References

[1] Okamura H. Self-compacting high-performance concrete. Concrete International. 1997; **19**(7):50-54

[2] Okamura H, Ozawa K, Ouchi M. Self-compacting concrete. Structural Concrete. 2000; **1**(1):3-17

[3] Goodier CI. Development of self-compacting concrete. Proceedings of the Institution of Civil Engineers: Structures and Buildings. 2003;**156**(4):405-414

[4] Lessard M, Salazar B, Talbot C. Self-consolidating concrete solves challenging placement problems. Concrete International. 2003;**25**(12):80-81

[5] Daczko JA. Self-Consolidating Concrete: Applying What We Know. Oxon: Spon Press; 2012. 289 p

[6] Japan Society of Civil Engineers. Recommendation for Self-Compacting Concrete. 1999

[7] Self Compacting Concrete European Project Group. The European Guidelines for Self Compacting Concrete. BIBM, CEMBUREAU, EFCA, EFNARC and ERMCO: Brussels; 2005. 63 p

[8] American Concrete Institute Committee 237. Self-Consolidating Concrete. ACI 237R-07. Michigan: American Concrete Institute; 2007. 30 p

[9] Ministry of Housing and Urban-Rural Development. Technical Specification for Application of Self-Compacting Concrete. Beijing: China Architecture and Building Press; 2012. 64 p

[10] Mehta PK. Global concrete industry sustainability. Concrete International. 2009;**31**(2):45

[11] Worrel E, Price L, Martin N, Hendriks C, Meida LO. Carbon dioxide emissions from the global cement industry. Annual Review of Energy and the Environment. 2001;**26**:301-329

[12] American Concrete Institute Committee 207. Guide to Mass Concrete. ACI 207.1R-05. Michigan: American Concrete Institute; 2005. 30 p

[13] Bamforth PB. Early-Age Thermal Crack Control in Concrete, CIRIA Report C660. London: Construction Industry Research and Information Association; 2007. 112 p

[14] Kwan AKH, Ng PL, Fung WWS. Research directions for high-performance concrete. In: Proceedings, The HKIE Civil Division Conference 2010: Infrastructure Solutions for Tomorrow; 12-14 April 2010; Hong Kong. 11 p

[15] Dinakar P, Manu SN. Concrete mix design for high strength self-compacting concrete using metakaolin. Materials and Design. 2014;**60**:661-668

[16] Alsubari B, Shafigh P, Jumaat MZ. Development of self-consolidating high strength concrete incorporating treated palm oil fuel ash. Materials. 2015;**8**:2154-2173

[17] Siddique R, Khan MI. Supplementary Cementing Materials. Berlin: Springer; 2011. 287 p

[18] Borosnyói A. Long term durability performance and mechanical properties of high performance concretes with combined use of supplementary cementing materials. Construction and Building Materials. 2016;**112**:307-324

[19] Sabir BB, Wild S, Bai J. Metakaolin and calcined clays as pozzolans for concrete: A review. Cement and Concrete Composites. 2001;**23**:441-454

[20] Wang Q, Shi MX, Wang DQ. Contributions of fly ash and ground granulated blast-furnace slag to the early hydration heat of composite binder at different curing temperatures. Advances in Cement Research. 2016;**28**(5):320-327

[21] Helmuth RA. Fly Ash in Cement and Concrete. Portland Cement Association: Illinois; 1987. 203 p

[22] American Concrete Institute Committee 232. Use of Fly Ash in Concrete. ACI 232.2R-03. Michigan: American Concrete Institute; 2003. 41 p

[23] Smadi MM, Haddad RH. The use of oil shale ash in Portland cement concrete. Cement and Concrete Composites. 2003;**25**(1):43-50

[24] Raado LM, Hain T, Liisma E, Kuusik R. Composition and properties of oil shale ash concrete. Oil Shale. 2014;**31**(2):147-160

[25] Oymael S. Suitability of oil shale ash as a constituent of cement. Oil Shale. 2007;**24**(1):45-58

[26] Feng NQ, Chan SYN, He ZS, Tsang MKC. Shale ash concrete. Cement and Concrete Research. 1997;**27**(2):279-291

[27] Chan SYN, Ji XH. Water sorptivity and chloride diffusivity of oil shale ash concrete. Construction and Building Materials. 1998;**12**(4):177-183

[28] Yeginobali A, Smadi M, Khedaywi T. Effectiveness of oil shale ash in reducing alkali-silica reaction expansions. Materials and Structures. 1993;**26**:159-166

[29] Malhotra VM, Ramachandran VS, Feldman RF, Aïtcin P-C. Condensed Silica Fume in Concrete. Floride: CRC Press; 1987. 221 p

[30] American Concrete Institute Committee Committee 234. Guide for the Use of Silica Fume in Concrete. ACI 234R-06. Michigan: American Concrete Institute; 2006. 63 p

[31] Kwan AKH. Use of condensed silica fume for making high-strength, self-consolidating concrete. Canadian Journal of Civil Engineering. 2000;**27**(4):620-627

[32] Ng IYT, Ng PL, Wong HHC, Kwan AKH. Roles of silica fume and fly ash in improving flowability, segregation stability and passing ability of self-consolidating concrete. In: Venurino M, editor. Proceedings, 9th CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete; 2007; Warsaw, Poland. Michigan: American Concrete Institute; 2007. pp. 109-123

[33] Aïtcin P-C, Flatt RJ. Science and Technology of Concrete Admixtures. Cambridge: Woodhead Publishing; 2016. 613 p

[34] Ramachandran VS. Concrete Admixtures Handbook: Properties, Science, and Technology. 2nd ed. New Jersey: Noyes Publications; 1995. 1183 p

[35] Rixom R, Mailvaganam N. Chemical Admixtures for Concrete. 3rd ed. London: E & FN Spon; 1999. 437 p

[36] Taylor HFW. Cement Chemistry. 2nd ed. London: Academic Press; 1990. 475 p

[37] Yoshioka K, Tazawa E, Kawai K, Enohata T. Absorption characteristics of superplasticizers on cement component minerals. Cement and Concrete Research. 2002;**32**(10):1507-1513

[38] Otha A, Sugiyama T, Uomoto T. Study of dispersing effects of polycarboxylate-based dispersant on fine particles. In: Proceedings, 6th CANMET/ACI International Conference on Superplasticizers and Other Chemical Admixtures in Concrete. Nice, France, Michigan: American Concrete Institute; 2000. pp. 211-228

[39] Uchikawa H, Hanehara S, Sawaki D. The role of steric repulsive forces in the dispersion of cement particles in fresh paste prepared with organic admixtures. Cement and Concrete Research. 1997;**27**(1):37-50

[40] Yoshioka K, Sakai E, Daimon M, Kitahara A. Role of steric hindrance in the performance of superplasticizers for concrete. Journal of the American Ceramic Society. 1997;**80**(10):2667-2671

[41] Kwan AKH, Chen JJ, Fung WWS. Effects of superplasticiser on rheology and cohesiveness of CSF cement paste. Advances in Cement Research. 2012;**24**(3):125-137

[42] Hammond G, Jones C. Embodied Carbon: The Inventory of Carbon and Energy (ICE), BSRIA Guide BG 10/2011. Building Services Research and Information Association: Berkshire; 2011. 128 p

Chapter 7

Research on Strength, Alkali-Silica Reaction and Abrasion Resistance of Concrete with Cathode Ray Tube Glass Sand

Salih Taner Yildirim

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.73873

Abstract

In this study, the effects on the mechanical and durability properties of concrete with cathode ray tube glass sand (CRTS) obtained by recycling the screens of cathode ray tubes (CRTs) were investigated. CRTS was used by the ratios of 5, 10, 15, and 20% in the concrete. The unit weight, workability, water absorption, compressive strength, flexural strength, ultrasonic pulse velocity, static and dynamic elastic moduli, abrasion resistance, and alkali-silica reaction (ASR) expansion tests on the concrete were examined. The use of CRTS improved specific properties of concrete according to the fraction of glass aggregate used between 0 and 20%. Plain concrete (P) and CRTS of 5% in concrete gave better results in terms of mechanical properties. Use of CRTS above 5% in concrete declined the mechanical properties but on the 90th day, CRTS concrete reduced the difference. CRTS up to 20% in concrete especially improved abrasion resistance in comparison to P without CRTS; furthermore, this addition did not increase ASR expansion to a deleterious level.

Keywords: concrete, cathode ray tube glass sand, mechanical properties, ultrasonic pulse velocity, alkali-silica reaction, abrasion resistance

1. Introduction

For centuries, glass has been one of the main man-made materials that characterize societies. It is part of everyday life in both developed and developing countries. So much consumer glass is regularly produced in the World. However, its disposal creates serious problems because only small percentages of glass are reused or recycled. As a result, most glass products become solid waste and consume ever-scarce landfill capacity [1, 2].

To facilitate problems related to disposal, many countries are currently legislating sustainable waste management and conservation of resources, which includes recycling. In particular, glass has inherent value that can be utilized in numerous applications [3, 4]. Demand for recycled glass has gradually increased in some European countries and North America. Currently, 34% of container glass in Great Britain is recycled, but this rate is far below that in other countries such as Germany, Switzerland, the Netherlands, and Finland where the recycling rates are as high as 80%. In the USA, the rates are considerably less, and millions of tons of waste glass remain as landfill [5, 6].

Adding value to a waste product generates both economic and environmental benefits that are particularly effective if certain inherent properties of a specific waste material are utilized. Concrete is an important construction material that can eliminate certain components of the waste stream with promising results [7]. The most successful and widespread modification is the use of fly ash, slags, and silica fume to partially replace ordinary Portland cement. In addition, other waste stream components such as glass, foundry sands, and rubber are successfully used as concrete ingredients. Studies of glass as an aggregate for concrete have been primarily limited to soda lime glass, which is used for household containers and bottles. On the other hand, studies on the use of LCD glass have also been conducted [8]. The chemical makeup of different glass widely varies even with the glass color, which affects the properties of concrete. In addition, various types of recycled glass can be used in concrete [4].

The recycling of old TV sets and computer monitors with cathode ray tubes (CRTs) poses additional problems. CRTs consist of four structures with different components and properties (screen or panel, cone or funnel, neck and frit junction). Most CRT components contain heavy metals (e.g., Pb, Ba, and Sr) that pose serious environmental health concerns. Thus, CRTs have a notably low recycling rate, which necessitates their disposal in specially engineered landfills [9, 10]. Moreover, depositing glass materials in engineered landfills is expensive [7]. Waste CRTs require a special procedure before they are sent to landfills because of their high lead content. In Hong Kong, a simple method with four steps is used to remove lead on the surface of CRTs: (i) removing the leaded funnel glass from the CRT; (ii) crushing the CRT into small particles of sizes below 5 mm; (iii) cleaning the lead from the glass surface by immersion in a 5% nitric acid solution for 3 h; and (iv) removing the remaining acid by rinsing in tap water [11]. The front panel, which is a component of the CRT, is made of barium strontium glass and is free of lead [12]. CRT can be used instead of raw aggregate if it is known it has good performance on properties and durability in concrete. Using of to CRT replace fine aggregate is possible owing to its close association with natural aggregate as chemical and composition [13].

According to Topçu and Canbaz and Ismail and Al-Hashmi, waste glass concrete exhibits slightly smaller slump values than plain concrete [14, 15]. In a study on workability by Kou and Xing, glass powder minimally decreases the workability according to flow table results [16]. It is expected that glass positively affects the mechanical properties of concrete because of its excellent mechanical properties if it is used as an aggregate or in finely ground powder as a partial cement replacement [2]. Ismail and Al-Hashmi showed that the replacement of sand with glass at up to 20% in concrete can increase compressive and flexural strength [15]. Nevertheless, a glass aggregate content of more than 20% leads to notable decrease in the

http://dx.doi.org/10.5772/intechopen.73873

compressive and flexural strength, ultrasonic pulse velocity and dynamic elasticity modulus [1, 14]. One of the problems encountered when using glass as an aggregate in concrete is glass cracking and progression of these cracks [2, 5, 14]. A smooth glass surface facilitates the movement of the cracks, and this effect decreases the strength [11]. The flexural strength of a mortar specimen with glass aggregate can be 10% less than that of a specimen without glass aggregate. Expansion from 1 to 4 mm in the size of the glass aggregate increases flexural strength from 2.6 to 3.2 MPa. Mortars with 3 and 4 mm glass aggregates have stronger resistance to cracks and exhibit high energy [17]. Investigations are still lacking in the area of abrasion resistance of concrete containing glass aggregates. In studies by Ling and Poon, Turgut, and Turgut and Yahlizade, the replacement of sand with glass aggregates in the mortar increased the abrasion resistance [18–20]. Use of glass aggregate at up to 20% in concrete resulted in better performance in comparison to plain concrete from the standpoint of material properties [20, 21].

It is also well known that silica in glass can chemically react with alkali in the cement matrix, which is known as ASR. The resulting ASR gel swells in the presence of moisture and causes potentially serious cracking damage [2, 5, 22]. Topçu et al. reported that the ASR caused expansion and internal stresses in the concrete in direct proportion to the amount of glass in the concrete. It was necessary to add 2% Li_2CO_3 and 20% fly ash to the mix to constrain the expansion below the acceptable limit [22]. As reported by Özkan, clear glass performed better than brown glass in terms of strength and durability. That study also considered mortar with up to 50% blast furnace slag, which replaced Portland cement, and it was found that 25% slag led to the least amount of ASR expansion. Large amounts of fly ash and slag reduced the early strength but significantly increased the alkali resistance of concrete [1]. Polley et al. and Kou and Poon reported that the use of fly ash significantly decreased the influence of the ASR [21, 23]. Lane and Ozyildirim concluded that the strength and durability increased when small amounts of silica fume were used with large amounts of fly ash or slag. ASR tests according to ASTM C1293 indicated that as little as 15% of fly ash was sufficient to prevent detrimental expansion. In addition, a slag ratio of at least 35% was found to be advisable. This performance was also achieved with 25% slag and 2.5% silica fume due to the beneficial combination of silica fume and blast furnace slag [24]. Cota et al. showed that waste glass of 7.5 or 15% did not deteriorate mechanical properties or ASR durability when Portland cement replaced 15% of metakaolin [25]. Ismail and Al-Hashmi noted that it is not always necessary to use pozzolana to prevent ASR. In that study, high-quality pozzolanic waste glass sand (67.72% SiO_2 and 6.9% CaO) that was modified with 10, 15, and 20% sand was used. The concrete strength and ASR durability increased with increasing waste glass content [15]. According to Schwarz et al., fine glass dust can improve the durability of concrete [26]. The results of Shayan and Xu indicate that if the glass particle sizes are thinner than 0.30 mm, they will not cause deleterious expansion. Particle sizes above 0.60 mm cause significant deleterious expansion [2]. In their other study by Shayan and Xu, powder glass did not cause ASR because it had pozzolanic properties [27]. According to Meyer, it is possible to reduce ASR expansion depending on the cement and climatic conditions and the structure and thickness of the glass [28]. In addition, because ASR swelling occurs only in the presence of moisture, measures to prevent the ingress of moisture are expected to be effective in preventing ASR damage.

The present study investigated the effects of substituting various amounts of CRT glass for fine aggregates in concrete on the following physical, mechanical, and durability properties: unit weight, workability, water absorption, compressive and flexural strength, ultrasonic pulse velocity, static and dynamic elastic moduli, abrasion, and ASR expansion. The crushed sand replacement by cathode ray tube glass sand (CRTS) constituted 5, 10, 15, and 20% by weight of the total aggregate.

2. Materials and methods

2.1. Materials and mix design

The cement in this study was CEM I/42.5 R according to TS EN 197-1 [29]. Fly ash (FA) was used to increase the resistance against ASR and supply utilization by recycling this waste material. CRTS obtained by recycling computer screens was provided from Exitcom Corp. in Turkey. The chemical and physical properties of the cement, FA, and CRTS used in this study are provided in **Table 1**. A superplasticizer was also added to ensure concrete workability.

Four different types and sizes of aggregate were used: river sand (0–3 mm), crushed sand (0–4 mm), coarse aggregate 1 (5–12 mm), and coarse aggregate 2 (12–20 mm). The coarse aggregates consisted of crushed stone and their maximum size was 20 mm. **Figure 1** shows river sand, crushed sand, and CRTS. The gradation curves for CRTS and the other fine aggregates are shown in **Figure 2**.

Five different mix designs were investigated, as shown in **Table 2**. These mix designs contained CRTS in the amounts of 0, 5, 10, 15, and 20% by weight of total aggregate crushed sand replacements. After the workability of fresh concrete was determined for each mix, five cubes of size 150×150×150 mm, five beams of size 100×100×400 mm, five cylinders of 150 mm in diameter and 300 mm in length, five cubes of size 71×71×71 mm, and five prisms of size 25×25×285 mm were cast to determine the compressive strength, flexural strength and pulse velocity, elastic modulus, abrasion, and ASR, respectively.

2.2. Test methods

Workability. The slump of fresh concrete was measured using the standard slump test apparatus according to ASTM C143 [30].

Densities and water absorption. Dry, saturated densities and water absorption of hardened concrete were measured according to ASTM C642 [31].

Compressive strength. The compressive strength of the hardened concrete was determined according to ASTM 39 [32] at the ages of 3, 7, 28, and 90 days for the cube specimens of 150×150×150 mm in size. These cubes were removed from the molds after 1 day and cured in water at 21°C before testing.

http://dx.doi.org/10.5772/intechopen.73873

Chemical properties				Physical and mechanical properties			
Constituent (%)	Cement	Fly ash	CRTS	Properties	Cement	Fly ash	CRTS
SiO_2	20.5	50.2	50.9	Specific gravity (g/cm^3)	3.12	2.04	2.70
Al_2O_3	4.65	12.7	2.62	Blaine (m^2/kg)	360	212	—
Fe_2O_3	3.40	9.00	0.12	Mass stability (mm)	2.00	—	—
CaO	62.7	12.53	1.54	Setting period start (min)	153	—	—
Free CaO	1.09	—	—	Setting period stop (min)	188	—	—
MgO	1.02	4.33	0.64	90 μ sieve (%)	0.20	—	—
SO_3	2.21	0.39	—	45 μ sieve (%)	12.8	—	—
Na_2O	0.18	2.75	3.60	2 day-strength (MPa)	30.2	—	—
K_2O	0.41	2.50	4.30	7-day strength (MPa)	51.1	—	—
PbO	—	—	0.29	28-day strength (MPa)	62.2	—	—
BaO	—	—	9.10				
Sb_2O_3	—	—	0.31				
ZrO_2	—	—	0.91				
SrO	—	—	5.97				
TiO	—	—	0.39				
CeO_2	—	—	0.25				
Cl^-	0.01	—	—				
Insoluble residue	0.60	—	—				
Ignition loss	2.15	0.54	—				

Table 1. Chemical composition and physical properties of cement, fly ash and CRTS.

Figure 1. Photographs of CRTS, crushed sand, and river sand used in the study.

Flexural strength. The flexural strength of the hardened concrete was determined at the ages of 3, 7, 28, and 90 days for the beams of 100×100×400 mm in size. These beams were removed from the molds after 1 day and cured in water at 21°C before testing. The flexural strength was

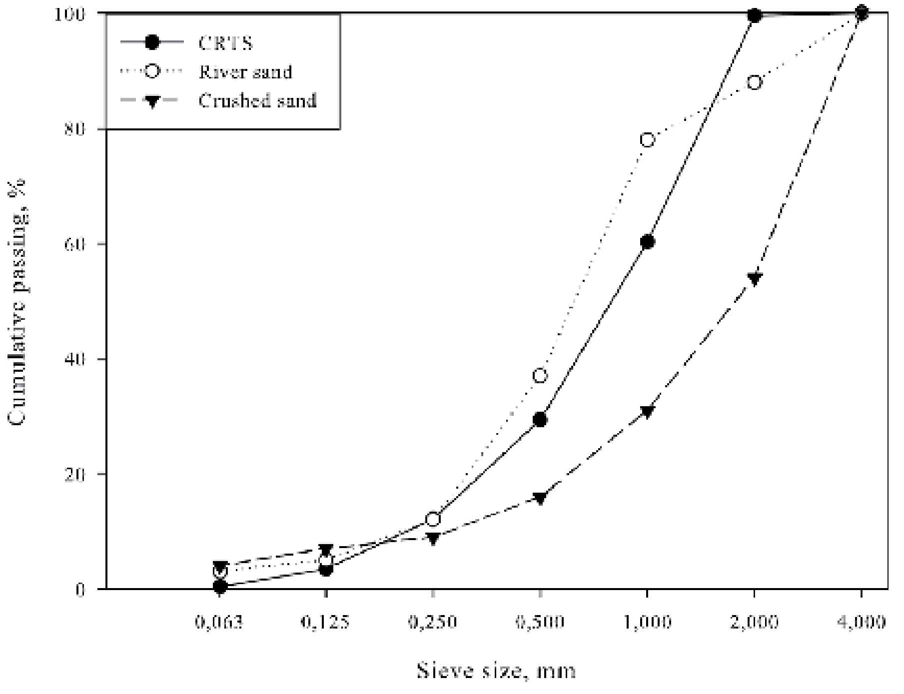


Figure 2. Particle size distributions of fine aggregates.

Components	CRTS content (%)				
	0	**5**	**10**	**15**	**20**
Cement (kg/m^3)	300	300	300	300	300
Fly Ash (kg/m^3)	60	60	60	60	60
Water (kg/m^3)	155	155	155	155	155
Natural sand (kg/m^3)	517	517	517	517	517
Crushed sand (kg/m^3)	360	270	180	90	0
CRTS (kg/m^3)	0	94	188	282	376
Coarse aggregate 1 (kg/m^3)	470	470	470	470	470
Coarse aggregate 2 (kg/m^3)	512	512	512	512	512
Admixture (%)	1.30	1.30	1.30	1.30	1.30
Water/(FA + C)	0.43	0.43	0.43	0.43	0.43
Slump (mm)	170	160	158	150	143
Unit weight (kg/m^3)	2379	2383	2387	2391	2395

Table 2. Concrete mix designs.

determined using three-point bending tests according to ASTM C78 [33] with an effective span of 300 mm.

Ultrasonic pulse velocity. The ultrasonic pulse velocity of the hardened concrete was determined by selecting a measurement distance of 400 mm at the ages of 3, 7, 28, and 90 days on the 100×100×400 mm beams. The measurements were performed according to ASTM C597 [34] before the flexural strength tests.

Static and dynamic elastic moduli. The static elastic modulus was determined on 150×300 mm cylinders at the age of 28 days in compression according to ASTM C469 [35]. The dynamic elastic modulus was determined using the 28-day data that were obtained from the ultrasonic pulse velocity of the beams according to ASTM C597, formula obtained from ASTM C597 was used to calculate the dynamic elastic modulus. The formula of dynamic elastic modulus was showed in Eq. (1).

$$V = \sqrt{\frac{E\,(1-\mu)}{\rho\,(1+\mu)(1-2\mu)}} \tag{1}$$

Alkali-silica reaction. ASR was determined on the mortar bars of 25×25×285 mm according to ASTM C1260 [36].

Abrasion. The amount of horizontal surface abrasion was determined on the cubes of 71×71×71 mm using the Bohme testing method according to BS EN 13892–3 [37] after 28 days.

3. Experimental studies and discussion

3.1. Workability

The workability was negatively affected with increasing CRTS content, as shown in **Table 2**. The slump value slightly decreased when the CRTS content increased by 5%. However, the slump decreased by only 2.75 cm when the CRTS content increased to 20%. According to Ling and Poon, fine particle size glass increases water absorption [38]. Similar to these results, Topcu and Canbaz reported that increasing glass content reduced the workability but the reduction was insignificant [15]. Concrete with glass requires more water to achieve the same workability [5, 21]. Ismail and Al-Hashmi, Kou and Xing, and Shayan and Xu, also reported that glass added to concrete decreases the workability [2, 15, 16].

3.2. Unit weight and water absorption

Table 3 indicates that up to 15% CRTS content in concrete increases the density of hardened concrete in comparison to plain concrete. However, glass content above 15% decreases the density [23]. Changing the glass content from 15 to 20% produces the largest increase in water absorption, which suggests that glass content above 15% leads to higher porosity than specimens without CRTS. The study by Shayan and Xu also indicates that the density decreases

CRTS content (%)	0	5	10	15	20
Slump (cm)	17	16	15.75	15	14.25

Table 3. Effect of CRTS content on the workability.

CRTS content (%)	**Dry density (kg/m^3)**	**Saturated density (kg/m^3)**	**Water absorption (%)**
0	2213	2354	6.46
5	2219	2363	6.26
10	2289	2427	6.05
15	2274	2413	6.09
20	2198	2354	6.97

Table 4. Densities and water absorption of the specimens.

with glass addition above 15% as aggregate or glass powder [2]. The dry and saturated density of the concrete exhibits identical trends. **Table 4** shows that the water absorption decreases from 6.46 to 6.05 when the CRTS composition reaches 10%. Water absorption increased when CRTS content is higher than 10% in the concrete. This increase is remarkable when the fraction is 20%.

3.3. Compressive strength

The use of 15 and 20% CRTS decreased the compressive strength in concrete over the first 28 days in **Figure 3**. The study by Maschio et al. (2013) presents a similar relationship [39]. After 28 days, the rate of increase of strength was faster than that of P and specimens with 5 and 10% glass aggregate and approached these values for 15 and 20% CRTS in concrete [8]. This result demonstrates that the glass contents of 15 and 20% have a pozzolanic effect that becomes more obvious after 28 days [15]. The glass replacements of 5 and 10% do not significantly change either the early or the end strength values in comparison with P [6]. The specimen with 5% CRTS exhibited a notably constant value throughout the period of 90 days, which approached approximately 40 MPa after 90 days. An increase of compressive strength was observed for 10, 15, and 20% CRTS from 28 to 90 days, which can be attributed to the pozzolanic effect of CRTS [40]. Intervals of minimum and maximum compressive strengths for all specimens were 13–24, 22–30, 32–39, and 37–41 MPa for 3, 7, 28, and 90 days, respectively. After 90 days, the difference between the minimum and maximum values of the specimens was relatively small [8]. It is remarkable that the interval decreased from 9 to 4 in 90 days. However, the increase in glass content generally decreases the compressive strength [2]. Ling and Poon explained that the compressive strength might be negatively affected by the bonding between the glass particles and the cement paste [11].

SEM micrograph in **Figure 4** displays the interface between concrete and CRTS exposed to compression. This micrograph was obtained by enlarging the field under SEM 500 times. This SEM micrograph was similar to those reported by Ling and Poon: a smooth surface of CRTS can lead to a weaker interface that results in loss of bonding between CRTS and cement paste,

http://dx.doi.org/10.5772/intechopen.73873

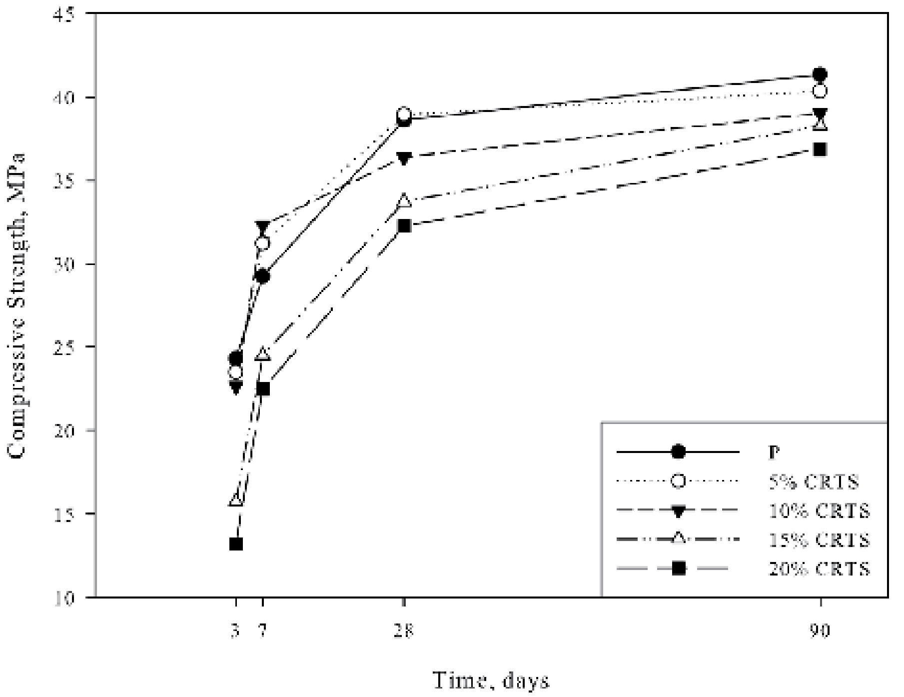


Figure 3. Improvement in compressive strength of the specimens over 90 days.

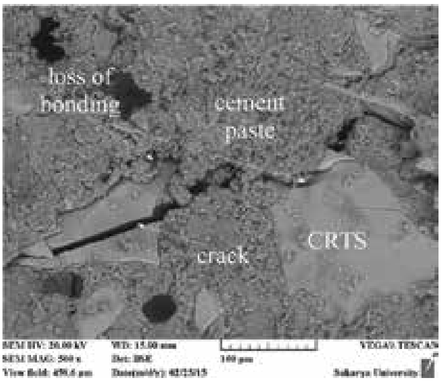


Figure 4. SEM micrographs showing the bond between CRTS and cement paste in concrete after compression loading.

and cracks originating from loading can spread faster [11, 41]. Therefore, the strength of the concrete with glass aggregate decreases [2, 5, 14, 17, 41].

3.4. Flexural strength

The flexural strength-time graph is shown in **Figure 5**. The specimen with 5% CRTS replacement is notably similar to the P sample throughout 90 days in terms of the compressive strength. The flexural strengths for the 5% CRTS and P samples on the 28th and 90th days

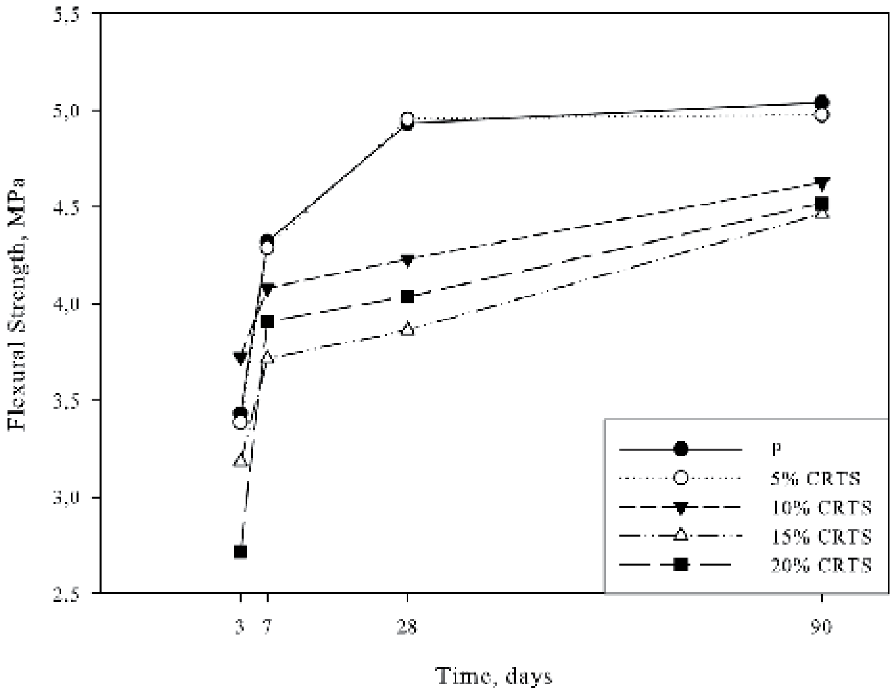


Figure 5. Improvement in flexural strength of the specimens over 90 days.

were almost the same. The specimens with 10, 15, and 20% CRTS have similar trends each other. The maximum difference in values of flexural strength on 90th day decreases to 0.7 MPa, whereas it is 1 MPa after 28 days. The flexural strengths of P and 5% CRTS concrete are approximately 5 MPa at 90 day, whereas the others approach approximately 4.5 MPa. The increase in glass content in the mix generally decreases the flexural strength [2, 8, 14].

3.5. Ultrasonic pulse velocity

The pulse velocity graph in **Figure 6** reveals that the specimen with 20% CRTS replacement exhibits relatively low values for the first 28 days in comparison with the others. The specimens with 5 and 10% CRTS replacement exhibit a relatively higher pulse velocity than P for the first 28 days. Their values are almost identical to that of P at the end of 90 days. All specimens have notably similar pulse velocity values at the end of 90 days, and there are also differences between 28 and 90 days, as shown in the graphs of compressive and flexural strengths in **Figures 3** and **5**. The ultrasound pulse velocity is approximately proportional to the compressive and flexural strengths [2].

3.6. Static and dynamic elasticity moduli

Static and dynamic elasticity modulus values are very similar in **Figure 7**. The dynamic elasticity modulus found using the ultrasonic pulse velocity is generally larger than the static

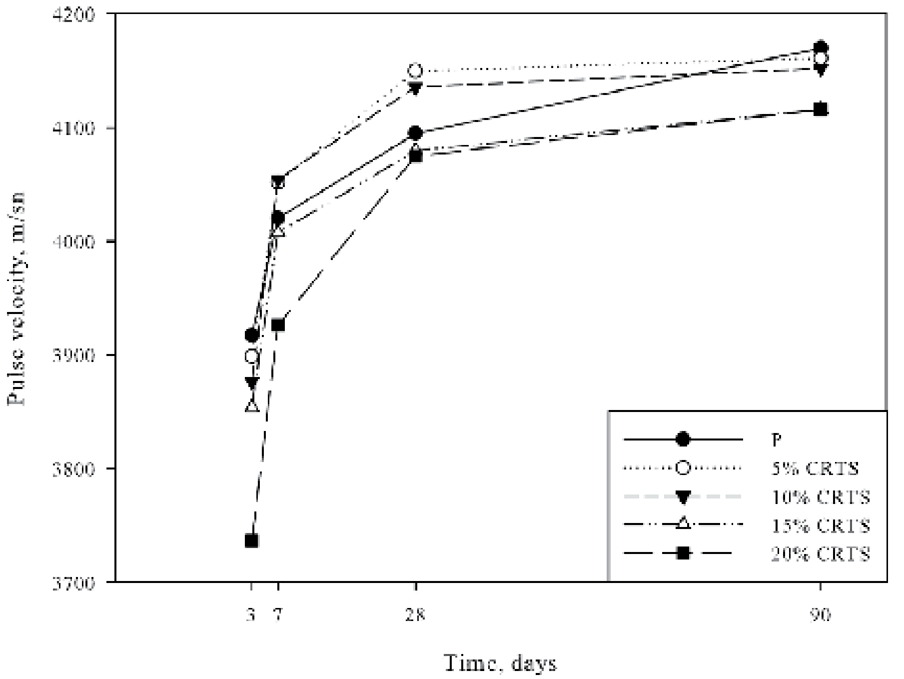


Figure 6. Improvement in ultrasonic pulse velocity of the specimens over 90 days.

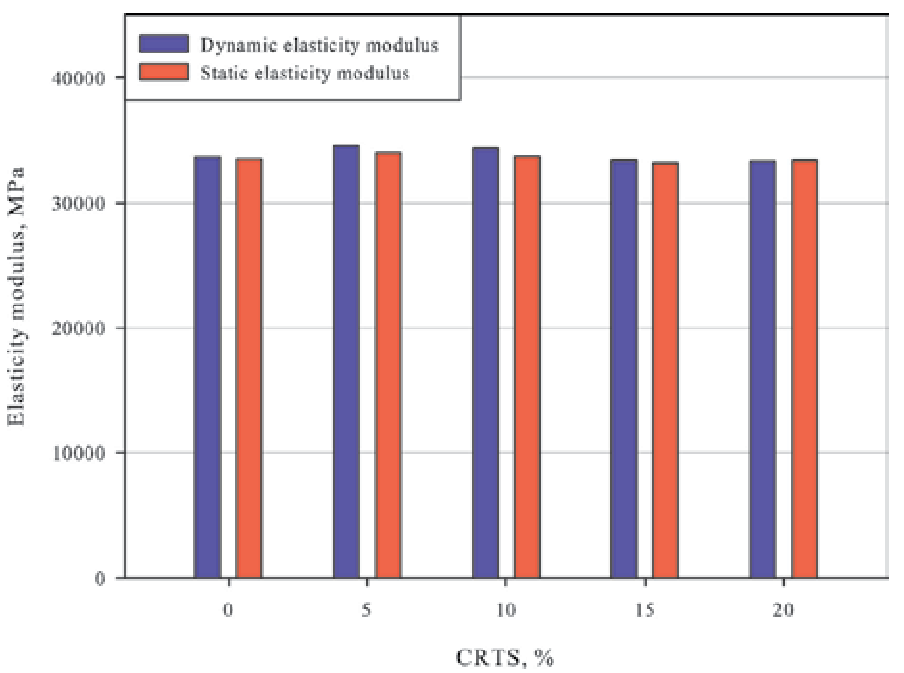


Figure 7. Static and dynamic elasticity moduli of the specimens at 28 days.

elasticity modulus. The specimen with 5% CRTS replacement in concrete has the highest value, and that with 10% glass replacement has a better value than the specimen without CRTS. The specimens with 15 and 20% replacement have notably similar values, which are slightly lower than that of the specimen without CRTS [2, 23]. The elasticity moduli of all specimens are related to the compressive strength, flexural strength, and ultrasonic pulse velocity at 28 days [42].

3.7. Alkali-silica reaction

The 21-day expansion of the mortar bars is shown in **Figures 8** and **9**. In **Figures 8** and **9**, the expansion can be observed to increase with increasing CRTS content and time. The bars with fly ash in **Figure 8** expand slightly less than the bars without fly ash (CRTS-F) in **Figure 9** because of the pozzolanic effect of fly ash [43]. After 21 days, all specimens with CRTS have similar values except for the specimens without CRTS. The highest expansion for the specimens with 20% CRTS is less than 0.03% in **Figures 8** and **9**, which is below the upper limit of 0.1% according to ASTM C1260. The study of Zhao et al. (2013b) also showed the expansion value of FA series mortar samples with glass sand are found to be below 0.1% [44]. The importance of using fine glass was reported by Ismail and Al-Hashmi, who used aggregate with a fineness modulus of 2.36, which decreased the ASR. In this study, the fineness modulus of the CRTS is 2.95, which indicates that the aggregate is sufficiently fine for ASR resistance.

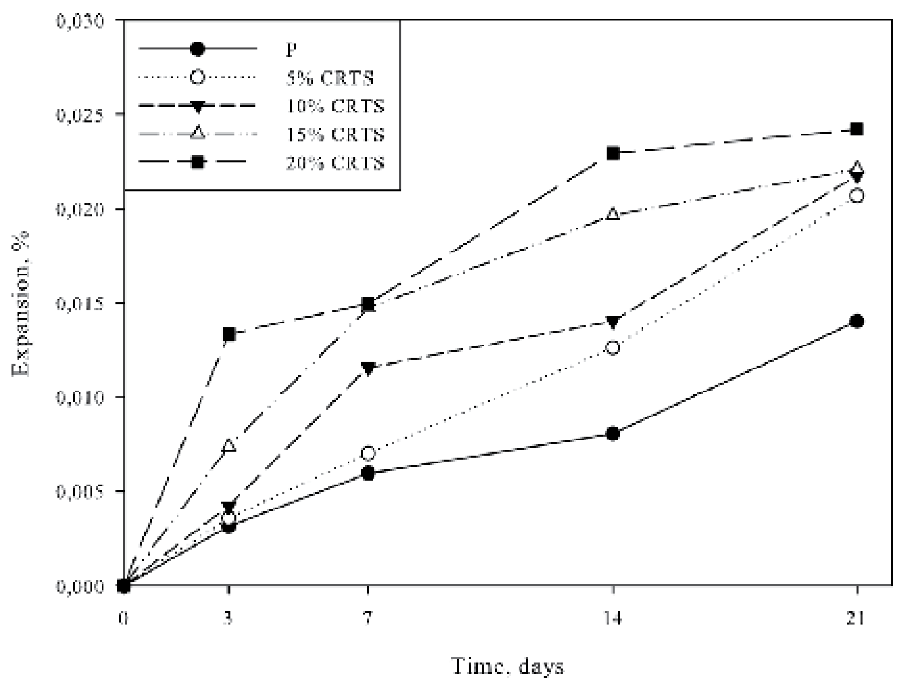


Figure 8. Improvement in ASR of the specimens over 21 days.

http://dx.doi.org/10.5772/intechopen.73873

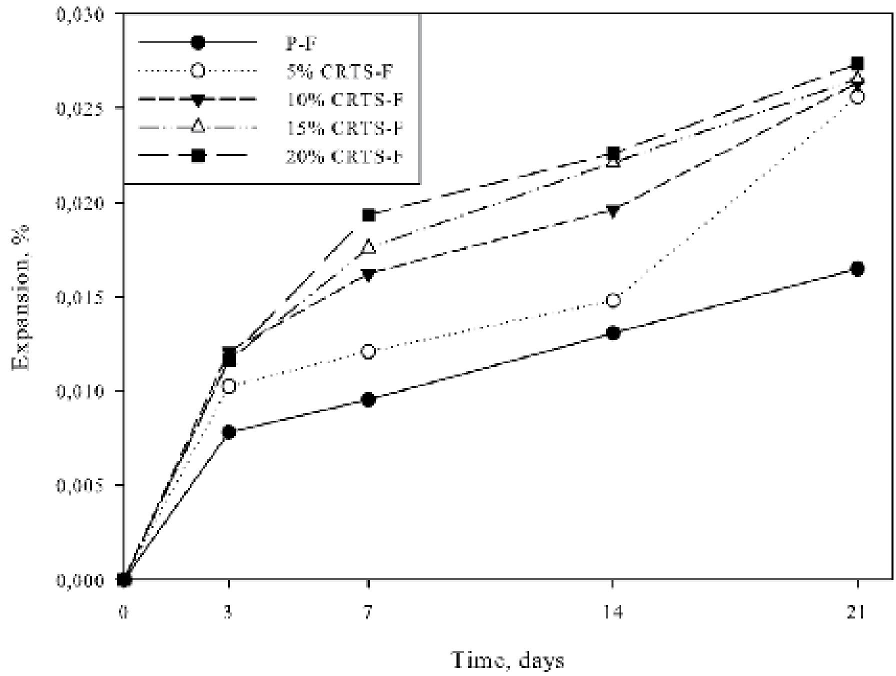


Figure 9. Improvement in ASR of the specimens without fly ash over 21 days.

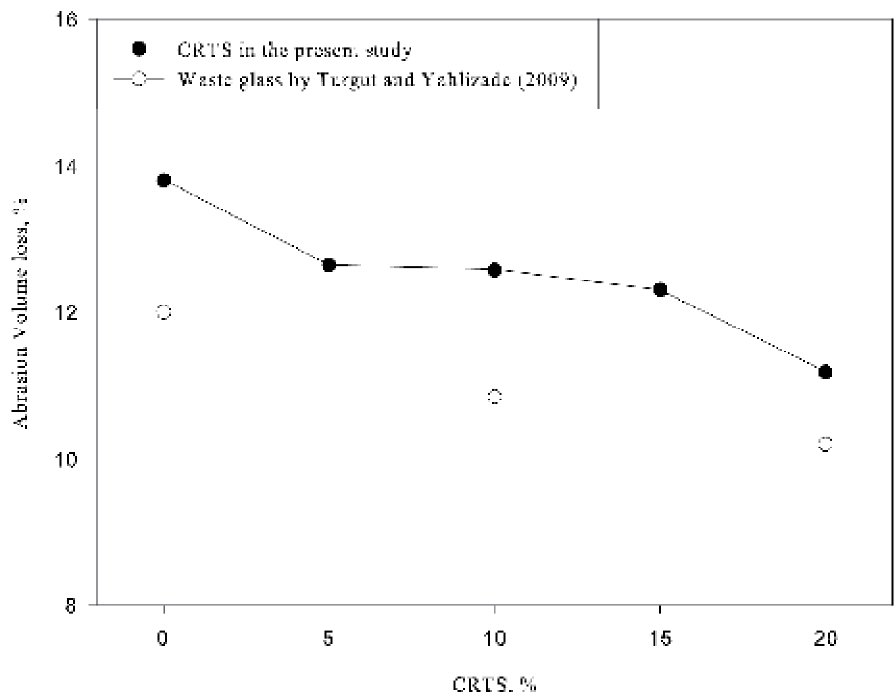


Figure 10. Change in abrasion loss (%) of the specimens after 28 days as a function of CRT comparing with the research by Turgut and Yahlizade.

3.8. Abrasion resistance

Figure 10 shows the results of abrasion volume loss (%) found using the Bohme abrasion test machine. It clearly appears that the abrasion volume loss (%) decreases with increasing [18–20, 45]. The research by Turgut and Yahlizade supports these results. They found that the use of glass replacement with fine aggregate up to 20% by weight decreased the abrasion volume loss (%). In this research, the decrease slows down between 5 and 15%; however, Turgut and Yahlizade did not investigate these proportions. The difference of abrasion volume loss of specimen with glass content of 20% compared to the specimen without CRTS is approximately 2.5% in this research; whereas it was 2% in the research by Turgut and Yahlizade. Their study was based on concrete paving blocks and window glass.

4. Conclusions

Based on the results of the experimental studies carried out in the research, the results obtained are presented below:

1. CRTS slightly affects the slump values; an increase in the glass content in concrete reduces the slump value.
2. CRTS content up to 10% increases the density and decreases water absorption. However, a CRTS content of 20% increases water absorption in the concrete. This shows that the CRTS up to 10% in concrete increases the filling by entering the gaps and introduces voids above 10%.
3. Increasing the CRTS content decreases the compressive and flexural strengths, except when the content is 5%. Although CRTS content of 15 and 20% reduces the strength, the strength of these specimen increases more than that of the other specimens after 28 days, which indicates a pozzolanic effect. This effect is less observed in specimens with 10% CRTS.
4. CRTS content of 15 and 20% leads to the lowest pulse velocity values in comparison with the other concrete. The specimens with CRTS content of 5 and 10% exhibit higher pulse velocity compared to the specimens without CRTS until 28 days have passed. All values are close to each other at 90 days.
5. Static and dynamic elasticity moduli exhibit similar trends to each other and also to the compressive strength at 28 days. The concrete specimens with CRTS content of 5 and 10% have larger moduli than P. The elasticity moduli decrease when the CRTS content reaches 15%. Specimens with 20% CRTS exhibit similar moduli to those with 15% CRTS.
6. An increase in CRTS content decreases the ASR resistance but not to a problematic level because the level is below the 0.1% ASTM C1260. The specimens with fly ash have lower values than those without fly ash. The use of fly ash in concrete with CRTS has a positive effect against ASR, as expected.

7. The abrasion volume loss (%) decreases with increasing CRTS content up to 20%. The decrease is approximately 2.5%.

In conclusion, the concrete with CRTS aggregate exhibits a performance similar to that of the concrete without CRTS. This result shows that the use of CRTS can contribute to the properties of concrete. The mixture of CRTS in concrete can be adjusted according to the application and desired specific properties. The performance of abrasion resistance of concrete with 20% CRTS is especially notable. Research is needed on concrete with more than 20% CRTS. Furthermore, the use of CRT funnels in concrete is also an important matter because of their lead content. Lead is harmful to the environment. In this respect, recycling of CRT funnels is important, and there is a need for research on this subject.

The study is notable in terms of the potential use of recycled CRTS because of the quantity of waste CRTS used. Concrete properties can be improved with CRTS, resulting in the reduction of piles of waste CRTs when they are used in concrete.

Acknowledgements

The author wishes to acknowledge the support of Prof. Dr. Christian Meyer (who has patented the "use of waste glass in concrete") from the Civil Engineering and Engineering Mechanics Department at Columbia University, who contributed important ideas to this study during a research on internal curing of concrete with the author in Carleton Laboratory at Columbia University.

Author details

Salih Taner Yildirim

Address all correspondence to: styildirim@kocaeli.edu.tr

Department of Civil Engineering, Kocaeli University, Kocaeli, Turkey

References

[1] Özkan Ö. Properties of mortars containing waste bottle glass and blast furnace slag. Journal of the Faculty of Engineering and Architecture of Gazi University. 2007;**22**(1):87-94. DOI: 10.1016/j.conbuildmat.2007.01.015

[2] Shayan A, Xu A. Value-added utilisation of waste glass in concrete. Cement and Concrete Research. 2004;**34**(1):81-89. DOI: 10.1016/S0008-8846(03)00251-5

[3] Reindi J. Development of non-traditional glass markets. Resource Recycling Conference; October, New York; 1991. pp. 76-78

[4] Jin W, Meyer C, Baxter S. Glascrete—Concrete with glass aggregate. ACI Materials Journal. 2000;**97**(2):208-213

[5] Shi C, Zheng K. A review on the use of waste glasses in the production of cement and concrete. Resources, Conservation and Recycling. 2007;**52**(2):234-247. DOI: 10.1016/j.resconrec.2007.01.013

[6] Limbachiya MC. Bulk engineering and durability properties of washed glass sand concrete. Construction and Building Materials. 2009;**23**(2):1078-1083. DOI: 10.1016/j.conbuildmat.2008.05.022

[7] Meyer C. The greening of the concrete industry. Cement and Concrete Composites. 2009; **31**(8):601-605. DOI: 10.1016/j.cemconcomp.2008.12.010

[8] Wang HY. A study of the effects of LCD glass sand on the properties of concrete. Waste Management. 2009;**29**(1):1335-1341. DOI: 10.1016/j.wasman.2008.03.005

[9] Andreola F, Barbieri L, Corradi A, Lancellotti I. CRT glass state of the art: A case study: Recycling in ceramic glazes. Journal of the European Ceramic Society. 2007;**27**(2–3):1623-1629. DOI: 10.1016/j.wasman.2008.03.005

[10] Andreola F, Barbieri L, Karamanova E, Lancellotti I, Pelino M. Recycling of CRT panel glass as fluxing agent in the porcelain stoneware tile production. Ceramics International. 2008;**34**(5):1289-1295. DOI: 10.1016/j.ceramint.2007.03.013

[11] Ling TC, Poon CS. Feasible use of recycled CRT funnel glass as heavyweight fine aggregate in barite concrete. Journal of Cleaner Production. 2012;**33**:42-49. DOI: 10.1016/j.jclepro.2012.05.003

[12] Hreglich S, Falcone R, Vallotto M. The recycling of end of life panel glass from TV sets in glass fibres and ceramic productions. In: Thomas Telford, Dhir RK, Limbachiya MC, Dyer TD editors. Recycling and Reuse of Glass Cullet, London; 2001. p. 123-134

[13] Iniaghe PO, Adie GU. Management practices for end-of-life cathode ray tube glass: Review of advances in recycling and best available technologies. Waste Management & Research. 2015;**33**(11):947-961

[14] Topçu IB, Canbaz M. Properties of concrete containing waste glass. Cement and Concrete Research. 2004;**34**(2):267-274. DOI: 10.1016/j.cemconres.2003.07.003

[15] Ismail ZZ, AL-Hashmi EA. Recycling of waste glass as a partial replacement for fine aggregate in concrete. Waste Management. 2009;**29**(2):655-659. DOI: 10.1016/j.wasman.2008.08.012

[16] Kou SC, Xing F. The effect of recycled glass powder and reject fly ash on the mechanical properties of fibre-reinforced ultra high performance concrete. Advances in Materials Science and Engineering. 2012;**2012**, Article ID 263243, 8 pages. DOI: 10.1155/2012/263243

[17] Siddiqui AM, Choudhury AH, Merchant IJ. Acoustic emission monitoring of the fracture behaviour of concrete containing various size and shape of glass aggregates. In: 26th European Conference on Acoustic Emission Testing; 15–17 September 2004; Berlin, Germany. pp. 115-130

[18] Ling TC, Poon CS. Properties of architectural mortar prepared with recycled glass with different particle sizes. Materials and Design. 2011;**32**(5):2675-2684. DOI: 10.1016/j.matdes.2011.01.011

[19] Turgut P. Limestone dust and glass powder wastes as new brick material. Materials and Structures. 2008;**41**(5):805-813. DOI: 10.1617/s11527-007-9284-3

[20] Turgut P, Yahlizade ES. Research into concrete blocks with waste glass. International Journal of Civil and Environmental Engineering. 2009;**1**(4):203-209

[21] Polley C, Cramer SM, Cruz RV. Potential for using waste glass in portland cement concrete. Journal of Materials in Civil Engineering. 1998;**10**(4):210-219. DOI: 10.1061/(ASCE)0899-1561(1998)10:4(210)

[22] Topçu IB, Boğa AR, Bilir T. Alkali–silica reactions of mortars produced by using waste glass as fine aggregate and admixtures such as fly ash and Li_2CO_3. Waste Management. 2008;**28**(5):878-884. DOI: 10.1016/j.wasman.2007.04.005

[23] Kou SC, Poon CS. Properties of self-compacting concrete prepared with recycled glass aggregate. Cement and Concrete Composites. 2009;**31**(2):107-113. DOI: 10.1016/j.cemconcomp.2008.12.002

[24] Lane DS, Ozyildirim C. Preventive measures for alkali-silica reactions (binary and ternary systems). Cement and Concrete Research. 1999;**29**(8):1281-1288. DOI: 10.1016/S0008-8846(98)00242-7

[25] Cota FP, Melo CCD, Panzera TH, Araújo AG, Borges PHR, Scarpa F. Mechanical properties and ASR evaluation of concrete tiles with waste glass aggregate. Sustainable Cities and Society. 2015;**16**:49-56. DOI: 10.1016/j.scs.2015.02.005

[26] Schwarz N, Cam H, Neithalath N. Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash. Cement and Concrete Composites. 2008;**30**(6):486-496. DOI: 10.1016/j.cemconcomp.2008.02.001

[27] Shayan A, Xu A. Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs. Cement and Concrete Research. 2006;**36**(3):457-468. DOI: 10.1016/j.cemconres.2005.12.012

[28] Meyer C. Glass concrete-putting sustainability to work in a decorative way. ACI Concrete International. 2003;**25**(6):55-58

[29] TS EN 197-1. Cement—Part 1: Compositions and Conformity Criteria for Common Cements. Ankara, Turkey: Turkish Standarts Institution. 2012

[30] ASTM C143. Standard Test Method for Slump of Hydraulic Cement Concrete. West Conshohocken, PA, USA: ASTM International; 2005. DOI: 10.1520/C0143_C0143M-05

[31] ASTM C642. Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. West Conshohocken, PA, USA: ASTM International; 2013. DOI: 10.1520/C0642-13

[32] ASTM C39. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. West Conshohocken, PA, USA: ASTM International; 2011. DOI: 10.1520/C0039_C0039M-11a

[33] ASTM C78. Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). West Conshohocken, PA, USA: ASTM International; 2010. DOI: 10.1520/C0078_C0078M-10

[34] ASTM C597. Standard Test Method for Pulse Velocity through Concrete. West Conshohocken, PA: ASTM International; 2009. DOI: 10.1520/C0597-09

[35] ASTM C469. Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. West Conshohocken, PA, USA: ASTM International; 2010. DOI: 10.1520/C0469_C0469M-10

[36] ASTM C1260. Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). West Conshohocken, PA, USA: ASTM International; 2014. DOI: 10.1520/C1260-14

[37] BS EN 13892-3. Methods of Test for Screed Materials: Determination of Wear Resistance—Bohme. London, UK: British Standards Institution. 2014. DOI:10.3403/30297860

[38] Ling TC, Poon CS. Effects of particle size of treated CRT funnel glass on properties of cement mortar. Materials and Structures. 2013;**46**(1–2):25-34. DOI: 10.1617/s11527-012-9880-8

[39] Maschio S, Tonello G, Furlani E. Recycling glass cullet from waste CRTS for the production of high strength mortars. Journal of Waste Management. 2013;**2013**, Article ID 102519, 8 pages. DOI: 10.1155/2013/102519

[40] Lee G, Poon CS, Wong YL, Ling TC. Effects of recycled fine glass aggregates on the properties of dry-mixed concrete blocks. Construction and Building Materials. 2013;**38**: 638-643. DOI: 10.1016/j.conbuildmat.2012.09.017

[41] Ling TC, Poon CS. Use of recycled CRT funnel glass as fine aggregate in dry-mixed concrete paving blocks. Journal of Cleaner Production. 2014;**68**:209-215. DOI: 10.1016/j.jclepro.2013.12.084

[42] Zhao H, Poon CS, Ling TC. Utilizing recycled cathode ray tube funnel glass sand as river sand replacement in the high-density concrete. Journal of Cleaner Production. 2013a;**51**: 184-190. DOI: 10.1016/j.jclepro.2013.01.025

[43] Almesfer N, Ingham J. Effect of waste glass on the properties of concrete. Journal of Materials in Civil Engineering. 2014;**26**(11):06014022. DOI: 10.1061/(ASCE)MT.1943-5533.0001077

[44] Zhao H, Poon CS, Ling TC. Properties of mortar prepared with recycled cathode ray tube funnel glass sand at different mineral admixture. Construction and Building Materials. 2013b;**40**:951-960. DOI: 10.1016/j.conbuildmat.2012.11.102

[45] Wright J, Cartwright C, Fura D, Rajabipour F. Fresh and hardened properties of concrete incorporating recycled glass as 100% sand replacement. Journal of Materials in Civil Engineering. 2013;**26**(10):04014073. DOI: 10.1061/(ASCE)MT.1943-5533.0000979

Chapter 8

Development of Clay Plasters Containing Thermoregulating Microcapsules for Indoor Walls

Ismael Sevilla, Francisco J. Castilla, David Sanz,
José L. Serrano, Juan F. Rodríguez and
Manuel Carmona

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72410

Abstract

This work shows the technical feasibility of incorporating phase change materials (PCMs) into clay plastering mortars to improve the thermal properties of the building envelopes. Due to the absence of regulated and internationally agreed-upon norms for clay mortars containing thermoregulating microcapsules (MPCMs), two tests following UNE-EN-998-1:2010 and UNE-EN-1015, were designed to provide the greatest similarity to its final application. Three different dosages 5, 10, and 15 wt% of MPCM relative to the dried mortar weight were used. Fresh mortars were physically characterized to determine its consistency, apparent density, period of workability and open time, and occluded air content. Physical and mechanical characteristics were determined for hardened mortar. The thermal characteristics of the specimens were analysed by using a differential scanning calorimetry, obtaining their apparent specific heat capacities and the enthalpy curves. Building simulation software is a fundamental tool for designing buildings with almost zero energy consumption. In this study, three identical architectural models were simulated. The reference building had inner coatings of clay-based mortar, mortar with 15% added material, and a conventional gypsum mortar. These buildings were subjected to the same exposure and radiation conditions, which allowed the result to be compared to evaluate the effect of incorporating the PCM.

Keywords: phase-change materials (PCMs), clay plaster, thermal energy storage (TES), energy demand

1. Introduction

One of the greatest problems facing society today is energy consumption and environmental pollution. One of the main consumers of energy is the domestic sector, which in the European

Union (EU), for example, represents 25% of the total energy [1]. In fact, given the direct (use of housing) and indirect (materials manufacturing, transport, construction, demolition, etc.) energy costs, it is estimated that the construction industry in developed countries consumes up to 40% of the total energy [2].

The residential sector accounts for 25% of the total energy consumption in the EU and 19% in Spain [3]. Construction, considered part of the industrial sector, accounted for approximately 1 and 2% of the energy consumed in the EU and Spain, respectively, in 2014, according to data from the 2016 edition of Eurostat. The energy consumed in the residential sector combined with all other construction totals 40% of the energy consumed [4].

This is why the future of construction and building cannot be contemplated without designing buildings that consume almost no power, that is, zero-energy buildings (ZEBs). In this regard, legislation related to energy savings in buildings is being implemented around the world. In the EU, [4] on energy efficiency in buildings (EPBD) was approved; its objective is buildings with almost zero-energy consumption in 2020, and more recently [5] on energy efficiency has emphasized the rehabilitation of the building stock of member states.

Some of the strategies to follow for achieving these objectives are reducing the energy demand of air-conditioning systems and searching for materials with smaller carbon footprints through life cycle assessment and life cycle energy analysis [6]. Such strategies must be considered in a more relevant way in the areas of the planet with considerable daily variations in temperature that cause notable differences in energy consumption between day and night. Such variations lead to periods of maximum load and of less activity (with the latter generally between midnight and early morning). If heat or cold thermal energy could be stored at convenience and released into the indoor environment during the moments of greatest demand, some or all of the load peaks could be displaced and other "passive" strategies could be exploited. In this way, energy is managed effectively, which provides economic and environmental benefits.

Indeed, passive conditioning in buildings that store thermal energy by means of phase changes (i.e., latent heat) is an increasingly common trend. It is not surprising, therefore, that during the last years, many studies have been published on the use of phase-change materials (PCMs) in buildings [7–9].

PCMs are substances that, through exothermic and endothermic processes derived from their change of state, are capable of storing large amounts of energy in the form of latent heat and exchanging it with the environment when thermal conditions require it. Among the various changes of state, the solid–liquid has the best characteristics for being used in building construction attending to the small volume change that occurs. According to their nature, PCMs are classified into three broad groups: inorganic, organic and eutectic mixtures; hydrated salts and paraffin are the most common compounds [10]. The main methods of incorporating PCMs are the direct, immersion and encapsulation methods. A detailed description of such systems can be reviewed in [11]. There are two types of encapsulation: macroencapsulation and microencapsulation. In the former, the PCM is packed in tubes, bags, spheres, panels or other containers and then incorporated into the building material. The latter method, microencapsulation, involves small PCM particles being enclosed in a thin film of a high-molecular-weight polymer that must be physical-chemically compatible with both the PCM and the building materials.

The first applications of PCMs to heating and cooling buildings described in the literature date back three decades [12]. In recent decades, a broad spectrum of work has focused on incorporating PCMs to store energy as latent heat into building materials such as plaster and cement walls, roofs, floors, sandwich panels, among others [7, 13]. However, as noted by [14], some difficulties remain in reliable applications, practical uses and validation through modeling processes [15, 16]. In this sense, some studies, such as the one by [17], have characterized and studied the behavior of PCMs embedded in compacted earth elements. However, although these properties are valued, authors do not numerically model the construction element within a complete architectural framework.

In that way, new trends are emerging that vindicate these construction systems, which have been developed by adapting to the climate of each region for years. Bioconstruction tries to relate the natural environment to the urban habitat by promoting the use of materials with practically no environmental impact and conceiving of architecture as a discipline that must be adapted to the environment and not the other way around. The use of new technologies and materials allows to recover the use of other traditional materials, such as earth (soil), which makes them more energy efficient and compliant with the requirements of the elements and current construction systems, thereby reducing the impact on the natural environment.

In this sense, clay presents itself as a material capable of satisfying these new needs. It is natural, recyclable and abundant in most regions of the world. Handling it does not require more resources than the ones used for extraction, and there is no need for transport or firing processes, which ensures that its environmental impact is much lower than that of other construction materials [18].

Since there has been no literature referred to the use of clay plasters containing thermoregulating microcapsules to passive buildings applications, the goal of this work is to study the technical feasibility of incorporating these materials into clay-plastering mortars to improve the thermal properties of the resulting building, contributing to its energy efficiency and habitability. In that way, three different composites containing 5, 10 and 15 wt% of microencapsulated phase-change materials (MPCMs) were synthesized and characterized. Due to the absence of regulated and internationally agreed-upon norms for clay mortars containing thermoregulating microcapsules, two tests following European Normative [19–27], which refers to mortars for masonry, were designed to provide the greatest similarity to its final application. Finally, energetic effects of incorporating PCMs into the coating mortar were simulated and a comparative analysis of the variation of the energy demand was made and based on an architectural model.

2. Materials and methods

The clay-based mortar lining used in this study consists of illite-kaolinite clays, siliceous sands at different granulometries and fiber (straw) without additional chemical additives. This commercial clay was supplied by the company Ecoclay®. The technical characteristics of the material are shown in **Table 1**.

Spherical microcapsules containing Rubitherm® RT27 with a shell from LDPE and EVA-mSD-(LDPE·EVA-RT27) were obtained following the method described in the Patent EP2119498 in a pilot plant spray drying. These microcapsules have an average particle size of 30 μm and a latent heat of 98.14 J/g (**Figure 1**).

The thermal properties of the microcapsules and the clay-based mortars were characterized by differential scanning calorimetry (DSC). Analyses were performed in the range from 0 to 40°C at a heating rate of 5°C/min. The PCM began to accumulate at a temperature of 5.33°C, ending at 32.71°C. In this temperature range, there was a total accumulation of 83.41 J/g, which is the heat storage capacity produced by the phase change of paraffin (i.e., its latent heat). The maximum accumulation point is 12.24 J/g·°C and occurs at 24.27°C (**Table 2** and **Figure 2**).

Materials were tested by following the normative [19–27], which refers to mortars for masonry, attending to the absence of regulated and internationally agreed-upon norms for clay mortars.

Three different dosages were used: 5, 10 and 15 wt% MPCMs per dried weight of mortar. Composite clay mortars were produced by weighting first the desired masses of clay, water and MPCMs and following a mixing protocol according to [23] and the recommendations of Ecoclay. The components were placed together in a tray and mixed firstly for 1 min at an agitation; the stirring was stopped and immediately activated again for other 30 s. Once this time of agitation was achieved, the agitation was stopped per 5 min, in order to reach the proper

Ds (kg/m^3)	LL (%)	LP (%)	IP (%)	Cf (%)
1543	23.8	14.7	9.4	1.52

Table 1. Physical characteristics of the Ecoclay-based-fiber clay mortar: density (Ds), liquid limit (LL), plastic limit (LP), plasticity index (IP), and fiber content (Cf).

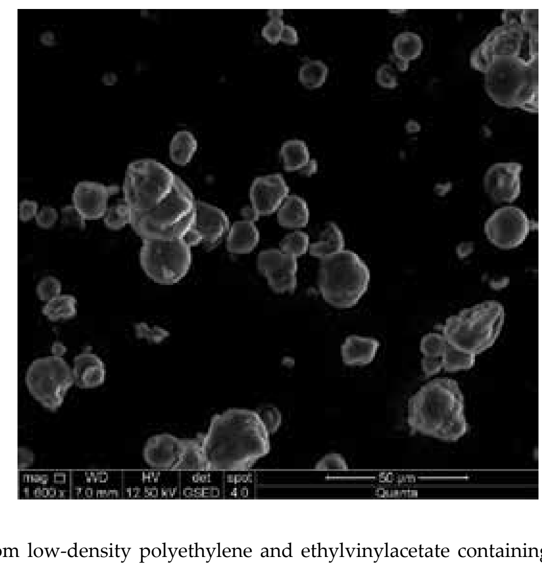


Figure 1. Microcapsules from low-density polyethylene and ethylvinylacetate containing Rubitherm®RT27 by spray drying.

	MCr (°C)	SHc (kJ/kgK)	HSc (kJ/kg)	Ds (kg/m³)	Dl (kg/m³)	Hc (W/(mK))	MT (K)
Rubitherm RT27	25–28	2.84	179	880	760	0.2	297.42

Table 2. Physical and thermal characteristics of Rubitherm RT27 (from http://www.rubitherm.com/) for encapsulation using spray-drying: melting/freezing range (MCr), specific heat capacity (SHc), solid density (Ds), liquid density (Dl), heat conductivity (Hc) and maximum operating temperature (MT). DSC was used to determine the SHc of the encapsulated paraffin (2.84 kJ/kg; the HSc was 83.41 kJ/kg for 46% microencapsulated paraffin).

hydration of the mixture. Finally, the mixing procedure was completed after 1 additional minute of agitation.

Test pieces were cured under laboratory conditions (20°C and 60% RH) during 14 days for favoring the chemical reactions in the presence of water, allowing to achieve the proper strength. Further, they were demolded over at least 4 days later (**Figure 3**).

2.1. Physical, mechanical, and thermal characterization

The physical characterization of fresh mortars was performed to determine the consistency using a shaking Table [24], bulk density and occluded air content [25, 26, respectively] and period of workability and open time [27]. Besides, some regulations were adapted to find the density of the test specimens [28], the water vapor absorption [29] and the water vapor permeability [22].

The mechanical study included the flexural strength and compressive strength of the hardened mortar following the [20] and the adhesive strength of plaster mortar and hardened plaster applied to substrates according to the norm [21] and the Shore C hardness following the [28].

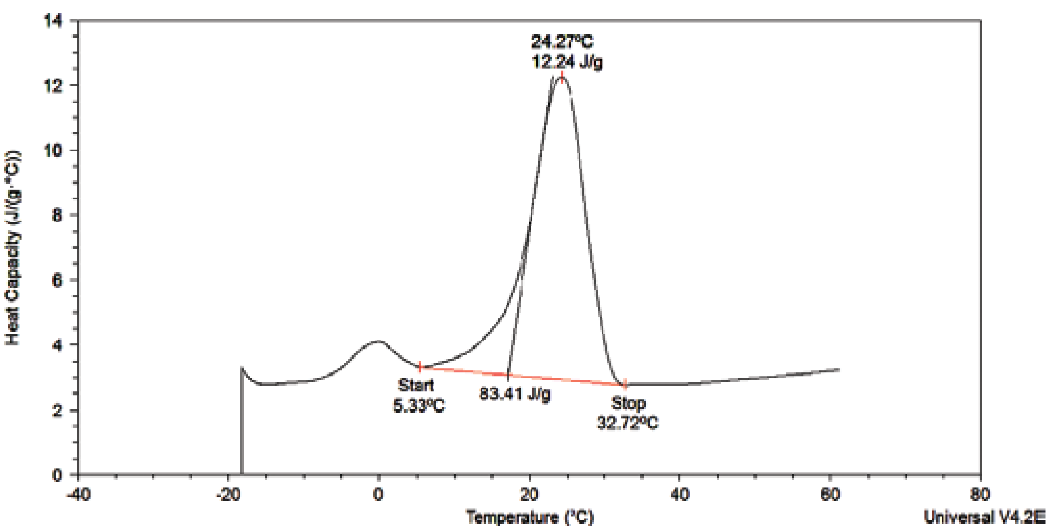


Figure 2. DSC curve of microcapsules of Rubitherm RT27 (from http://www.rubitherm.com/) for encapsulation using spray drying.

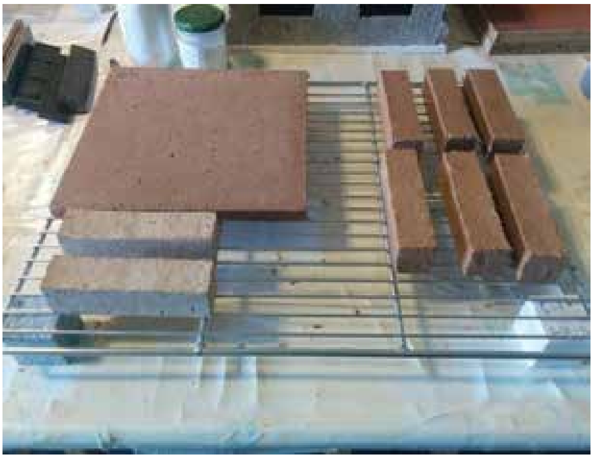


Figure 3. Specimens used for physical, thermal, and mechanical characterization.

Finally, the thermal behavior of the specimens was tested using DSC with a TA Instruments Q100 calorimeter, from which the apparent heat capacity and the enthalpy curves were obtained. The thermal conductivities and the thermal energy storage (TES) capacities were calculated using homemade equipment described and proved in previous works [30, 31].

2.2. Thermal behavior modeling

Experimental results of the resulting construction material were parameterized and modeled using EnergyPlus energy simulation software provided of its graphical interface, DesignBuilder®. This software has been used by [15] to evaluate the energy demand of a reference architectural model containing PCMs. For the proper whole building energy simulation, the program requires the inputs of enthalpy curve of the material, the thermal conductivity and the apparent heat capacity.

The simulation was performed using the finite difference algorithm (CondFD). This algorithm divides the surfaces of walls, floors and ceilings into a system of nodes and uses the implicit method of finite differences to solve the heat transfer equation numerically [32].

2.2.1. Geometry and boundary conditions

The architectural model for the simulation was generated using SketchUp® and it had a simple geometry for ensuring a homogeneous internal airflow throughout the volume, avoiding the presence of preferential heat flows (**Figure 4**). There were no partitions and the internal air was in constant contact with the envelope of the building. This enclosure allowed the volume of indoor air to interact with the external conditions (without infiltrations or ventilation); in this sense, the enclosure was designed to have a high thermal transmittance without insulation except the bottom plate. The gaps were oriented to the west, south and east to ensure that solar radiation was collected throughout the day. Finally, heating, cooling and lighting systems were not incorporated. With these design criteria, it was possible to establish a volume of controlled air that interacted with the environments in which they were located.

Figure 4. Three-dimensional view of the model building. Total surface area: 112.52 m^2. Latitude: 38.99°. Longitude: −3.9°. Elevation: 629 masl.

The building was located in a central Spanish city (Ciudad Real). This area has a semi-arid continental climate with hot summers (average monthly temperatures above 22°C) and cold winters (average monthly temperatures below 6°C). The annual temperature range can be ranged between 44.3 and −9.4°C, according to the Ciudad Real meteorological observatory. The daily temperature range is also considerable, with ranges of 5–10°C in winter and 15–20°C in summer. The climatic data used in the simulation were obtained from the American Society of Air Conditioning, Refrigeration and Heating (ASHRAE). The hypotheses used with the simulations were developed for summer conditions with simulation periods of 15 days and an integration time step less than 1 min. The selected period was summer, July15–31; each season lasted 408 h.

2.2.2. Construction parameters

The same building was simulated by using two different envelopes of a clay coating containing 15% of thermoregulating microcapsules and other free of PCMs. Results were also compared with those obtained using gypsum as a conventional mortar coating. The thickness of the coating considered was 3 cm, following the manufacturer's recommendations.

3. Results

3.1. Fresh mortar: physical properties

Because this material was applied as a layer of mortar on the inside of the wall, its rheological properties were fundamental. The densities of the samples and the increase in the mixing water required to produce the same runoff of the standard mortar were 1823.34, 1550.07, 1491.19 and 1406.12 kg/m^3 and 0, 9, 18 and 30%, for microcapsules contents of 0, 5, 10 and 15%, respectively. This result indicates that the higher the microcapsule content, the lower the density of the fresh mortar and lower the workability of the mortars.

The open time of the fresh mortar showed that both the standard mortar and the mortars containing different amounts of the MPCMs exceeded the strength determined by the corresponding standard (0.5 N/mm^2) within 6 days of being mixed. On the fourth day, the four samples were very similar in strength, with a significant increase with the presence of microcapsules. On the fifth day, the difference in strength between the different samples increased; the samples containing more of the PCM were stronger. By the sixth day, the trend had reversed, with the standard sample and the sample containing 5% PCM being the strongest.

The occluded air content of the mortar increased substantially when the PCM was incorporated. For the standard sample, it was calculated to be 7%, but with the first addition, this value increased to 14%. There was a downward trend as the dosage increased; the 10% sample contained 14% occluded air, and the 15% sample contained 12% occluded air.

3.2. Hardened mortar: physical properties

The results of the retraction calculation increased as the PCM was added (**Table 3**). These values were 3.22% for the standard sample, 4.71% for the 5% sample, 5.47% for the 10% sample and 6.71% for the 15% sample. As with the apparent density of the fresh mortar, the density of the hardened mortar was evidently influenced by the addition of the MPCMs to the clay mortar (**Table 3**). Logically, the density difference between the dry components (1543 kg/m^3 for the clay mortar and 866 kg/m^3 for the PCM) means that adding the PCM to the mixture necessarily displaced the clay mortar, which caused the density to decrease.

The water vapor absorption capacity decreased as the number of microcapsules increased; however, the high hygroscopic capacity of the clay meant that all the samples, regardless of the PCM content, presented better results than other conventional mortars, such as gypsum or mortars of cement and lime (**Figure 5**). The permeability to water vapor followed the same trend as the absorption of water vapor, that is, both decreased as the PCM was added. This is due to the hydrophobic character of the PCM microcapsules. The standard sample had a permeability of 2.28×10^{-11} kg·m/m^2·s·Pa. After the first addition, this value decreased to 1.42×10^{-11} kg·m/m^2·s·Pa. For the samples containing 10 and 15% by weight, the permeabilities were 1.04×10^{-11} and 0.95· × 10^{-11} kg·m/m^2·s·Pa, respectively. These values represent decreases of 37.7, 54.4 and 58.3%.

Mortar	R (%)	Da (kg/m^3)	Wvp (kg·m/m^2·s·Pa)
MS	3.22	1645.86	2.28×10^{-11}
5%	4.71	1447.26	1.42×10^{-11}
10%	5.47	1437.08	1.04×10^{-11}
15%	6.71	1383.00	0.95×10^{-11}

Table 3. Physical characteristics of the clay mortar samples containing microcapsules at 5, 10, and 15% contents: master sample (MS), retraction (R), apparent density (Da), and water vapor permeability (Wvp).

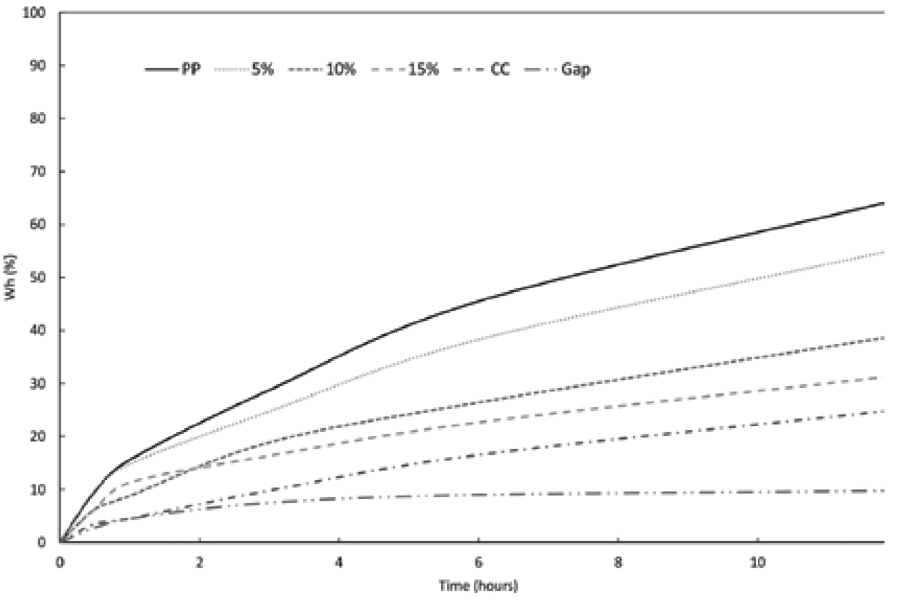


Figure 5. Water vapor absorption curves after a 50–80% increase in the relative humidity for 5, 10, and 15% microcapsule contents, the standard sample (PP), a lime and cement mortar (CC), and gypsum mortars applied by a machine (Gap). The water content (Wh) is shown as a function of time.

3.3. Hardened mortar: Mechanical properties

The results of the mechanical compression and bending tests are shown in **Table 4**. The mechanical strength of the mortars decreased in all cases with respect to the standard sample but it tended to be recovered with the amount of microcapsules. The reductions in compression and flexion for the sample containing 5% of MPCMs respect to the standard sample were 53 and 45%, respectively, indicating that this material meets the minimum requirements to plaster. With respect to the compressive strength, the decrease in strength was 50% for the 10% sample and 46% for the 15% sample. The decrease in the flexural strength was similarly attenuated, by 33% for the 10% sample and by 24% for the 15% sample, with respect to the standard sample.

Mortar	CS (N/mm^2)	FS (N/mm^2)	AS (N/mm^2)	USC (units)
MS	1.76	0.69	0.10	61
5%	0.82	0.38	0.11	38
10%	0.88	0.46	0.10	32
15%	0.95	0.52	0.12	24

Table 4. Mechanical characteristics of the clay mortar samples containing microcapsules at 5, 10, and 15% contents: master sample (MS), compressive strength (CS), flexural strength (FS), adhesion strength (AS) and Shore C hardness (USC).

In the same way, the adhesion test results showed that the perpendicular tensile strength was stable regardless of the amount of the PCM added, even with respect to the standard sample. As for the Shore C surface hardness, a significant decrease in the hardness occurred as the PCM content increased.

3.4. Hardened mortar: Thermal properties

The total latent heat (Ql) and the influence of the melting temperature range of the PCM on the thermal behavior of the mortars were determined by using DSC. **Figure 6** shows the apparent heat capacity (**Figure 6a**) and the enthalpy (**Figure 6b**) of the mortars as a function of the temperature. The apparent heat capacity of the standard sample was completely linear, whereas all the mortars containing MPCMs present a peak that increases with the MPCM content and in the same melting temperature range of the pure PCM. These results indicated that the higher the thermoregulating material used to produce the mortar, the higher the TES capacity of the developed composite.

From this information, the enthalpy curves were determined (**Figure 6b**). Excluding the temperature range in which latent heat accumulates, DSC showed that a certain amount of energy was required to increase the sample's temperature; we call this the specific heat (Cp). The average specific heat (Cpm) of the standard sample (clay mortar) was 1.0 J/g, which is similar to results obtained for crude earth, whereas that of paraffin is approximately 3.5 J/g. This is why an increase in the Cpm of more than 0.3 J/g is seen as the amount of the PCM is increased. The catalog of construction elements in the Spanish Technical Building Code [33] (i.e., CAT-ECv6.3 MARCH10.doc) lists a heat capacity of 1 J/g°C for several types of mortars, which is in agreement with the data obtained in this study. In the same way, Ql increased as the MPCM content of the mortar increased. For the 5% sample in the influence temperature range of the PCM, it was 2.8 J/g; it was 5.5 J/g for the 10% sample and 10.5 J/g for the 15% sample.

The thermal conductivity remained stable across the different samples; no trend was observed as a function of the amount of the PCM incorporated. Its average value was 0.3 W/m°C (**Table 5**). The TES parameter (kWh/m^3), which evaluates the storage capacity per unit volume, progressively increased with the amount of the PCM incorporated. With the first incorporation of 5% PCM by weight with respect to the standard mortar, an increase of 9% was seen; however, for the higher dosages, the TES capacity increased significantly, by 42% for the 10% PCM sample and by 65% for the 15% sample (**Table 5**).

3.5. Simulation results

The results of the simulations performed for summer conditions are shown in **Figure 7**. It can be seen that the clay mortar with added MPCMs attenuated the temperature peaks in comparison with the reference material building without PCM.

HVAC equipment simulation system has been used to evaluate architectural design strategies in the initial stages of projects, to optimize the environmental and energy-related aspects

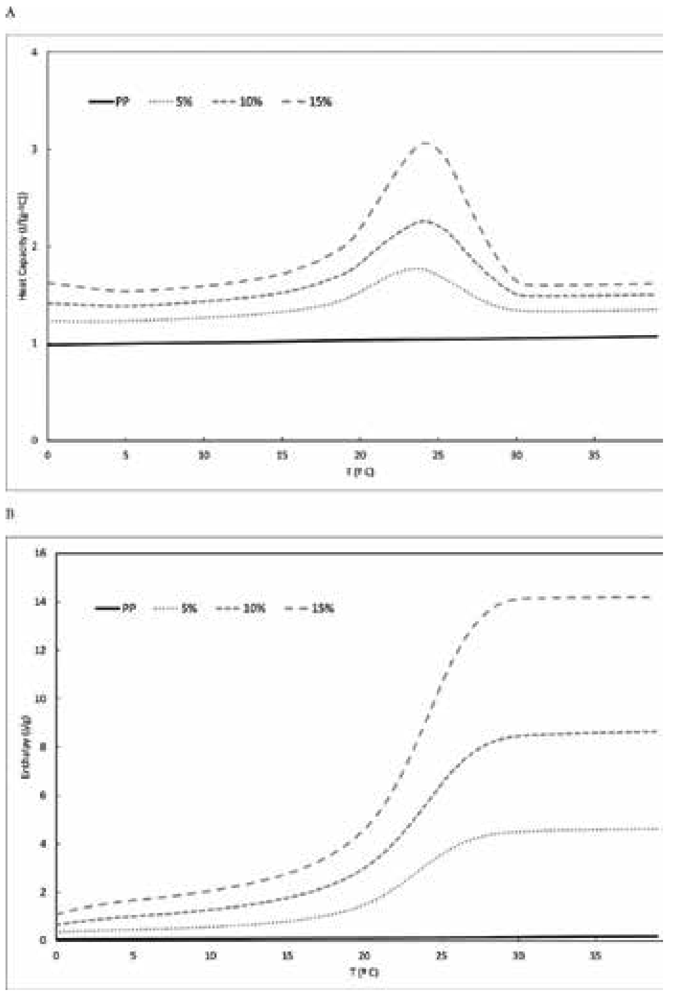


Figure 6. Apparent heat capacity (A) and enthalpy (B) of the mortars containing 0, 5, 10, and 15% of MPCMs.

of buildings and to check the performance of HVAC equipment before modeling the system in detail.

To this end, the model constantly regulates the interior temperature of the building by means of a cooling system when it exceeds the set temperature range. In our case, this range corresponded to conditions for thermal comfort, that is, a maximum of 24°C and a minimum of 21°C. The attenuation and reduction of the temperature peaks by the incorporated PCM meant that less energy was needed to reach the established comfortable conditions (**Table 6**). Under summer conditions (for a study period of 408 h), the simulations show an energy savings between 2 and 4% in the building with the coating containing 15% PCM by weight in comparison with the building with the coating of Ecoclay based-fiber mortar. Relative to gypsum plaster, a savings of almost 10% was produced by adding the PCM to the clay mortar.

Mortar	Ti (°C)	Tf (°C)	Tma (°C)	Map (J/g°C)	Qlt (J/g)	Cpm (J/g°C)	TES (kWh/m³)
MS	—	—	—	—		1.01	5.22
5%	15.63	31.26	23.57	1.77	2.87	1.28	5.71
10%	14.03	30.55	24.35	2.26	5.53	1.48	7.45
15%	11.10	30.65	24.39	3.07	10.59	1.53	8.62

Table 5. Summary of the results obtained using DSC and the equipment prepared for the thermal characterization of the samples of clay mortar containing microcapsules at 5, 10, and 15% contents: master sample (MS), initial accumulation temperature (Ti), final accumulation temperature (Tf), maximum accumulation temperature (Tma), maximum accumulation point (Map), total latent heat (Qlt), average specific heat (Cpm) and thermal energy storage (TES).

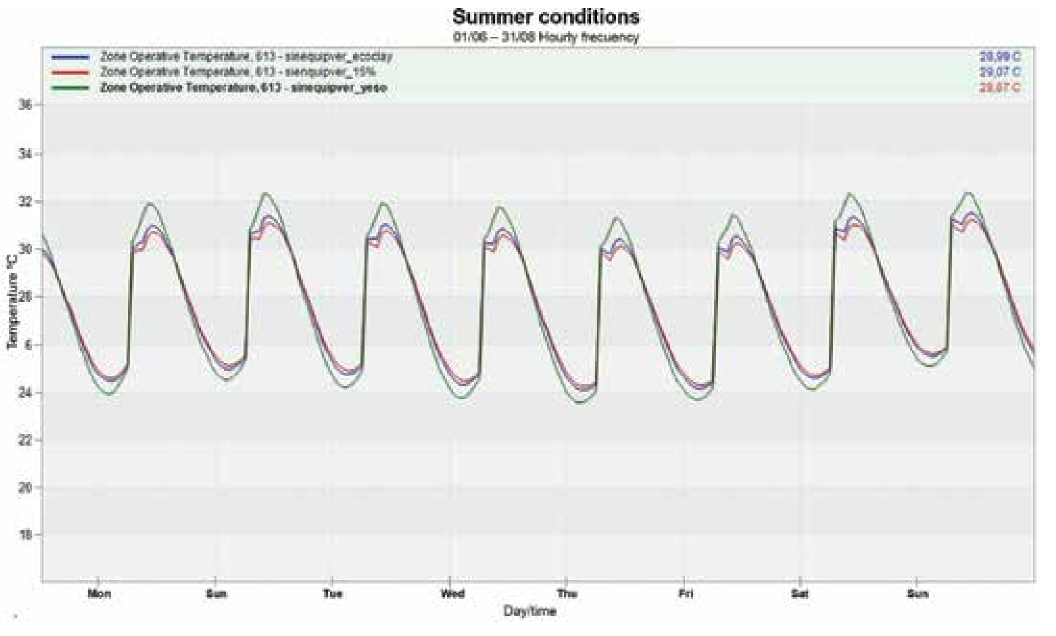


Figure 7. Simulated building temperatures for different types of plaster: clay mortar with a 15% of MPCMs, the standard sample (ecoclay) and a gypsum (Yeso). Summer conditions (July 15–31).

Mortar	TE_{site} (kWh)	TE_{source} (kWh)	$ETBA_{site}$ (kWh/m²)	$ETBA_{source}$ (kWh/m²)
B. $MS_{heating}$	593.58	626.63	5.28	5.57
B.$15\%_{heating}$	584.73	617.28	5.20	5.49
B. $Gap_{heating}$	646.01	681.97	5.72	6.04

Table 6. Summary of results obtained by simulating the energy demand using the HVAC (heating/ventilation/air conditioning) option for the different plaster types: clay mortar with a 15% microcapsule content, the master sample (MS), and gypsum mortars applied by a machine (Gap). Summer conditions (July 15–31); 15-day simulation periods, and a step size of less than a minute. Total simulation time: 408 h. Total energy at the site (TE_{site}), total energy from the source (TE_{source}), energy for the total building area at the site ($ETBA_{site}$), and energy per total building area at the source ($ETBA_{source}$).

4. Summary and conclusions

Despite the absence of regulated and agreed-upon rules for the characterization of clay-based mortars, it has been possible to propose a test methodology capable of establishing the technical feasibility of this construction material. Considering the nature of materials derived from crude earth and the descriptions in [19–27], the standard series used for mixing, molding and curing of clay mortars allows the comparative analysis of the results of different dosages.

The results of the fresh mortar tests have been used to evaluate the influence of incorporating a PCM on mixing and workability. One of the conclusions drawn is that the addition of a PCM requires the amount of mixing water to be increased to reach the established runoff values. These data show how the addition of a PCM supposes a decrease in the mortar's workability. Regarding the air content occluded in the mortar, it is observed that the microcapsules are deposited between the clay sheets, which increases the distance between them and increases the number of voids.

In the hardened state, the specimens show that the effects of retraction start to be considerable when the amount of the PCM reaches 10%. However, the response to this increase in retraction should be not to increase the amount of the PCM but to increase the amount of mixing water. This aspect should be analyzed using different clay mortar granulometries to improve workability by adding a PCM, thereby avoiding the increase in the amount of mixing water.

Clay-based products tend to perform well in terms of absorption capacity and water vapor permeability. The water vapor absorption capacity decreases as the number of microcapsules increases; however, the high hygroscopic capacity of clay means that all the samples, regardless of the amount of the PCM added, present better results than other conventional mortars, such as gypsum or cement and lime mortars. The permeability to water vapor follows the same trend as the absorption of water vapor, that is, it decreases as a PCM is added. This is due to the hydrophobic character of PCM microcapsules.

The results of the flexion-compression tests show a decrease in strength in both cases; this is more significant in compression (53.5% with respect to the standard dosage) than in flexion (45%) for the sample containing 5% PCM. The decrease in strength experienced with the first addition of the PCM is justified by the loss of density of the material due to the incorporation of the PCM and the increase in occluded air that it generates in the mortar, as previously mentioned. This argument might explain the increase in resistance between the samples containing 5, 10 and 15% PCM. The voids generated by the first addition of microcapsules are supplemented by increasing numbers of microcapsules as the content increases. This decreases the number of pores, which results in a stronger material. These types of mortars are not designed to withstand mechanical stresses but do maintain their compressive strength within the acceptable range indicated by the regulations [1].

The results of the adhesion test show that the perpendicular tensile strength is stable regardless of the dosage used, even with respect to the standard dosage. As for the Shore C surface hardness, a significant decrease occurs as the PCM dosage increases. This is due to the increase in the amount of occluded air and because increasing the dosage increases the probability that the measurement is performed on an agglomeration of microcapsules.

Using DSC and thermal characterization tests, it was possible to verify that incorporating paraffin microcapsules into the clay mortar is effective. The latent heat increases as the PCM content increases, as expected when the addition is performed correctly. It is 2.87 J/g for the 5% sample in the influence temperature range of the PCM, 5.53 J/g for the 10% sample and 10.59 J/g for the 15% sample.

Currently, building simulation software is a fundamental tool for designing buildings with almost zero-energy consumption. In this study, three identical architectural models were simulated. The reference building had inner coatings of clay-based mortar, mortar with 15% added material and a conventional gypsum mortar. These buildings were subjected to the same exposure and radiation conditions, which allowed the result to be compared to evaluate the effect of incorporating the PCM.

Simulations were performed under summer conditions. The results showed that the incorporation of PCM microcapsules into the clay mortar resulted in a decrease of up to 0.5 kWh/m^2 (in the simulation period), that is, 10% in the energy required for cooling compared to gypsum mortar. In environmental terms, assuming an emission factor of 0.385 kg of CO_2 eq/kWh [34], it would mean a savings of about 25 kg of CO_2 equivalent in 15 days. Finally, we affirm that clay mortar allows the incorporation of a PCM without reducing other characteristics that prevent such use. The use of such mortar is more advantageous in summer in climates such as the one at the center of the Iberian Peninsula. This solution will be of great interest for projects involving rehabilitation and improvement in terms of energy efficiency when it is difficult to work on the whole envelope and for small-scale interventions involving interior conditioning.

Acknowledgements

This study is part of D. Ismael Serrano's Final degree dissertation. The authors would like to thank the Laboratory Technician Pedro Palomino for all his services. We would also like to thank Ecoclay and the Institute of Chemical and Environmental Technology (ITQUIMA) for supplying the materials necessary to conduct this study and for their observations and help with the laboratory work.

Author details

Ismael Sevilla[1], Francisco J. Castilla[1], David Sanz[1]*, José L. Serrano[1], Juan F. Rodríguez[2] and Manuel Carmona[2]

*Address all correspondence to: David.Sanz@uclm.es

1 Polytechnic School of Cuenca, University of Castilla-La Mancha (UCLM), Cuenca, Spain

2 Department of Chemical Engineering, University of Castilla-La Mancha, Ciudad Real, Spain

References

[1] Haurie L, Serrano S, Bosch M, Fernandez AI, Cabeza LF. Single layer mortars with microencapsulated PCM: Study of physical and thermal properties, and fire behaviour. Energy and Buildings. 2016;**111**:393-400

[2] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy and Buildings. 2008;**40**(3):394-398

[3] Fargallo AP, Alés VF, Rodríguez JM. Comparison of energy-saving restoration costs based on Spain's initial constraints [single-family zone B4]. Revista de la Construcción. 2015;**14**(2):44-50

[4] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union 18.06. 2010

[5] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32. Official Journal, L 315. 2012; 1-56

[6] Carabaño R, Hernando SM, Ruiz D, Bedoya C. Life Cycle Assessment (LCA) of building materials for the evaluation of building sustainability: The case of thermal insulation materials. Revista de la Construcción. Journal of Construction. 2017;**16**(1):22-33

[7] Kuznik F, Virgone J. Experimental investigation of wallboard containing phase change material: Data for validation of numerical modeling. Energy and Buildings. 2009;**41**(5): 561-570

[8] Mandilaras I, Stamatiadou M, Katsourinis D, Zannis G, Founti M. Experimental thermal characterization of a Mediterranean residential building with PCM gypsum board walls. Building and Environment. 2013;**61**:93-103

[9] Navarro L, de Gracia A, Colclough S, Browne M, McCormack SJ, Griffiths P, Cabeza LF. Thermal energy storage in building integrated thermal systems: A review. Part 1. Active storage systems. Renewable Energy. 2016;**88**:526-547

[10] Cabeza LF, Castell A, Barreneche CD, De Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: A review. Renewable and Sustainable Energy Reviews. 2011;**15**(3):1675-1695

[11] Memon SA. Phase change materials integrated in building walls: A state of the art review. Renewable and Sustainable Energy Reviews. 2014;**31**:870-906

[12] Lane GA. Solar heat storage. Latent heat materials. 1983

[13] Castellón C, Medrano M, Roca J, Cabeza LF, Navarro ME, Fernández AI, Lázaro A, Zalba B. Effect of microencapsulated phase change material in sandwich panels. Renewable Energy. 2010;**35**(10):2370-2374

[14] Zhang Y, Zhou G, Lin K, Zhang Q, Di H. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. Building and Environment. 2007;**42**(6):2197-2209

[15] Tabares-Velasco PC, Christensen C, Bianchi M. Verification and validation of EnergyPlus phase change material model for opaque wall assemblies. Building and Environment. 2012;**54**:186-196

[16] Lu S, Liu S, Huang J, Kong X. Establishment and experimental verification of PCM room's TRNSYS heat transfer model based on latent heat utilization ratio. Energy and Buildings. 2014;**84**:287-298

[17] Serrano S, Barreneche C, Rincon L, Boer D, Cabeza LF. Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA. Construction and Building Materials. 2013;**47**:872-878

[18] Morel JC, Mesbah A, Oggero M, Walker P. Building houses with local materials: Means to drastically reduce the environmental impact of construction. Building and Environment. 2001;**36**(10):1119-1126

[19] EN 998-1:2016. Specification for mortar for masonry. Part 1: Rendering and Plastering Mortar

[20] EN 1015-11:1999/A1:2006. Methods of test for mortar for masonry. Part 11: Determination of Flexural and Compressive Strength of Hardened Mortar

[21] EN 1015-12:2016. Methods of test for mortar for masonry. Part 12: Determination of Adhesive Strength of Hardened Rendering and Plastering Mortars on Substrates

[22] EN 1015-19:1998. Methods of test for mortar for masonry. Part 19: Determination of Water Vapor Permeability of Hardened Rendering and Plastering Mortars

[23] EN 1015-2:1998. Methods of test for mortar for masonry. Part 2: Bulk Sampling of Mortars and Preparation of Test Mortars

[24] EN 1015-3:1999. Methods of test for mortar for masonry. Part 3: Determination of Consistence of Fresh Mortar (By Flow Table)

[25] EN 1015-6:1998/A1:2006. Methods of test for mortar for masonry. Part 6: Determination of bulk density of fresh mortar

[26] EN 1015-7:1998. Methods of test for mortar for masonry. Part 7: Determination of Air Content of Fresh Mortar

[27] EN 1015-9:1999. Methods of test for mortar for masonry. Part 9: Determination of Workable Life and Correction Time of Fresh Mortar

[28] UNE 102042:2014. Gypsum plasters. Other test methods. Spanish Normative

[29] Earth plasters. Terms and definitions, requirements, test methods. Deutsch Normative

[30] Barreneche C, de Gracia A, Serrano S, Navarro ME, Borreguero AM, Fernández AI, Carmona M, Rodriguez JF, Cabeza LF. Comparison of three different devices available in Spain to test thermal properties of building materials including phase change materials. Applied Energy. 2013;**109**:421-427

[31] Borreguero AM, Valverde JL, Rodríguez JF, Barber AH, Cubillo JJ, Carmona M. Synthesis and characterization of microcapsules containing Rubitherm® RT27 obtained by spray drying. Chemical Engineering Journal. 2011;**166**(1):384-390

[32] AL-Saadi SN, Zhai ZJ. Modeling phase change materials embedded in building enclosure: A review. Renewable and Sustainable Energy Reviews. 2013;**21**:659-73

[33] Código Técnico de la Edificación (CTE) [Technical Building Code], Documento Básico: Seguridad En Caso de Incendio. Ministerio de Fomento (CTE). REAL DECRETO. February 2010

[34] Reglamento de Instalaciones Térmicas en los Edificios [Regulation of Thermal Installations in Buildings - RITE]. Factores de emisión de CO_2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España. Ministerio de Industria, Energía y Turismo de España. 2016

Edited by Amjad Almusaed and Asaad Almssad

This book has been written to represent the efficient applications of sustainability upon building designs. The book intends to illustrate various techniques of action of sustainability on building conceptions. The book is divided into four parts and eight chapters.

Part I "Introduction to the Target Theme" includes a chapter with title "Introductory Chapter." It makes an overview of the meaning and the target of sustainable building and sustainable building material.

Part II "Sustainable Building Design, Process, and Management" discusses many forms and concepts of sustainable building and includes three chapters.

Part III "Energy Efficiency upon Sustainable Building Design" includes one chapter.

Part IV "Sustainability in Building Materials: Study Cases" includes three chapters.

Published in London, UK

IntechOpen

ISBN 978-1-83881-441-0
9 781838 814410