

Joint mAsTer of Mediterranean Initiatives on renewAbLe and sustainAbLe energy

Palestine Polytechnic University

Deanship of Graduate Studies and Scientific Research

Master Program of Renewable Energy and Sustainability

Utilizing Phase Change Materials for Enhancing Concrete Insulation for Energy Saving in Buildings

By

Mo`taseem Osama A. (Alzeer Alhusaini)

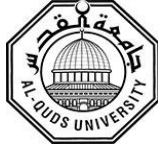
Supervisor

Prof. Maher Al-Jabari

Thesis submitted in partial fulfillment of requirements of the degree

Master of Science in Renewable Energy & Sustainability

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The undersigned hereby certify that they have read, examined and recommended to the Deanship of Graduate Studies and Scientific Research at Palestine Polytechnic University and the Faculty of Science at Al-Quds University the approval of a thesis entitled:

Utilizing Phase Change Materials for Enhancing Concrete Insulation for Energy Saving in Buildings.

Submitted by

Mo`tasem Osama A. (Alzeer Alhusaini)

in partial fulfillment of the requirements for the degree of Master in Renewable Energy & Sustainability .

Graduate Advisory Committee:

Prof./Dr.
(Supervisor), University (typed)

Signature: _____ Date: _____

Prof./ Dr.
(Co-supervisor), University (typed)

Signature: _____ Date: _____

Prof./Dr.....
(Internal committee member), University (typed).

Signature: _____ Date: _____

Prof./Dr.
(External committee member), University (typed).

Signature: _____ Date: _____

Thesis Approved by:

Name: _____

Dean of Graduate Studies & Scientific Research

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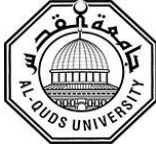
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Abstract

In order to come to a sustainable building environment, the construction industry requires new energy saving concepts. One method is to use phase change materials (PCM), which have the ability to absorb and to release thermal energy at a specific temperature. PCM are added to concrete mix designs for improving the thermal insulation of concrete in building constructions. Such an approach can assist in energy saving through minimizing conductive heat loss through walls, a phase change material obtained from waste candles was added to concrete as a replacement to medium aggregate and as a replacement to cement in three different particles sizes.

Then an experimental study was performed for investigating the effect of percentage addition of PCM on thermal characteristics (thermal conductivity, specific heat and thermal diffusivity). In addition, the associated impact of PCM on the concrete mechanical characteristics (compressive strength, water absorption and concrete workability) was investigated. It was found that adding waste candle as a replacement to medium aggregate is better than adding it as a replacement to cement. Adding 5% waste candle as a replacement to medium aggregate gave the best results.

A new approach is developed through surface treatment of PCM modified concrete with sodium silicate to increase to compressive strength of concrete. It was found that increasing compressive strength by 7.2% as a compensation for the loss due to PCM addition.

A physical model for two small rooms were constructed using PCM modified concrete (at 20% PCM as a replacement of medium aggregates) and using control concrete (standard B250 concrete). Each room was then subjected to external heating through a power supply of 1400 W for 60 min, then, each of them was allowed to be cooled by natural convection. It was found that the internal temperature of the room with PCM modified concrete, during cooling period, was at a higher temperature than that with control concrete by 2.5 oC. Increased the duration of a comfortable temperature inside building and increased the energy saving in building was happened by reducing thermal conductivity and increasing the thermal storage of walls.



استخدام مواد تغيير الطور لتعزيز العزل الخرساني لتوفير الطاقة في المباني

بواسطة

معتصم أسامة عبد المجيد الزير الحسيني.

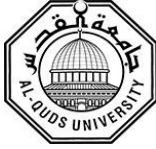
المخلص

من أجل الوصول إلى بيئة بناء مستدامة يتطلب من الصناعات الإنشائية استخدام مفاهيم جديدة لتوفير الطاقة. تتمثل إحدى الطرق في استخدام مواد تغيير الطور، التي لديها القدرة على امتصاص وإطلاق الطاقة الحرارية عند درجة حرارة معينة. يتم إضافة مواد تغيير الطور إلى تصميمات الخلطة الخرسانية لتحسين العزل الحراري للخرسانة في المباني. يمكن أن تساعد هذه الطريقة في توفير الطاقة من خلال تقليل الموصلية الحرارية للجدران، تمت إضافة مادة تغيير الطور (PCM) التي تم الحصول عليها من الشموع المستهلكة إلى الخرسانة كبديل للركام المتوسط وكبديل للإسمنت في ثلاثة أحجام مختلفة.

أجريت دراسة تجريبية للتحقق من تأثير إضافة النسب المئوية من مادة تغيير الطور على الخصائص الحرارية (التوصيل الحراري والحرارة النوعية والانتشار الحراري) للخرسانة. بالإضافة إلى ذلك، تم البحث في التأثير المصاحب عند إضافة مادة تغيير الطور على الخصائص الميكانيكية للخرسانة (قوة الانضغاط وامتصاص الماء وقابلية التشغيل الخرساني). وقد وجد أن إضافة مادة تغيير الطور كبديل للركام المتوسط أفضل من إضافتها كبديل للإسمنت. بحيث أعطت إضافة 5٪ من مادة تغيير الطور كبديل للركام المتوسط أفضل النتائج.

تم تطوير مفهوم جديد من خلال المعالجة السطحية للخرسانة المعدلة بإضافة مادة تغيير الطور مع سيليكات الصوديوم لزيادة قوة ضغط الخرسانة. وقد وجد أن تم تحقيق زيادة قوة الضغط بنسبة 7.2٪ كتعويض عن الخسارة الناتجة عن إضافة مادة تغيير الطور.

تم إنشاء نموذج لغرفتين صغيرتين باستخدام الخرسانة المعدلة PCM (بنسبة 20 ٪ PCM كبديل للركام المتوسط) واستخدام الخرسانة المضبوطة (الخرسانة B250 القياسية). ثم تعرضت كل غرفة للتدفئة الخارجية من خلال مصدر طاقة 1400 واط لمدة 60 دقيقة، ثم سمح بتبريد كل منها عن طريق الحمل الحراري الطبيعي. وقد وجد أن درجة الحرارة الداخلية للغرفة مع الخرسانة المعدلة PCM خلال فترة التبريد كانت في درجة حرارة أعلى من درجة حرارة الخرسانة القياسية عند 2.5 درجة مئوية. زيادة مدة درجة الحرارة المريحة داخل المبنى وزيادة توفير الطاقة في المبنى تحقق عن طريق تقليل الموصلية الحرارية وزيادة التخزين الحراري للجدران.



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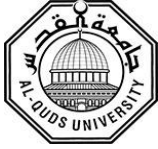
DECLARATION

I declare that the Master Thesis entitled “Utilizing Phase Change Materials for Enhancing Concrete Insulation for Energy Saving in Buildings.” is my own original work and hereby certify that unless stated. All work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

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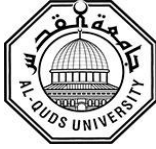
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DEDICATION

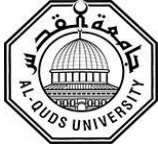
“Say: Allah will see your works and so will His Messenger and the believers; then you shall be returned to the Knower of the unseen and the visible and He will inform you of what you were doing.” Quran, At-Tawba [9.105]

Praise be to Allah in the beginning and the end

To my true source of hope, to the people who keep me facing struggles and hardships, my dear wife and my dear parents.

To my dear brothers and sisters, your great hearts and pure souls are only compatible with your constant encouragement and support.

Thank you from the depths of my heart.



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List of Abbreviations

PCM	Phase Changing Materials
K	Thermal Conductivity
Q	Electric Power or Rate of Heat Transfer
T	Time
L	Thickness of Concrete Specimen
A	Area of Concrete Specimen
ΔT	Temperature Difference
ASTM	American Society for Testing Materials
PS	Palestinian Standard
w/c	Water/Cement
ρ	Density
α	Thermal Diffusivity of Cured Concrete
WA	Percentage Water Absorption
c_p	Specific Heat of Cured Concrete
T	Temperature
m_w	Mass of Water
m_c	Mass of Concrete Specimen

Chapter One

Introduction

Chapter One

Introduction

1.1 General Introduction

Building energy consumption accounts for more than a third of total primary energy consumption in many countries. Improving energy efficiency in buildings is an effective way to improve overall energy efficiency around the world and has great benefit for the economy [1].

Methods for improving energy efficiency in buildings can be divided into two categories: passive and active methods. Passive methods improve the energy efficiency of the building by using materials with low thermal conductivity. Active methods enhance the building's energy efficiency by using materials with a high thermal energy storage capacity. Energy can be stored by thermal energy storage materials in three ways, namely sensible heat, latent heat or chemical reactions. The materials used to store thermal potential energy are phase changing materials (PCM) [2].

Latent heat thermal energy storage is an attractive technology. It has received great attention over the past decades for the heating and cooling purposes of buildings. The use of high thermal energy storage materials in the building not only reduces the energy cost and size of air conditioning systems, but can also flatten indoor temperature fluctuations thus improving indoor thermal comfort [3].

Thermodynamically, when the temperature rises (for example in the daytime), the PCM absorbs heat in an endothermic process and changes the phase from solid to liquid. As the temperature decreases (for example at night), the PCM releases heat in an exothermic process and returns to its solid phase. Paraffin waxes, salt hydrates, fatty acids, eutectic organic and inorganic compounds are the most widely used PCMs over the past 30 years [4]. The PCM to be used for thermal energy storage purposes must meet desired thermal-physical, kinetic and chemical requirements such as cycle stability, and the ability to use the thermal storage material multiple times to store and release heat as required by the application. In applications, many difficulties have been encountered regarding the effective use of PCM. Difficulties are related to the selection of substances and factors that influence the successful and effective use of PCM [5].

1.2 Background

This research requires backgrounds in both the fields of heat transfer and concrete technology. It also deals with energy conservation in buildings.

From a heat transfer perspective, thermal conduction is the transfer of heat by microscopic collisions of atoms and molecules and by the movement of electrons within the body. To determine the ease with which you conduct a particular medium, engineers use thermal conductivity, also known as the conduction coefficient or conductivity constant. Thermal conductivity (k) is defined as the amount of heat transfer (Q), which is transmitted in time (t) through a thickness (L), in a normal direction to the surface of a area (A), due to the temperature difference (ΔT). The steady-state conduction is the form of conduction that occurs when the temperature difference (s) driving the conduction is constant, such that (after equilibration time), the spatial distribution of temperatures in the conducting object does not change any more. "Thermal resistance" can be thought of as electrical resistance. In such cases, temperature plays the role of voltage, and the heat transferred per unit time (heat power) is the electric current. In transitory conduction, temperatures change over time (non steady-state conduction). The law of heat conduction, also known as Fourier's law, states that the time rate of heat transfer through a substance is proportional to the negative temperature gradient and area, at right angles to this gradient, through which the heat flows. Heat flux is the amount of energy that flows through a unit area per unit time.

In the field of building technology, the thermal conductivity of the building envelope is the most important thermal property that controls energy losses in buildings. Concrete has moderate thermal conductivity, which is much lower than metals, but much higher than other building materials such as wood. Hence, concrete is a poor insulator.

When the water in the concrete freezes, it expands by about nine percent. When water freezes in wet concrete, it creates pressure in the concrete pores, creating internal stress then, when goes back to liquid phase internal stress are eliminate. The cumulative effect of successive freeze-thaw cycles with concomitant disruption of paste and aggregate can ultimately cause concrete to expand, crack, scale and crumble. Thus, controlling energy storage in concrete e.g. using PCM can assist in protecting concrete against damage from freeze-thaw cycle.

Improving the thermal properties of concrete can be achieved by modifying its mix contents through various mineral and organic additives (such as PCM). This research field creates interests among researcher in renewable energy as well as civil engineering. There are various

scientific journals around the world interested in publishing articles in the subject of improving the thermal properties of concrete. Some of them are related to renewable energy and green buildings, such as Renewable and Sustainable Energy Reviews, Energy and Buildings, Journal of Advanced Concrete Technology and Journal of Building Engineering, which are published by Elsevier.

1.3 Problem Statement

Ideally, building walls, roofs and floors must be perfect insulator with no losses of energy used for heating and cooling. However, in reality there is are heat losses by conduction in building envelope and thus can be considered as a major factor for energy losses in building. This implies that more energy is needed for heating and cooling the building. The consequence of this problem is an increase in size and capacity of the HVAC system. This results in larger capital and operating costs.

In this research, it is proposed to use phase change materials with suitable melting temperature and suitable incorporation method in concrete. In specific, it is proposed to use waste phase change material from candle to enhanced concrete insulation characteristic. This gives better insulation in walls, roofs and floors and thus reduces energy consumption and the energy cost in buildings.

1.4 Research Goal and Objectives

The research objective of this research is to use PCM waste in concrete mixture that can increase the insulation characteristic of buildings and thus reduce energy costs. The study aims to:

1. To provide a comprehensive review of the literature on PCM used in concrete in terms of thermal insulation and other important characteristic.
2. To develop a method for improving the thermal insulation of concrete.
3. To confirm the technical feasibility of using phase change materials from waste in the concrete mixture to improve thermal insulation.
4. To carry out a full experimental parametric study for the use of phase change materials using Paraffin wax waste.

1.5 Research Questions and Hypothesis

Building on the problem identified in the previous section, the following research questions are covered in this paper.

Main problems:

What is the effect of using phase change material (Paraffin wax waste) on thermal characteristic of concrete for energy saving in buildings?

Sub-problems:

What are the effects of using phase change material (Paraffin wax waste) on the thermal properties of concrete (the thermal conductivity and specific heat)?

What are the effects of using phase change material on concrete stability and compressive strength?

Testing the technical feasibility of treating the PCM modified concrete with a chemical solution for substituting the associated loss of compressive strength?

Designing and constructing a physical model for experimental measurement of energy saving in building utilizing PCM in concrete walls?

Hypothesis:

It is hypothesized that adding phase change material waste in concrete will reduce the thermal conductivity and thus will increase the thermal insulation and thermal storage capacity. This reduces energy consumption and led to stable comfort temperature.

1.6 Research Methodology

The experimental method is adopted in this study. The general methods include casting concrete with phase change materials and testing thermal conductivity by using steady state thermal method (using a designed and home constructed device). The heat capacity will be tested by using icebox as a calorimeter. The box is covered by thermal insulation material. The thermal diffusivity is obtained from its expression as based on its definitions.

The compressive strength of PCM-concrete and water absorption will be investigated using the known ASTM procedures to study the effect of phase change material on concrete hydration reaction. Details of the materials, equipment and methods are given in chapter three.

1.7 Research Significance and Relevance

This research topic is of great interest to researchers and professional in the field of green building and those interested in energy management. The importance of this research stems from the great benefits that the success of this product (PCM waste) will have in the field of energy and environmental conservation and the cost of operating a building energy system. This approach is also important as a kind of solution to concrete damage due to thermal attack through freeze thaw cycle, in recent years many journals have been interested in this trend of research like Elsevier, Sage and pergamon.

This research topic is of great interest to researchers and professionals in the field of green buildings and those interested in energy management. The importance of this research stems from the great benefits that the success of this product (Waste PCM) will bring

The result of this study will be valuable to the industry as well as to the related researchers in developing better concrete mix.

1.8 Scope and Thesis Outline

This thesis consists of five chapters. The first chapter contains a brief introduction to the work. In addition, a short background and the purpose of this thesis is defined and also a description of method together with limitations of the work. Chapter two presents a literature review of research activities that has been carried out in this area of research.

The shortcomings of previous research will also be highlighted and what could be added in this area. The third chapter explains the experimental work that is a large part of the work of this thesis. Test preparation, casting, and materials are explained here.

Chapter four shows the overall results of the experimental work, a discussion of the results is conducted with reflections on what it may depend on and what it will reflect on it and a comparison with previous studies. Chapter five provides a thesis summary, lists the findings of this research, and general conclusions that summarize the work. Conclusions are based on experimental work, calculations, results, comparisons and analysis. This chapter also includes additional potential research areas that complement this thesis, and provides recommendations for future research.

Chapter Two

Literature Review

Chapter Two

Literature Review

2.1 Introduction

Previous studies on using PCM in energy saving in building focused mainly on thermal characteristics of concrete. Investigated properties included thermal conductivity, specific heat capacity and thermal diffusivity. There was no full study that concerned all related aspects for certain PCM material.

About 64% of the studies reviewed measured only the thermal conductivity (k-value) of cement-based materials. In contrast, there are only a limited number of studies that have investigated other thermal properties of cement-based materials. And 20 % of reviewed studies measured the three characteristic, thermal conductivity, specific heat and thermal diffusivity, by about 3% measured thermal conductivity and thermal diffusivity, and about 2% just measured specific heat, while about 9% measured thermal conductivity and specific heat, and about 2% measured specific heat and thermal diffusivity. However, the energy consumption of buildings depends on all the thermal properties of the concrete.

Previous studies have shown that about 20-50% decreases in the k-value and 13-20% decreases in the specific heat (Cp-value) of cement-based materials are obtained after hardening [5].

The steady-state and transient methods are the two main experimental methods used to measure the value of k. Only about 40% of the studies reviewed used the steady-state method as the method for measuring the thermal conductivity of cement-based materials. While the rest (60%) used the transient thermal method. The hot box and hot plate are the most frequently chosen technologies based on the steady-state method, although hot wiring is the main technique adopting the transient method [5].

The studies reviewed used different types of calorimeters and laser flashing methods to measure the heat capacity and thermal diffusion of cement-based materials, respectively.

Heat is released during the hardening process of concrete due to the exothermic reaction to cement hydration. Thus, the inclusion of PCM in fresh concrete will affect the hydration process.

PCM phase change materials use latent heat of phase change to control temperatures within a specific range. When the temperature rises above a certain point, the chemical bonds in the material will begin to disintegrate and the material will absorb heat in an endothermic process as the state changes from solid to liquid. As the temperature decreases, the substance will release energy and return to the solid state. Thus, phase change materials can provide an increase in heat storage capacity, especially in buildings with low thermal mass. The temperature range varies depending on the materials used as the phase change materials [4].

There are several materials that can be used as PCM. A common method for differentiating PCMs is to split it into an organic, inorganic, and easily fused PCM mixture. These categories are further divided based on the different components of PCM as shown in Fig.2.1.

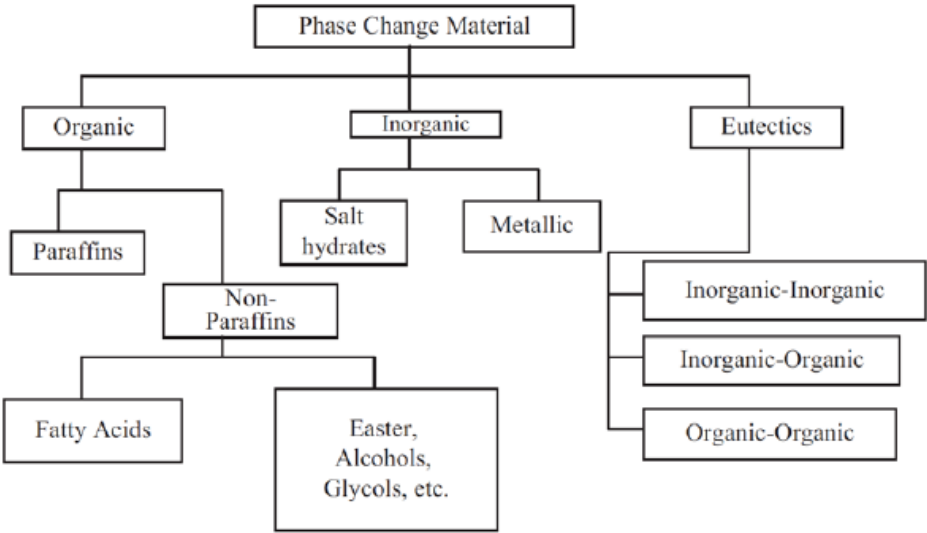


Figure 2.1: General categorization of PCM [6].

The organic PCM has many advantages such as: chemical stability, compatibility with construction materials recyclability and high heat of fusion. The advantages and disadvantages of organic, inorganic, and eutectic PCM are compared and summarized in Table 2.1 [6].

Table 2.1: A comparison between PCM type and the advantage-drawbacks for each type [6].

Organic		Inorganic		Eutectic	
Advantages	Drawbacks	Advantages	Drawbacks	Advantages	Drawbacks
No supercoiling	Flammable	High volumetric latent heat storage capacity	Corrosive to metals	Sharp melting points	Limited data on thermo physical
No phase segregation	Low thermal conductivity	Higher thermal conductivity than organic PCM	Super cooling phase segregation	Properties can be tailored to match requirement	High cost
Low vapor pressure	Low volumetric latent heat	Low cost	Congruent melting		
Large temperature range		Non-flammable	High volume change		

2.2 Concrete and its Characteristics

Concrete is a composite material because it is made up of a number of materials. The concrete consists mostly of Portland cement, medium and coarse aggregate, sand, and water that are added to the mix.

Cement hydration is a chemical reaction in which the main compounds in cement form chemical bonds with water molecules and become hydrates that cause mechanical strength [7]. Moisture content, temperature, type of aggregate, type of reinforcing material, and concrete density are the main factors affecting the heat storage capacity of concrete. The specific heat capacity of concrete increases at elevated temperatures [8].

Mechanical properties of concrete including compressive and tensile strength, modulus of elasticity, and stress and strain response to materials formed at elevated temperatures.

Compressive strength is a major design factor in concrete. Compressive strength is the ability of a material or structure to withstand loads that tend to reduce volume, as opposed to tensile strength. The compressive strength of concrete at ambient temperature depends on the water-to-cement ratio, curing conditions, type and total volume, mixture types and stress type [9].

The strength of concrete depends on the following factors such as the ratio of water to cement, strength of cement application, quality of concrete materials, and quality control during

concrete production. The compressive strength test can be performed either on cubes or on cylinders. There are several standard codes recommending the use of a concrete cylinder or concrete cube as a standard sample for testing. Compression strength was measured in accordance with the standard procedure of BS EN 12390-3:2019, which provides a standard test method for compressive strength for cubic concrete samples. To test the cubes for concrete, we can use cubes (15 x 15 x 15) cm or cubes (10 x 10 x 10) cm depending on the volume of aggregate used to make concrete. For most concrete works, cubic molds (10x10x10) cm are usually filled into molds and loosened properly to reduce any air voids available in the concrete and after 24 hours these molds are opened and samples are soaked in water for processing. These cubes are tested by compression testing machine after 7, 14, 21 and 28 days post-curing.

Concrete contains moisture in different forms, and the type and amount of moisture has a great influence on thermal conductivity. On average, the thermal conductivity of conventional concrete of normal strength is, at room temperature, between 1.4 and 3.6 W/m°C [10]. Specific heat is the amount of heat per unit mass required to change the temperature of a substance by one degree and is often expressed in terms of heat capacity, which is the product of a specific heat and density. The specific heat is strongly influenced by the moisture content, the type of aggregate and the density of the concrete [11].

Thermal diffusivity of a material is defined as the ratio of thermal conductivity to the volumetric specific heat of a material. It measures the rate of heat transfer from an exposed surface of a material to the inner layers. The higher the diffusivity, the faster the temperature rises at a certain depth in the material [9].

The concrete slump test measures the consistency of fresh concrete before it hardens. It is performed to check the workability of fresh concrete and thus the ease of flow of concrete. It can also be used as an incorrectly labeled mixed batch [12]. Slump was performed according to ASTM C143 standard procedure.

Water absorption is necessary to cement hydration, which gives concrete its mechanical strength. The amount of water needed for this hydration must be properly determined. Too much water increases the porosity of concrete. Hence, its mechanical performance and durability are reduced. Lack of water in the mixture will lead to incomplete hydration reactions of the cement and reduce the workability of fresh concrete, and most of the weight of natural aggregate has absorption capabilities of 1 to 2%.

Porosity is a measure of the size of voids in concrete. Permeability is the rate at which moisture flows through concrete under a pressure gradient. The voids through which moisture can move must be interconnected and of a certain size.

2.3 PCM Modified Concrete

The addition of PCM directly into concrete has shown some promising results by reducing its thermal conductivity and increasing its thermal mass at certain temperatures. However, PCM concrete exhibited some undesirable properties such as strength, uncertain long-term stability, and low fire resistance. Several studies have been conducted on PCM modified concrete and have shown a positive effect by reducing indoor temperatures in warm climates [13]. Combining concrete structures with PCM has been experimented with in many different ways. One of the solutions considered is to drill holes in concrete and then fill them with PCM [14,15] and to test the feasibility of actually filling hollow spaces in a concrete hollow floor using PCM. The concrete was filled with PCM paraffin with a melting temperature of 27.5 °C. Other approaches included the addition of encapsulated PCM with the design of the concrete mix as an alternative to medium aggregate or as an alternative to cement.

The types of addition and percentage of PCM used in previous studies are summarized in table 2.2.

Table 2.2: The types of addition and percentage of PCM used in previous studies.

Type of PCM addition	PCM addition (%)	Ref
As a percentage of total volume of concrete	0.5-3%	[16]
Immersion, impregnation PCM added as replacement by total volume of concrete	10-50%	[17]
Encapsulated PCM added as replacement by total volume of concrete	5-25%	[18]

The various methods of incorporating PCM into concrete can be categorized into immersion (immersion of porous concrete in liquid PCM), impregnation (vacuum impregnation of PCM into separated aggregate) and encapsulation (mixing of PCM encapsulated into a concrete mixture) [18]. Encapsulation appears to be a suitable method for combining concrete with PCM [19].

Since most PCM designed for construction applications passes a liquid phase, encapsulation is necessary to avoid problems such as PCM seepage to the surface and diffusion of low-viscosity liquids throughout the material [20]. Hence, methods such as direct incorporation and PCM immersion into building materials are not well suited for long-term applications [21]. Packaging materials should not react with PCM or show signs of deterioration over time. Currently, two main methods are used for PCM encapsulation, i.e. micro and macro encapsulation. These two methods give different sizes and shapes to PCM and influence the way PCM is incorporated into a material or construction [6].

The thermal mass material can absorb the solar radiant heat in the day as latent heat and then release it at night. The heat storage capacity of concrete increases when PCM is used. The extent of heat capacity improvement is related to the type of PCM and the foundation method applied during PCM concrete production.

2.3.1 Long-Term Stability of PCM Modified Concrete

For the successful large-scale application of PCM in the construction sector, it is critical that the PCM and PCM-container endure cycling over an extended period without showing signs of deterioration. There are two main factors that control the long-term stability of PCM storage, which are poor material stability, for example super cooling and phase separation, and corrosion between the PCM and the container system [22]. PCM degradation may lead to decreased capacity to store latent heat and variation in phase change temperature. Sharma et al. Performed accelerated aging tests with stearic acid and paraffin wax, both of which are organic PCM [23]. The use of both stearic acid and paraffin wax performed well and showed no systematic deterioration of the melting point over 1500 heat cycles. However, fatty acids, palmitic acid and myristic acid have proven better long-term stability [24]. This may make it more suitable for building applications compared to other fatty acids.

A comprehensive review of the thermal stability of organic, inorganic, and eutectic PCMs has been conducted by the authority [25], which covers the investigations on the thermal stability of PCMs conducted over the past few decades. Paraffin showed good thermal stability. In general, new building materials, components and structures have to be examined by accelerated climate aging [26]. PCM is no exception. Moreover, a durability assessment can also be performed [27].

2.3.2 Effect of PCM on Enhancing Concrete Resistance against Freeze and Thaw Cycle

In colder climates, concrete may deteriorate due to freezing and thawing of water in a porous concrete system [28]. Since the volume of ice formed is approximately 9% higher than the volume of water, there are expanding stresses in the concrete upon freezing temperatures if there is not enough space to accommodate this expansion. If the water saturation level in concrete is higher than a critical value (theoretically 91% and practically about 86-88% [28]) then the concrete may be damaged [29]. In practice, this problem is solved by drawing air, since air bubbles are intentionally introduced into the concrete by means of chemical additives [30]. If well distributed and spaced properly, it is able to accommodate volumetric expansion without causing pressure or cracking. Using PCM rather than air retention in such a situation provides the ability to accommodate this situation because concrete will stay warmer for a longer period of time. It may prevent snow build-up and ice formation inside concrete pores. This could be very useful for some applications, such as airport runway pavements. This possibility has been explored in several previous studies. For example: Farnam et al. [31] used two types of PCM were (methyl prize-winning with a phase change temperature of 1.9 °C and a latent fusion heat of 160.4 J/g and a paraffin oil with a phase change temperature of 2.9 °C and a latent fusion temperature of 129.4 joules / g) either built in tube system or embedded in a lightweight aggregate.

2.3.3 Effect of PCM on Properties of Fresh Concrete

If PCM is added to the mixture as microcapsules or impregnated into Lightweight Aggregate (LWA), it may affect the properties of fresh concrete. If PCM saturated LWA is used, the PCM may not be able to penetrate the small pores of LWA. Hence, these pores will remain filled with air. If this LWA were placed in the mix, it might drink the water from the concrete and thus dehydrate the system [32]. Sakulich and Bentz advised that LWA be saturated with water. When microencapsulated PCM are used, test results showed that the workability of concrete may be affected due to its small size and thus large surface area [33]. For example, Snoeck et al. found that adding PCM micro-capsules reduces workability in proportion to the volume of PCM addition. A decrease in the flow capacity was observed regardless of the method of adding PCM micro-capsules to the mix, that is, by substituting a portion of the medium aggregate or simply by adding it to the mix. Because of these influences, Šavija et al. [34]. Relatively high amount of super plasticizer for mixtures (ultra-hard reinforcement compound, ultra-plastic support material), as large proportions of limestone powder have been replaced by PCM. A decrease in workability with PCM addition was also observed by Hunger

et al. [35]. However, they were able to obtain concrete with partially good or excellent operability. Pilehvar study [36] in Fig. 2.2 shows the workability of fresh Geopolymer concrete and Portland cement concrete (PCC) containing different amounts of MPCM [36].

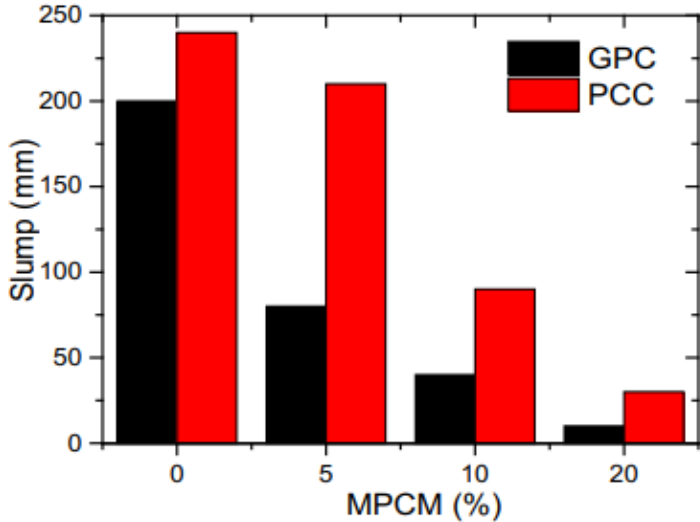


Figure 2.2: The workability of fresh geopolymer concrete and Portland cement concrete (PCC) containing different amounts of MPCM [36].

2.4 Thermal Characteristics of PCM Modified Concrete

Previous studies showed that about 20–50% reductions in k-value (Thermal conductivity) by using PCM in concrete. In Hunger study [37], the thermal conductivity of the self-compacting concrete with 5% PCM was reduced from 3.4 W/mK to 2.1 W/mK for conduction as shown in figure 2.3.

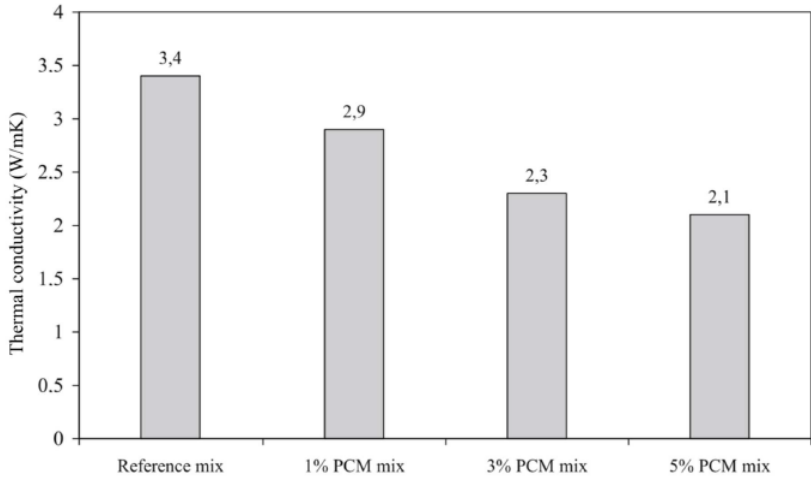


Figure 2.3: Thermal conductivity of the self-compacting concrete PCM (weight % of PCM) [37].

In Zhang study [38], the thermal conductivity of cement mortar decreased from 2.12 W/mK to 1.85 W/mK. Figure 2.4 is quilted from his study for 2.5% PCM samples as replacement.

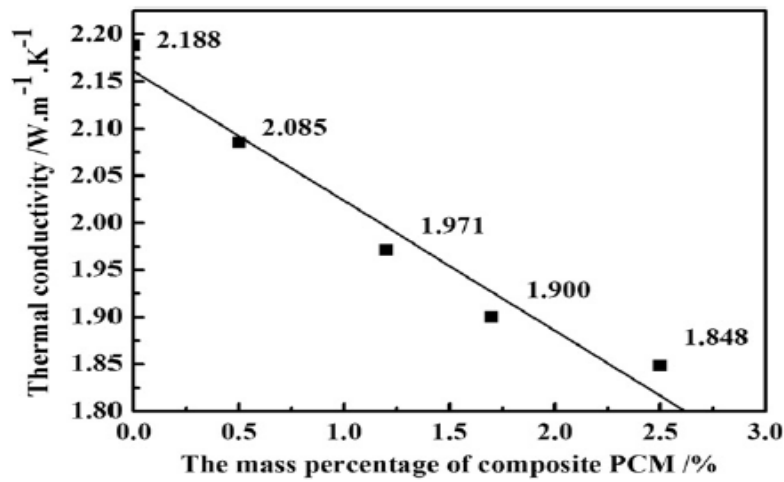


Figure 2.4: Thermal conductivity of the cement mortar boards with the n-octadecane/EG composite PCM [38].

2.5 Compressive Strength of PCM Modified Concrete

The compressive strength of PCM modified concrete is well reported to decrease with the addition of PCM. In B. Saviga study [16], the compressive strength decrease 30 % when adding 50% PCM. In Eddhakhak study [17], showed the compressive strength of the PCM modified concrete (added by total weight of concrete) measured after 28 days decreased with increasing the percentage addition of PCM as shown in figure 2.5.

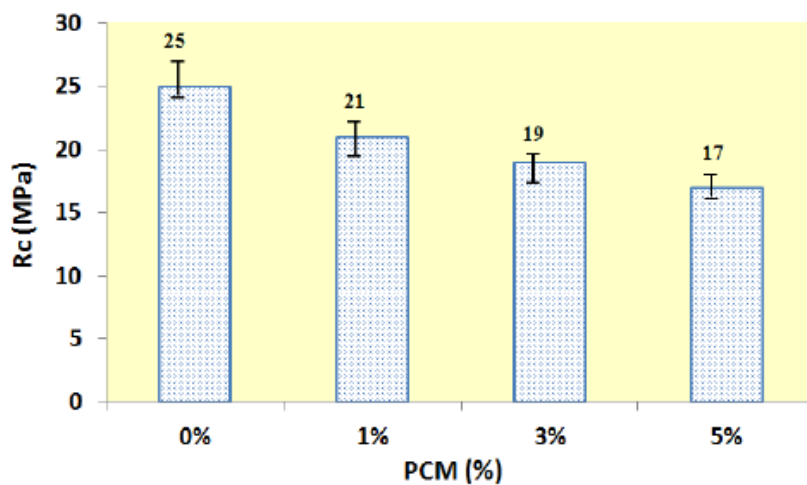


Figure 2.5: The compressive strength of the PCM modified concrete measured after 28 days [17].

The addition of PCM clearly results in a loss of mechanical strength of the initial and final concreting. However, it remains useful for some construction applications. This result is to be expected since the PCM does not represent mechanical resistance; accordingly, their presence in concrete impairs the overall resistance of the composite material. Another explanation is likely associated with the delay of the cement hydration reaction induced by the addition of PCM.

In Zhang study [38], the Compressive strengths of the cement mortar cubes with 2.5% PCM decreased from 23.7 MPa to 10.5MPa, see figure 2.6.

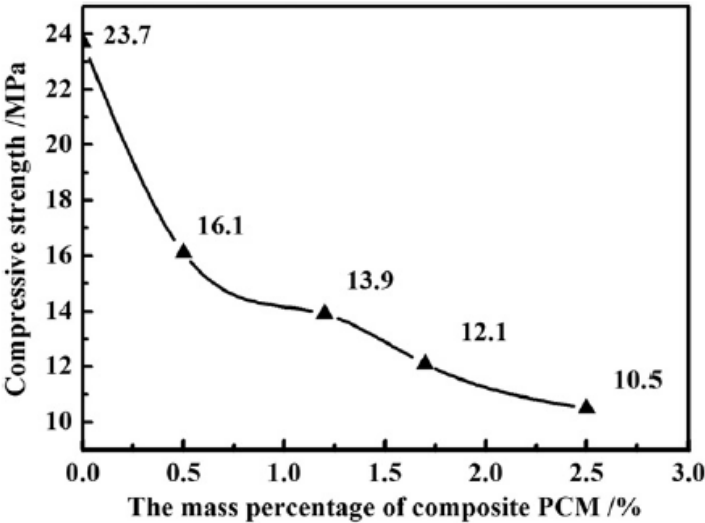


Figure 2.6: The compressive strength of the cement mortar cubes with the n-octadecane composite PCM mass percentages of 0, 0.5, 1.2, 1.7 and 2.5% [38].

2.6 Heat Capacity of PCM Modified Concrete

The addition of PCM greatly increases the heat capacity of the modified concrete and improves heat storage. In table 2.3 the specific heat and total heat storage values for PCM concrete mixtures are summarized [17]. There are no adequate studies on the heat capacity of PCM concrete.

Table 2.3: Specific heats of PCM modified concrete [17].

Replacement (%)	Cp (kJ/kg.K)
Reference	0.82
1	1.03
2	1.39
3	1.5

2.7 Density of PCM Modified Concrete

The density results of cement paste containing MPCM with its mass ratio ranging from 0% to 25% by weight of cement are shown in figure 2.7. Cement paste density decreased with increasing MPCM mass ratio [40].

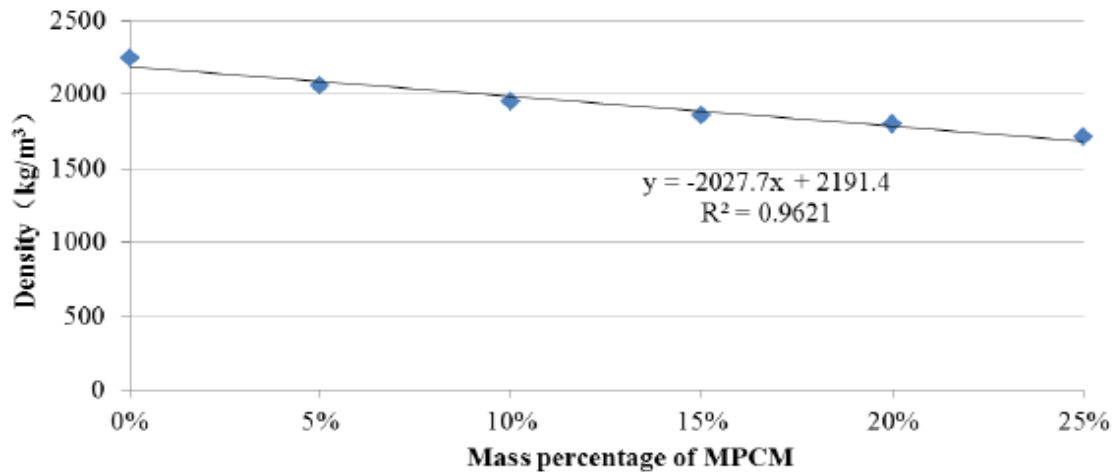


Figure 2.7: Density of hardened cement paste with different mass percentages of MPCM [40].

2.8 Energy Saving in Building

Memon [39] study revealed that combining natural weight aggregate concrete with coated paraffin significantly reduces energy consumption in buildings. They set up a small test room with five shingle panels and one panel on top and placed a 500W lamp as a 600mm heat source above the top panel. The thermocouples were located in the center of the test chamber. The top plate was cooled naturally for 2 hours after heating for 2 hours. Indoor room temperatures were measured using the normal weight of aggregate concrete and phase variable materials of the aggregate concrete at normal weight in figure 2.7 [39].

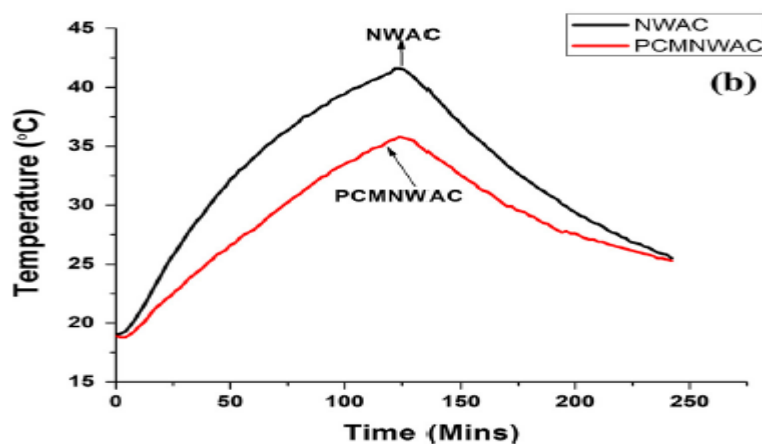


Figure 2.8: Indoor temperature variation curves of the test rooms with the top boards containing different mass percentages of PCM.

2.9 Gab of Knowledge in Previous Work

In general, there are various knowledge gap in PCM modified concrete literature. Our literature reviews revealed that there is no studies focusing on using phase change material in concrete mix and using PCM as a substitute for cement and medium aggregates in concrete. However, there is still a lack in studies comparing between different particle sizes of PCM-concrete. In previous literature previously discussed, there are no comprehensive studies on the change in the thermal properties of concrete when using PCM in the concrete mixture. Most researchers investigated just the k-value as an index to evaluate the thermal behavior of concrete. However, there is still a lack of knowledge in the relationship between the different percentage of PCM in concrete and the specific heat value of concrete. In addition, there is a lack of knowledge in energy efficient concrete application in different weather conditions related to freeze. Studies focusing on the long-term durability of the material are not available, and cost considerations have been ignored in the studies. All of this implies that more work is needed to study the relationship between density and specific heat value of PCM-concrete. More experimental studies are required to evaluate the thermal efficiency of concrete under different weather conditions and applications. There is also a need for a full parametric study of all and combined properties of PCM modified concrete, and a potential chemical treatment of PCM modified concrete to compensate for the loss of mechanical properties due to addition of PCM.

Chapter Three

Experimental Work

Chapter Three

Experimental work

3.1 Introduction

This chapter addresses the materials, the procedure of mixing PCM concrete and the used apparatus for measuring thermal and mechanical properties. It also contains data analysis of test results and the results of this analysis.

3.2 Materials

A commercially available Type I ordinary Portland cement (OPC) conforming to ASTM C150 was used. Crushed coarse aggregate from a local source were used (from Abu Shusheh Crusher Corporation, Hebron, Palestine). For fine aggregated and sand (from Daymoona, Naqap desert area). A paraffin-based solid supplied by Tanco International Ltd (Tel Aviv) was used as PCM, with the properties as listed in table 3.1.

Table 3.1: Properties of paraffin-based solid PCM [41].

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)	Density (kg/m ³)
Paraffin wax	39-41	173-266	0.167 (liquid, 63.5 °C)	790 (liquid, 65 °C)
			0.346 (solid, 33.6 °C)	916 (solid, 24 °C)
			0.339 (liquid, 45.7 °C)	

Three types of crushed particles of PCM where used, including fine, medium and coarse particles, with PCM particle sizes of 2.14, 4.65 and 10.1 mm, respectively. In this research, I was not able to get paraffin with melting points less than 30 ° C, so I used paraffin with a melting point from 39 to 41 ° C, as the measurements that I made are not affected by the melting point due to the similarity of paraffin properties with the exception of the heat capacity calculations. Temperatures ranging from 40 to 45 ° C to ensure the effect of the latent heat of fusion on heat capacity.

3.3 Concrete Mix Design

A standard concrete mix design of B250 with a fixed water to cement ratio of 0.7 was used in all experiments as a base. The mix proportion was 1:2:4 for cement, sand and aggregates (fine and medium), according to weight basis. The mix consisted of 732 kg/m³ sand, 768 kg/m³ medium aggregates, 329 kg/m³ fine aggregates. Then, it was modified by adding the selected amount of PCM as a replacement of aggregates or cement at various percentages of 5%, 10%, 15%, and 20%, as listed in table 3.2 and table 3.3. Testing samples for control and PCM modified concrete mix with 10 × 10 × 10 cm³ dimensions were prepared, as shown in figure 3.1.



(a)

(b)

Figure 3.1: PCM modified concrete specimens, (a) PCM modified concrete specimens demolded after 24 hours (b) PCM modified concrete specimen with 10 × 10 × 10 cm³ dimensions.

Table 3.2: The mix design for B250 concrete and modified concrete with PCM added as a replacement of cement.

Mix Code	Standard Concrete Materials					PCM
	Cement	Fine Aggregate	Medium Aggregate	Sand	Water	
	Kg	Kg	Kg	kg	Kg	
B250	6.12	6.58	15.3	14.6	4.3	0
PCM5	5.81	6.58	15.3	14.6	4.3	0.30
PCM10	5.50	6.58	15.3	14.6	4.3	0.61
PCM15	5.20	6.58	15.3	14.6	4.3	0.91
PCM20	4.89	6.58	15.3	14.6	4.3	1.22

Table 3.3: The mix design for B250 concrete and modified concrete with PCM added as a replacement of medium aggregate.

Mix	Standard Concrete Materials					PCM
	Cement	Fine Aggregate	Medium Aggregate	Sand	Water	
	Kg	Kg	Kg	kg	kg	
B250	6.12	6.58	15.3	14.6	4.3	0
PCM5	6.12	6.58	14.6	14.6	4.3	0.76
PCM10	6.12	6.58	13.8	14.6	4.3	1.53
PCM15	6.12	6.58	13.0	14.6	4.3	2.30
PCM20	6.12	6.58	12.3	14.6	4.3	3.07

The prepared samples were triplicated for each investigated parameter for the three sizes of paraffin wax, as listed in table 3.4. The total number of samples prepared in this work was about 280 samples.

Table 3.4: Investigated parameters and the types of prepared samples for each PCM percentage addition.

Parameter	Size 1			Size 2			Size 3		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Specific heat	•	•	•	•	•	•	•	•	•
Thermal conductivity	•	•	•	•	•	•	•	•	•
Compressive strength	•	•	•	•	•	•	•	•	•
Water absorption	•	•	•	•	•	•	•	•	•

3.4 Tools

The apparatus and equipment used in this research included:

1. Standard sieve test apparatus to determine the particle size distribution of the aggregates.
2. Concrete mixing and handling devices including trowel, concrete mixing tub, concrete scoop, weight machine and curing tank for concrete specimens.
3. Slump test apparatus, including tamping rod, slump cone, slump plate and a ruler.
4. Steel molds to cast the concrete with $10 \times 10 \times 10 \text{ cm}^3$ dimensions as shown in appendix B.
5. Oven to dry samples and materials.
6. Concrete compression testing machine (Matest, Italy).
7. Thermal conductivity measurement apparatus (designed and constructed in this research, as detailed in section 3.6.1).
8. Heat capacity measurement calorimeter (designed and constructed in this research, as detailed in section 3.6.2).

3.5 Experimental Methods

The experimental work was done through the following main steps:

1. Preparing the PCM according to the required size. This was done by crushing the raw material of PCM using Ball Mill Machine, then screening using Taylor standard sieves to obtain the required size range.
2. Measurement of the particle size of the prepared PCM particles. Figure 3.2 shows the images of the three different PCM sizes used. The particles of the PCM were laid on a black background. A professional Canon camera was used, and was placed 15 cm away from the PCM and a photo was taken. The image was saved/sent to import by Adobe Reader- Ph-illustrator.2012 which is used to analyze the particle size. The particles were assumed to be spheres with a circular 2D projection. The program measured the overall length and width of the image and calculated the total area. Then, it estimates the total area covered by particle. The total number of particles was also determined by the program. The projection area of one particle was obtained by dividing the covered area by the number of particles. The average particle size was obtained from the area covered by one particle, using the geometric relation of area of a circle.
3. Testing concrete materials (cement, aggregate and sand) for being conformed to ASTM specifications.
4. Preparing the fresh concrete mixture by mixing the cement with sand, aggregates, and tap water for 10 min manually using a trowel.
5. Performing the required tests of slump using fresh concrete.

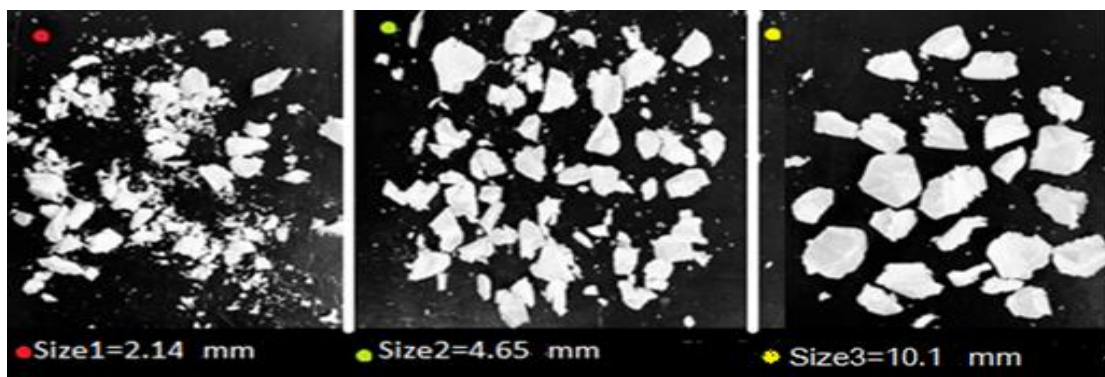


Figure 3.2: PCM with three different sizes: fine particles (2.14mm), medium particles (4.65mm) and coarse particles (10.1mm).

6. The prepared samples were casted in steel molds and placed in the laboratory conditions, then removed after 24 hours. After that, they were allowed to cure in a water bath for

24 hours. Then, they were left to cure for the required time for the remaining period in the laboratory conditions.

7. Measuring the compressive strength, water absorption, thermal conductivity and the heat capacity for the prepared samples according to the procedures detailed in the following sections.

3.6 Measuring Thermal Characteristics

3.6.1 Constructing Thermal Conductivity Device and its Measurement

The thermal conductivity of the concrete was measured by the hot plate thermal conductivity method, similar to the procedures specified by ASTM (C177-19). Homemade device was made in house. The insulation test room was made of wood, with two layers of foam insulation, as shown in 3.3 (a). The first layer had a thickness of 9.5 cm and the second layer had a thickness of 6.5 cm. In addition, the test specimen was surrounded with rock wool insulation of 2 cm thickness. The bottom of the room was completely isolated by using a thermal stone. This insures no heat transfer to the surroundings through the sides or bottom surfaces. A concrete specimen with a depth of 1 cm and a cross-sectional area of 10x10 cm² was placed in the isolated test chamber. The bottom surface of the concrete sample was exposed to a heat source uniformly distributed through a metal plate with an electric power of 250W. The power supply provided a bottom temperature above 200 °C. The top surface was allowed to cool by natural convection through surrounding air. This set-up ensured a one-dimensional vertical heat transfer by conduction through the concrete specimen. Two temperature sensors were used to measure the specimen surface temperatures (bottom and top temperatures, T₁ and T₂, respectively).

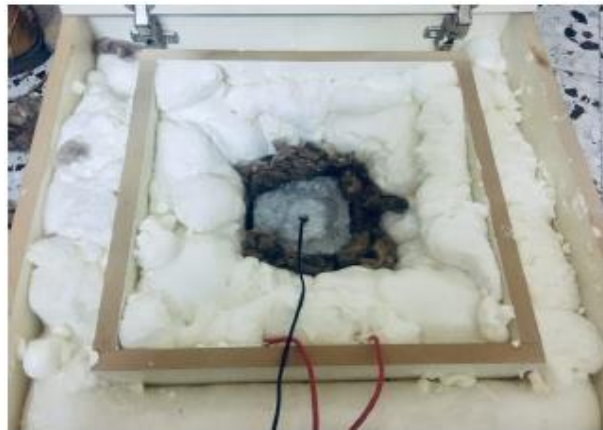
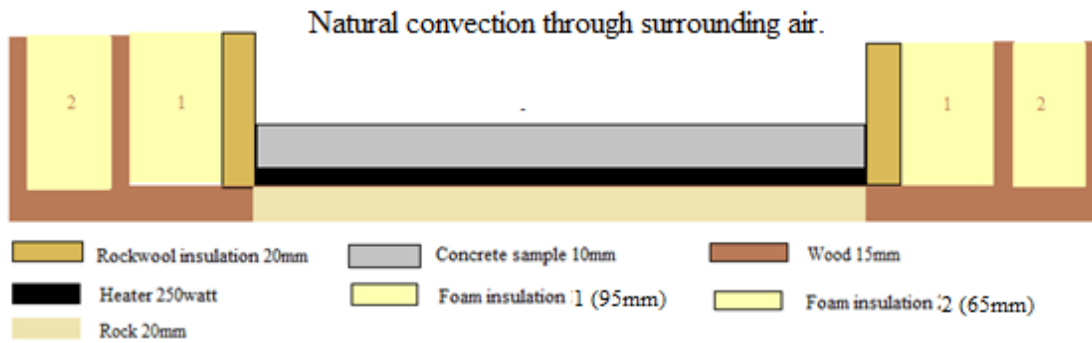


Figure 3.3: The thermal conductivity testing tool.

Steady-state method was used. Steady state conduction was achieved after a transient heat transfer period. Steady-state method is usually designed to measure the thermal conductivity of standard cubic concrete specimen (10X10X10) cm³. However, a thin specimen with a 1 cm thickness was used in this research see figure 3.4. It was found that a steady state condition was achievable within a practical time period of about 90 minutes, as indicated in figure 3.5, which includes two plots for bottom and surface temperatures. Such a transient curve was obtained for each test of thermal conductivity to ensure that a steady state heat transfer was achieved.



Figure 3.4: Optimum concrete thin specimen with a 1 cm thickness.

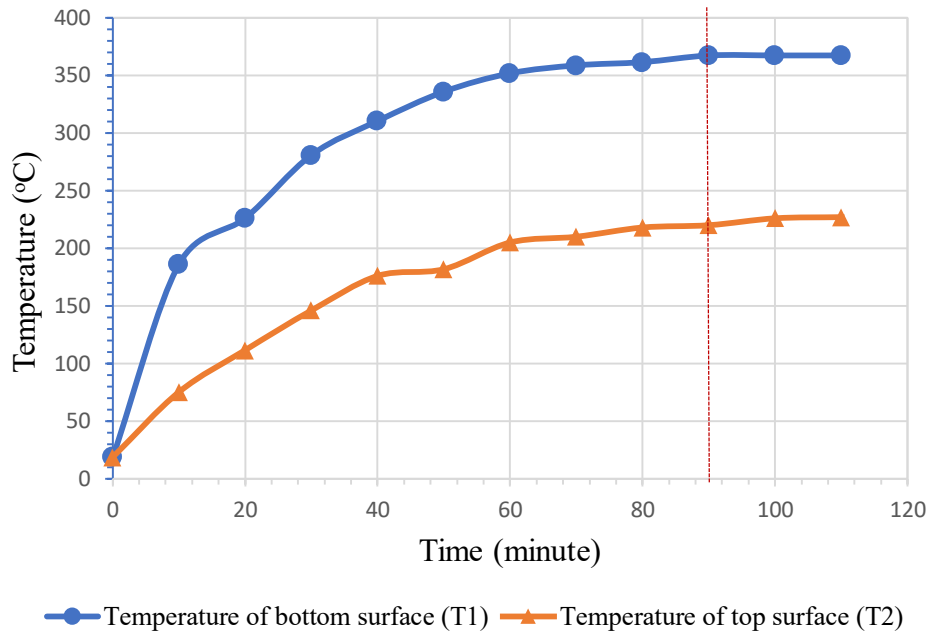


Figure 3.5: The temperatures of bottom and top surfaces of concrete specimen for transient and steady state heat transfer periods.

3.6.2 Measurement of Specific Heat

An exemplary thermal measurement method was used to measure specific heat, similar to the procedures specified by ASTM (E1269). A homemade thermal calorimetric device was made of foam box covered with a layer of rock wool. The concrete sample was placed in a plastic container inside the insulation box to increase the thermal insulation capacity, as shown in Fig.3.6.

A standard cubic concrete sample ($10 \times 10 \times 10$) cm³ was used with a known mass. Prior to testing, the sample was conditioned at room temperature for approximately 24 hours. Hot water with a temperature in the range of 48-52 °C was poured into a plastic container. Then, the initial temperature of the concrete sample was measured and recorded. Then, the sample was immersed in hot water, and the isolation box was closed for the time required to reach thermal equilibrium between the sample and the water. One thermometer inserted into the box to measure the water temperature.

A heat equilibrium condition was achieved over a period of 40 to 60 minutes as shown in Fig.3.7. Despite this, the test lasted an hour to ensure the accuracy of the readings. The pre-measured heat loss to the surrounding (equivalent to 1.9 °C decrease in temperature) was compensated for in the energy balance calculations.



Figure 3.6: A homemade thermal calorimetric device for testing of specific heat.

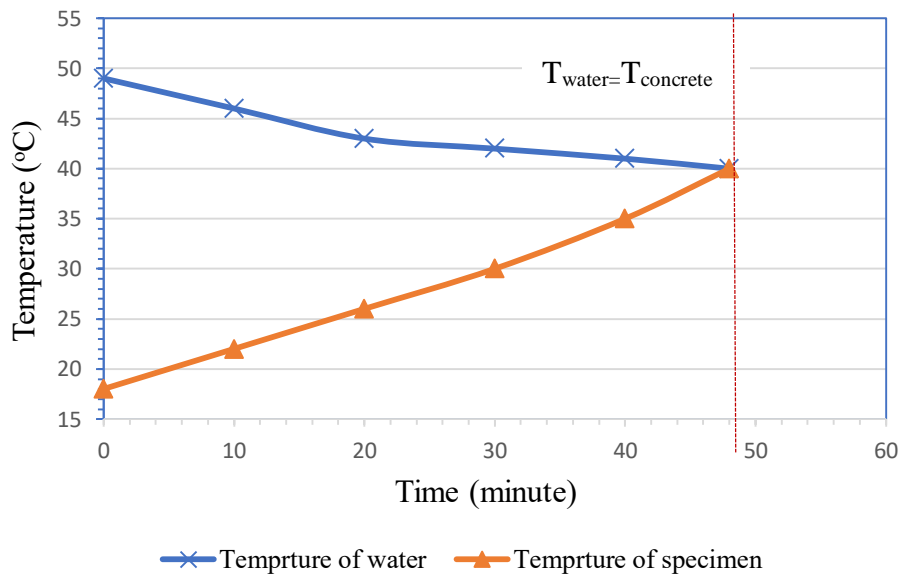


Figure 3.7: The temperatures of water and concrete specimen as functions of time during specific heat testing.

3.7 Measurement of Compressive Strength

The compressive strength of concrete specimens was performed according to BS EN 12390-3:2019 test as shown in figure 3.8.



Figure 3.8: Compressive strength measurement device (MATEST).

The compressive strength of concrete for any element can be calculated by dividing the load applied at the point of failure by the cross-sectional area of the face to which the load was applied.

3.8 Measurement of Workability

Slump tests were performed to measure the workability of fresh concrete according to ASTM C143, the see figure 3.9. The first step was placing the slump mould on a flat, non-absorbent smooth surface. After that, the dry components of the concrete were well mixed until a uniform color was obtained and the required amount of water was added. The concrete mixture was placed in the mould to a quarter of its height. The concrete was compressed 25 times uniformly with the help of a tamper bar throughout the area. The concrete mixture was placed in the mould to about half of its height and pressed again. Likewise, concrete was placed up to three-fourths of its height and then up to its full height. Then, each layer was compressed 25 times uniformly with the help of a tamper. For the second and subsequent layers, the tamp rod was penetrated into the base layer. The upper surface of the mould was cut by trowel or tamping rod so that the mould is completely filled. After that, the mould was removed

immediately in a vertical direction. When the concrete had completely stabilized, the drop in concrete was measured in millimeters, which is the slump required for the concrete.



Figure 3.9: Slump test measurement tools.

3.9 Measurement of Water Absorption

The water absorption test was performed after 28 days in accordance with ASTM C-642. The sample was placed in the oven, dried for 24 hours, and then weighed; the mass was registered as W_1 . Then the sample was immersed in distilled water for 48 hours. Using a clean, dry towel, the sample surface was dried. The sample was weighed and the mass recorded as W_2 . The water absorption percentage was obtained using the following mass balance equation:

$$WA = \frac{W_2 - W_1}{W_1} * 100\% \quad (3.1)$$

Where WA is the percentage of water absorption in the concrete.

3.10 Surface Treatment with Sodium Silicate Additive Materials

For selected samples, their surfaces were treated with sodium silicate solution (40%), in order to verify investigate its effect on compensating the loss for compressive strength due to addition of PCM. The treatment was performed by brushing at a coverage rate of 250 ml/m². This was done for PCM modified samples containing 20% PCM as a replacement of cement and similarly for samples containing 20% PCM as a replacement for medium aggregate. The treated specimens were cured for 28 days, and the compressive strength was measured after seven days of applying sodium silicate.

3.11 Building physical Modeling and Investigating the Energy Efficiency

The experimental setup consisted of two identical shaped cubicles of concrete, one with B250 concrete (control), and the other one with the 20% PCM modified concrete an alternative to medium aggregate size 3. Figure 3.11 shows the two cubicles modeling shapes of concrete. The dimensions of the cubicles were (27 x 27 x 27) cm. The walls have a thickness of 5 cm. The concrete models were instrumented with temperature sensors. The first temperature sensor was located in the middle of the wall, and second sensor was located at the external side of the wall to measure outdoor temperature. A 1400W heat source faraway 300mm was directed at one wall of the models. The concrete models were naturally cooled for 1 hr after heating for 1 hr. Figure 3.11 shows the change inside temperature along cooling and heating cycle.

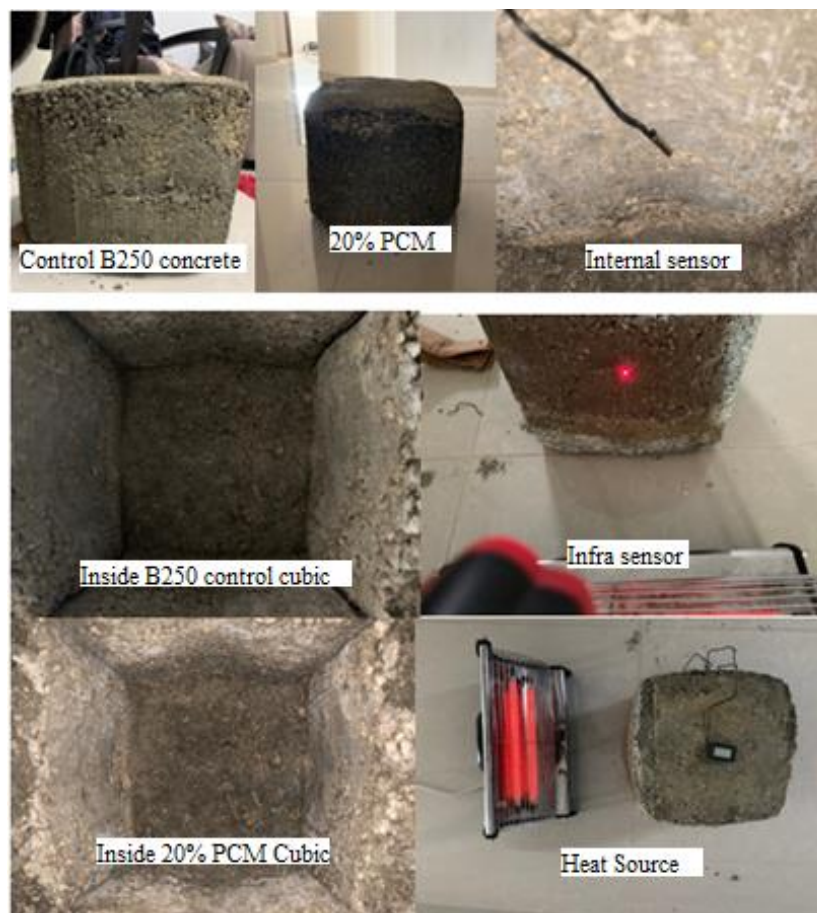


Figure 3.10: The Physical Modeling of Thermal Insulation of concrete, with dimensions of the modeling are (27x27x27) cm. The wall have a thickness of 5 cm.

3.12 Data Analysis

3.12.1 Thermal Conductivity

The thermal conductivity (k) was determined from the measured two temperatures of the concrete specimens (T_1 and T_2 , as described in section 3.6.1), according to Fourier's first law of steady state conduction, written as follows:

$$k = \frac{Q}{A} \frac{L}{T_1 - T_2} \quad (3.2)$$

Where Q is the rate of steady state heat transfer determined by the electric power supply (250w), A is the cross-sectional area of the concrete specimen ($10 \times 10 \text{ cm}^2$), and L is the concrete specimen thickness (1 cm).

3.12.2 Specific Heat

The specific heat of the concrete (c_p) was determined from the measured initial temperature of the cold sample of concrete (T_{c1}), the initial temperature of the hot water (T_{w1}) and the temperature of the final thermal equilibrium condition between water and concrete (T_e). Then it is estimated from the energy balance according to the following equation:

$$c_p = \frac{m_w c_{pw} (T_{w1} - T_e)}{m_c (T_e - T_{c1})} \quad (3.3)$$

Where m_w is the water mass, c_{pw} is the water specific heat and m_c is the concrete mass.

3.12.3 Thermal Diffusivity

Thermal diffusion is defined as the thermal conductivity divided by the density and specific heat capacity at constant pressure, according to the following equation:

$$\alpha = \frac{k}{\rho c_p} \quad (3.4)$$

Where ρ is the density (Kg/m^3).

Chapter Four

Results and Discussion

Chapter Four

Results and Discussion

4.1 Introduction:

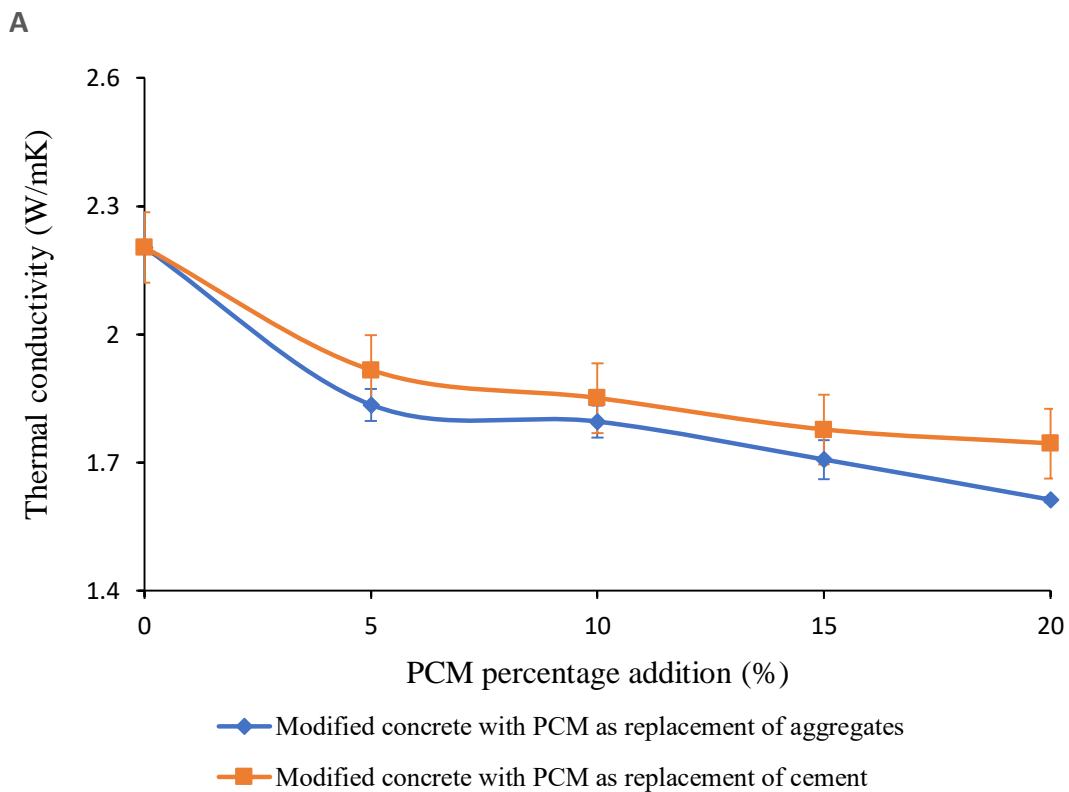
In this chapter, thermal and mechanical characteristics of PCM concrete introduced in this experimental test is discussed. All tests results are compared with similar results in previous studies. The treatment of PCM modified concrete with sodium silicate and PCM-concrete physical model will be discussed in the last section.

4.2 Thermal characteristics

This section include the result of thermal characteristic, which including: thermal conductivity, heat capacity and thermal diffusivity.

4.2.1 Thermal Conductivity

Figure 4.1 shows the thermal conductivity results of PCM modified concrete as a function of PCM-Added percentage for two cases of cement replacement and aggregate replacement. It includes three figures a, b and c for three PCM sizes, 2.14mm, 4.85mm and 10.1mm, respectively.



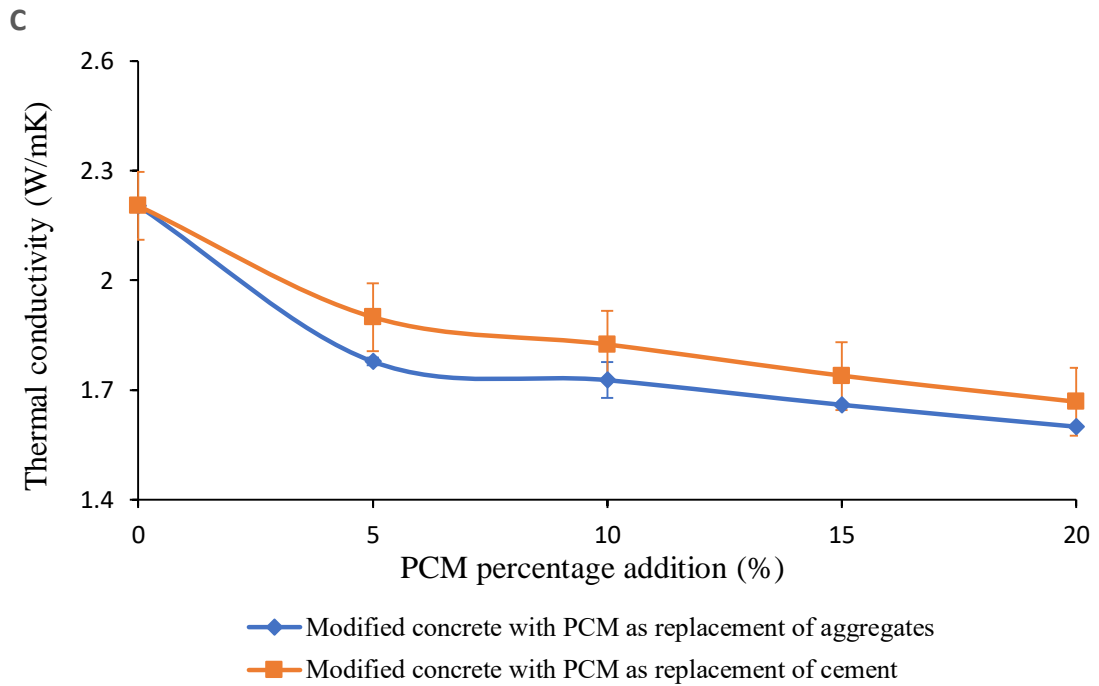
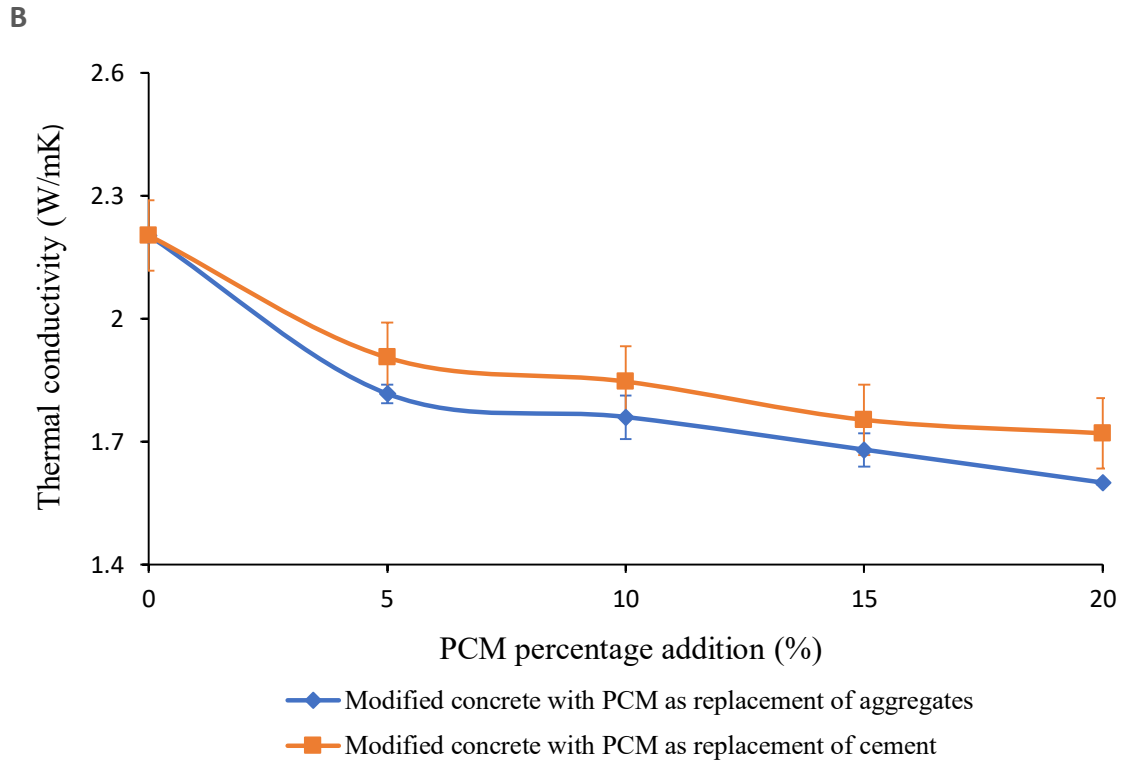


Figure 4.1: The thermal conductivity results of PCM modified concrete as functions of percentage additions of PCM for two cases of cement replacement and aggregates replacement. for fully cured concrete at 28 days (A) for particle size 1= 2.14mm (B) for particle size 2= 4.85mm (C) for particle size 3= 10.1mm.

The thermal conductivity obtained for the control sample is 2.2 W/mK. This value falls within the reported range for the thermal conductivity of concrete with a mixture design of B250 which is used for control samples (0.9 to 3.4 W/mK [35-38]). In fact, the thermal conductivity depends on the bulk density and moisture content of the concrete.

It is clear that the addition of PCM significantly affects the thermal conductivity of concrete. The percentage decrease in thermal conductivity was observed from 2.2 to 1.59 W/mK. The thermal conductivity decreases markedly at the start of the curve by 5% PCM. For concrete with PCM impregnated with LWA, a decrease in thermal conductivity has been reported in multiple studies [42].

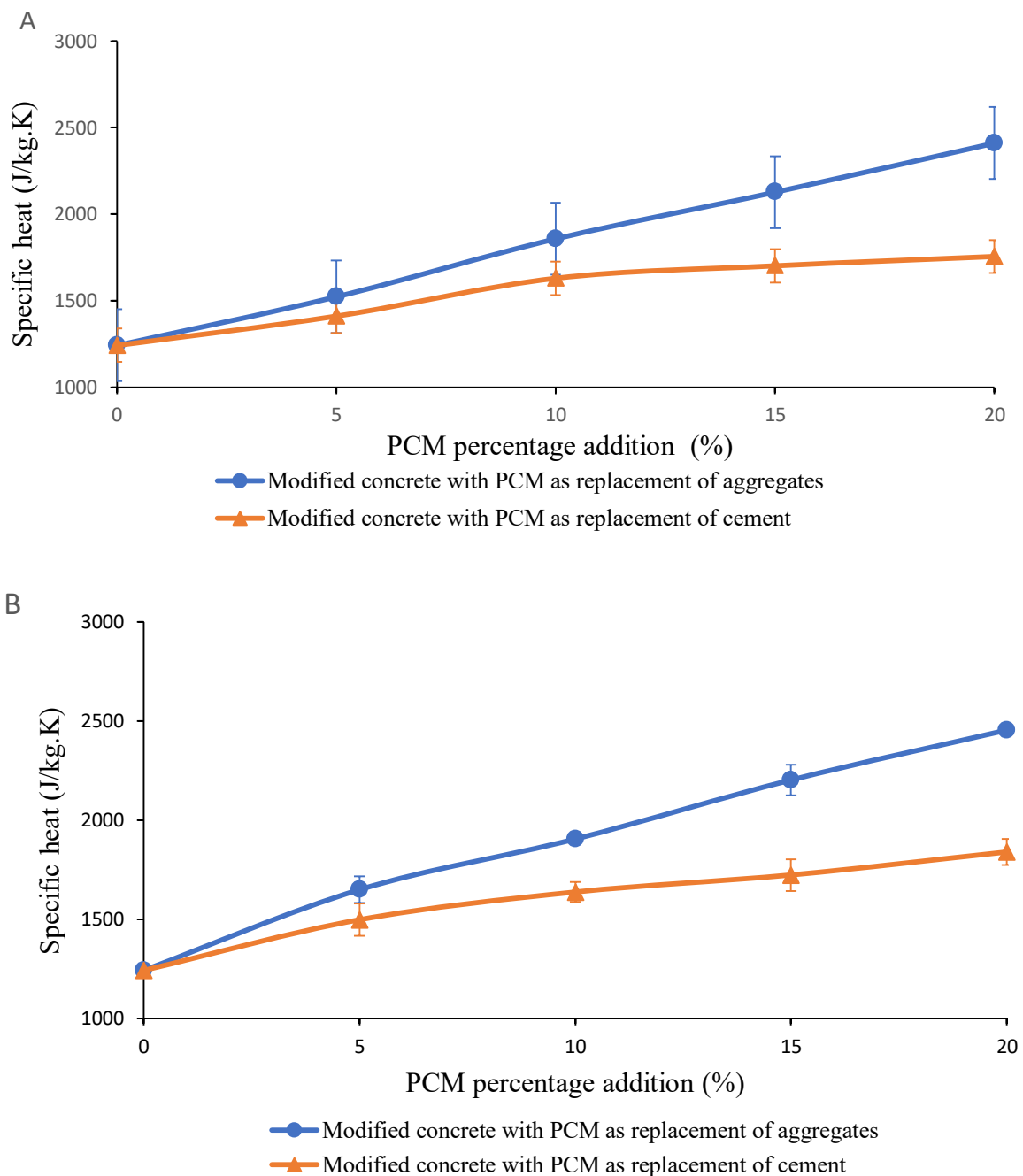
From figure 4.1, the thermal conductivity of modified concrete using PCM as replacement of medium aggregate is lower than the thermal conductivity of modified concrete using PCM as replacement of cement, because the amount of PCM used as replacement for medium aggregate is more than the amount of PCM used as replacement for cement. This demonstrates that the thermal conductivity depends not only on the percentage of PCM, but also on the average size of particles in the mixture composition. Increasing particle size of PCM decreases the thermal conductivity slightly. At larger PCM percentage addition the difference of thermal conductivity between replacement for aggregate or for cement is noticeable. Clearly, the lowest value of thermal conductivity is with 20% PCM replacement as a medium aggregate, the thermal conductivity decreased by 27.7% compared to the reference (B250 control).

The thermal conductivity decreases with increasing PCM percentage as a replacement for cement because when the PCM content increases, the value latent heat of the concrete increases. The PCM has high latent heat and low thermal conductivity with higher heat capacity. In addition, the fusion of PCM make pore blocking to get less permeability and less conduction. This agrees with previous study, which showed that the thermal conductivity decreased in proportion with the PCM addition. Hunger [37], the thermal conductivity decrease from 3.4 W/mK to 2.1 W/mK when 5% PCM by weight of concrete is added. Therefore, it is expected that the thermal conductivity of PCM cementations composites would be somewhat reduced.

Reducing the thermal conductivity of the concrete increases the ability to melt ice and snow formed on the surface of a building, because the concrete will stay warmer for a longer period of time. It prevents snow from accumulating and ice from forming on the surface.

4.2.2 Specific Heat

Figure 4.2 shows the specific heat capacity results of PCM modified concrete as functions of percentage additions of PCM for two cases of cement replacement and aggregates replacement. It includes three figures a, b and c for three PCM sizes, 2.14mm, 4.85mm and 10.1mm, respectively. In this research, I was not able to get paraffin with melting points less than 30 °C, so I used paraffin with a melting point from 39 to 41 °C, as the measurements that I made are not affected by the melting point due to the similarity of paraffin properties with the exception of the heat capacity calculations. Temperatures ranging from 40 to 45 °C to ensure the effect of the latent heat of fusion on heat capacity.



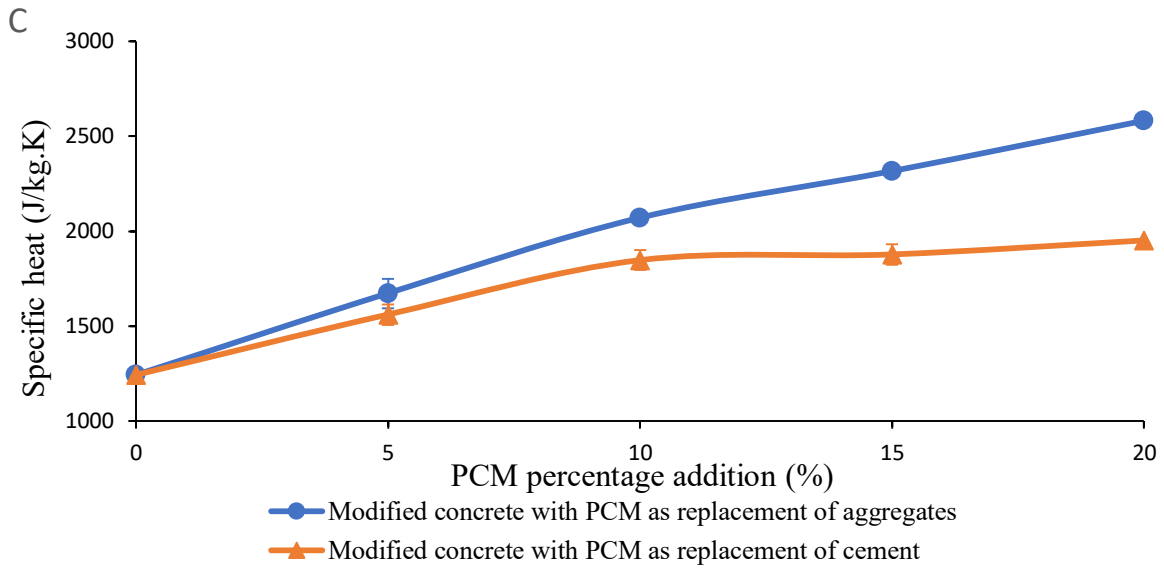


Figure 4.2: The specific heat capacity results of PCM modified concrete as functions of percentage additions of PCM for two cases of cement replacement and aggregates replacement. for fully cured concrete at 28 days (A) for particle size 1= 2.14mm (B) for particle size 2= 4.85mm (C) for particle size 3= 10.1mm.

The specific heat capacity obtained for the control sample is 1242 J/kg.K. This value is within the reported range of the specific heat capacity of concrete with a mixture design of B250 which is used for control samples (840 J/kg.K to 1800 J/kg.K [17]). In fact, the specific heat is very dependent on the moisture content and increases greatly with the higher the water to cement ratio.

In fact, the addition of PCM increases the heat capacity of the PCM modified concrete and significantly improves its thermal storage. This is due to the high latent heat of fusion per unit volume, which stores more energy in a given volume. An increase in heat capacity can be clearly observed when PCM is added as replacement to medium aggregate. In addition, when particle size of PCM increase, the heat capacity slightly increase.

The highest heat capacity is for modified concrete with 20% PCM as a replacement of medium aggregate, the heat capacity increases by 51.8% compared to B250 control. This is because the high phase change material latent heat and the phase change material particle has high heat capacity. In figure 4.2, it is noticeable that the larger difference between replacement by weight of cement and medium aggregate is at 15%+20% because of the high PCM latent heat. A. Eddhahak-Ouni [17] said that when adding 5% encapsulated PCM by weight of cement, the heat capacity increases from 820 J/kg.K to 1500 J/kg.K. However, we still have insufficient studies about the heat capacity of PCM-concrete.

4.2.3 Thermal Diffusivity

Figure 4.3 shows that when PCM is added to the concrete as a replacement of medium aggregate and as a replacement of cement, in three different particles sizes, the thermal conductivity decreases and the heat capacity increases. The thermal diffusivity inversely proportional to the heat capacity and directly to the thermal conductivity. In general, the thermal diffusivity of PCM modified concrete using PCM as a replacement for medium aggregate is more than the thermal diffusivity of it using PCM as a replacement for cement, because more PCM addition get more latent heat and this due to high heat capacity.

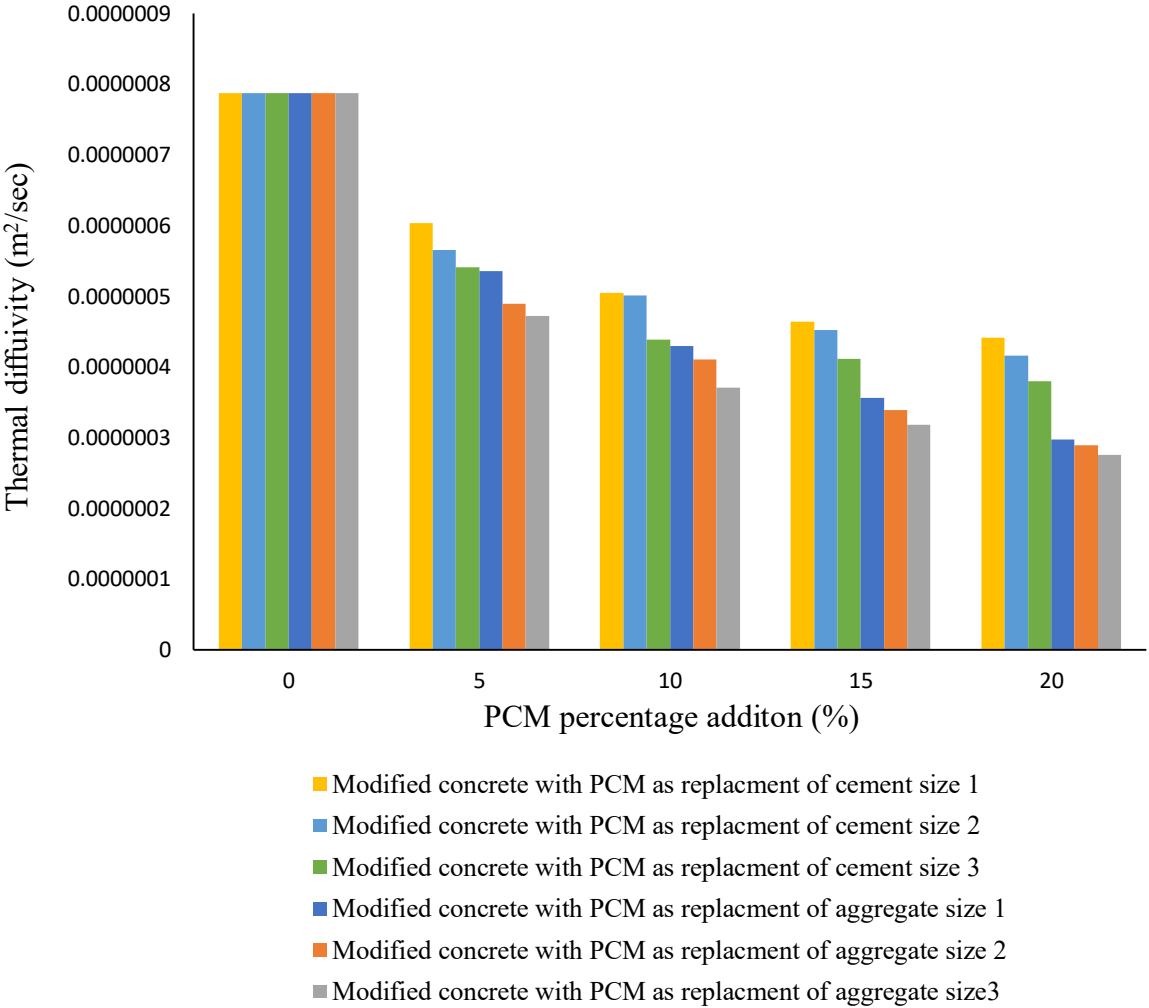
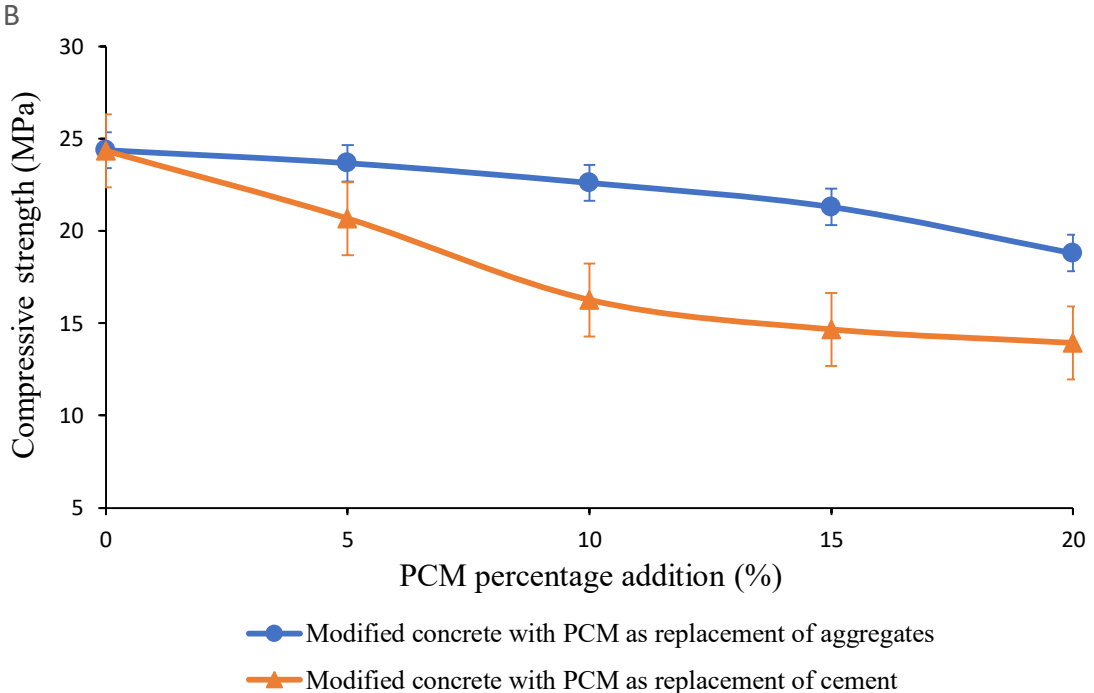
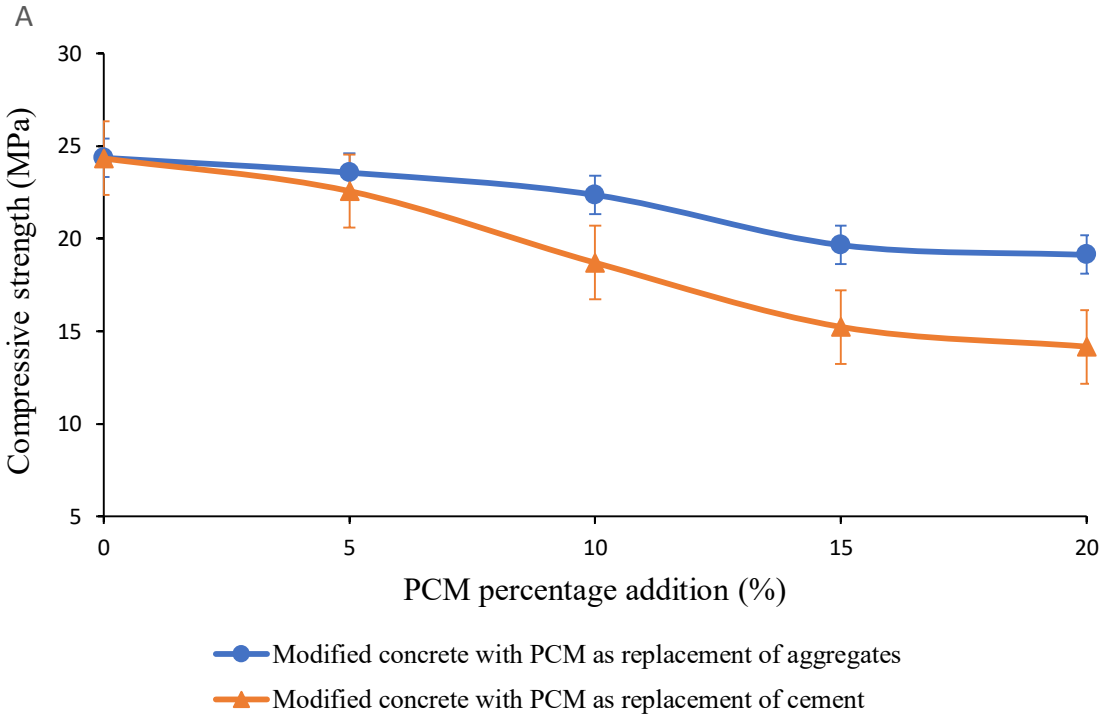


Figure 4.3: The thermal diffusivity results of PCM modified concrete as functions of percentage additions of PCM for two cases of cement replacement and aggregates replacement, for three PCM particle sizes, for fully cured concrete at 28 days.

4.3 The Compressive Strength

Figure 4.2 shows the compressive strength test results of PCM modified concrete as functions of percentage of added PCM for two cases of cement replacement and aggregates replacement. It includes three figures a, b and c for three PCM sizes, 2.14mm, 4.85mm and 10.1mm, respectively.



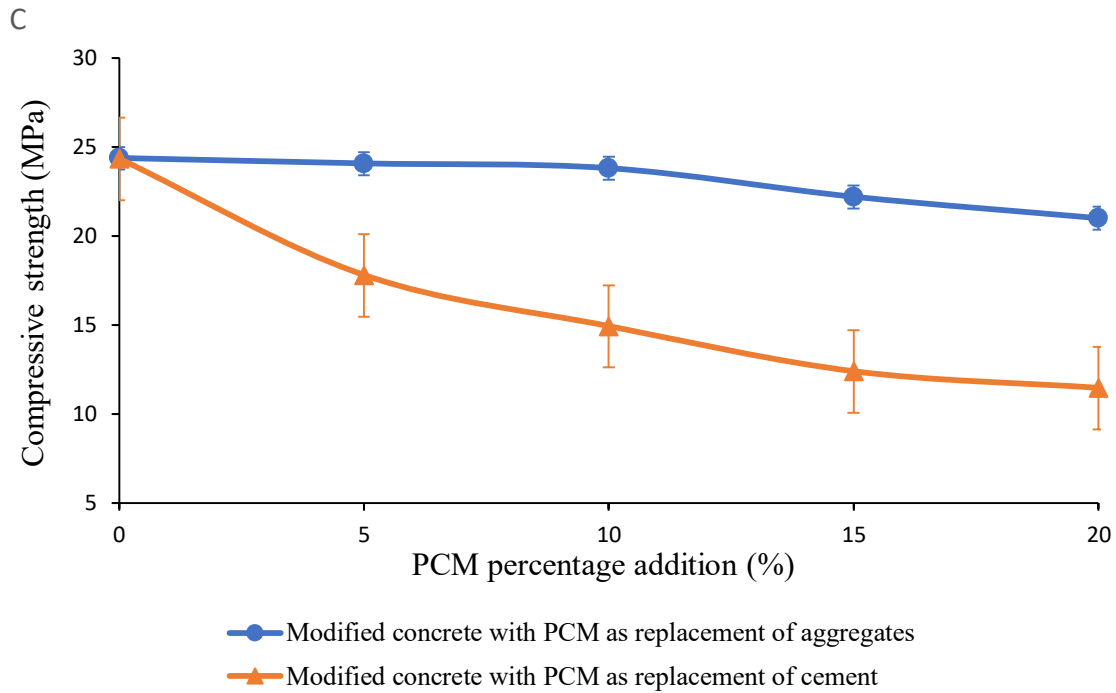


Figure 4.4: The compressive strength results of PCM modified concrete as functions of percentage additions of PCM for two cases of cement replacement and aggregates replacement. for fully cured concrete at 28 days (A) for particle size 1= 2.14mm (B) for particle size 2= 4.85mm (C) for particle size 3= 10.1mm.

The obtained compressive strength of control sample is 24.3 MPa, this is within the reported range of compressive strength for concrete with a mix design of B250 used for control (22.5 MPa to 27.5 MPa according to BS EN 12390-3:2019 Code).

Figure 4.4 represents a comparative analysis of compressive strength in terms of percentage sizes of added PCM and PCM particles. In general, the compressive strength decreases with the increase in the percentage of PCM added to the sample. The compressive strength using PCM as a replacement of medium aggregate give more compressive strength and acceptable value in comparison with using PCM as a replacement of cement, because the amount of PCM as a replacement of aggregate is more than the amount of PCM as a replacement to cement. In addition, an increase in compressive strength can be clearly observed when PCM with large size added as a replacement of medium aggregate, because of the nearly same size between medium aggregate and PCM particle size 3. The results presents an acceptable value of compressive strength using PCM as a replacement of medium aggregate is with 5%+10% PCM at all sizes and 15%+20% at size 4.85mm. In addition, acceptable value of compressive strength using PCM as a replacement of cement is with 5% PCM at size 2.14mm.

Figure 4.5 show that the hydration process of PCM modified concrete using PCM as a replacement of cement and as a replacement of medium aggregate is lower than control concrete B250. When the amount of PCM in mix increases, the hydration process of mix decreases because the latent heat of paraffin wax is high, which leads to the storage of the reaction heat and thus leads to the reduction of hydration. The hydration process with using PCM as a replacement of medium aggregate is lower than with using PCM as a replacement of cement, because the amount of medium aggregate in mix is more than the amount of cement.

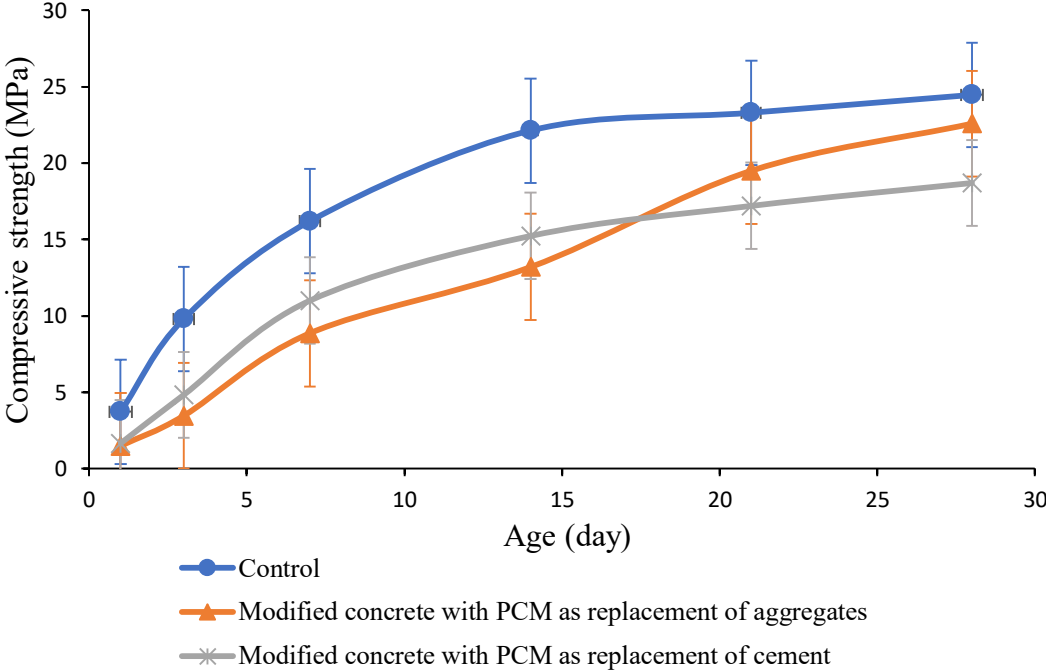


Figure 4.5: Compressive strength for 10% PCM added to concrete as a replacement to medium aggregate and as a replacement to cement for Size (2.14mm), and compressive strength for control in 1, 3, 7, 14, 21 and 28 day.

From Fig.4.6, it can be seen that PCM addition leads to loss of mix compressive strength. This is confirmed by the results obtained in previous studies and this is in agreement with the previous study, see figure 4.5. B. Šavija [16] found that when 10% PCM is added as a substitute for cement, the compressive strength is reduced by 8 MPa, and when 20% PCM is added as an alternative to the medium aggregate it is reduced by 12 MPa. A. Eddhahak-Ouni [17] found that when 5% PCM is added by weight of cement, the compressive strength is reduced by 8 MPa. Cui [40] found that when the mass percentages of PCM were 5%, 10%, 15%, 20% and 25%, the declines in compressive strength with respect to the control cement paste were 11.5%, 32.69%, 48.07%, 55.77% and 66.34%, respectively.

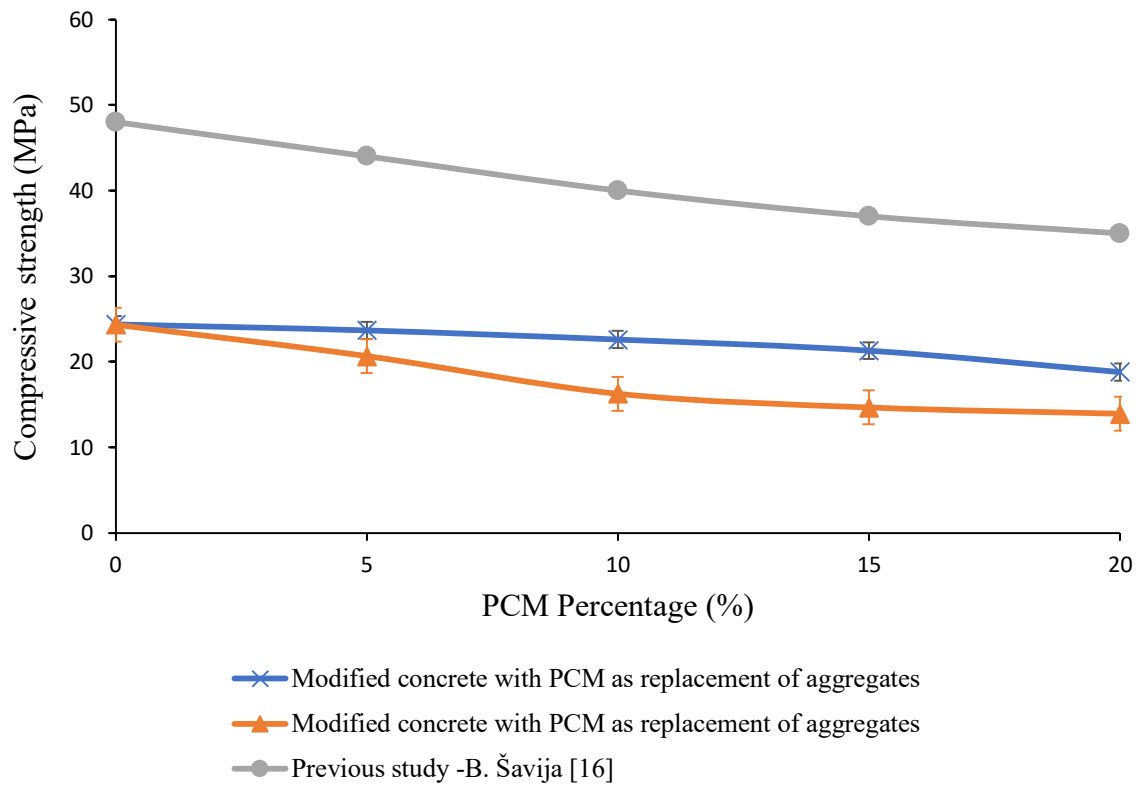


Figure 4.6: Compressive strength for PCM added to concrete as a replacement to medium aggregate and as a replacement to cement for Size 2 (4.85mm) and compressive strength for previous study B. Šavija [16].

4.4 Workability

Figure 4.7 shows the workability results of PCM modified concrete as functions of percentage additions of PCM for two cases of cement replacement and aggregates replacement. It includes three figures a, b and c for three PCM sizes, 2.14mm, 4.85mm and 10.1mm, respectively.

When PCM is added to concrete as a substitute for cement, its workability decreases, due to which the rich concrete mixture (cement content is high) becomes more workable, and also since sufficient cement will have suitable lubrication for easy movement, which means more workability.

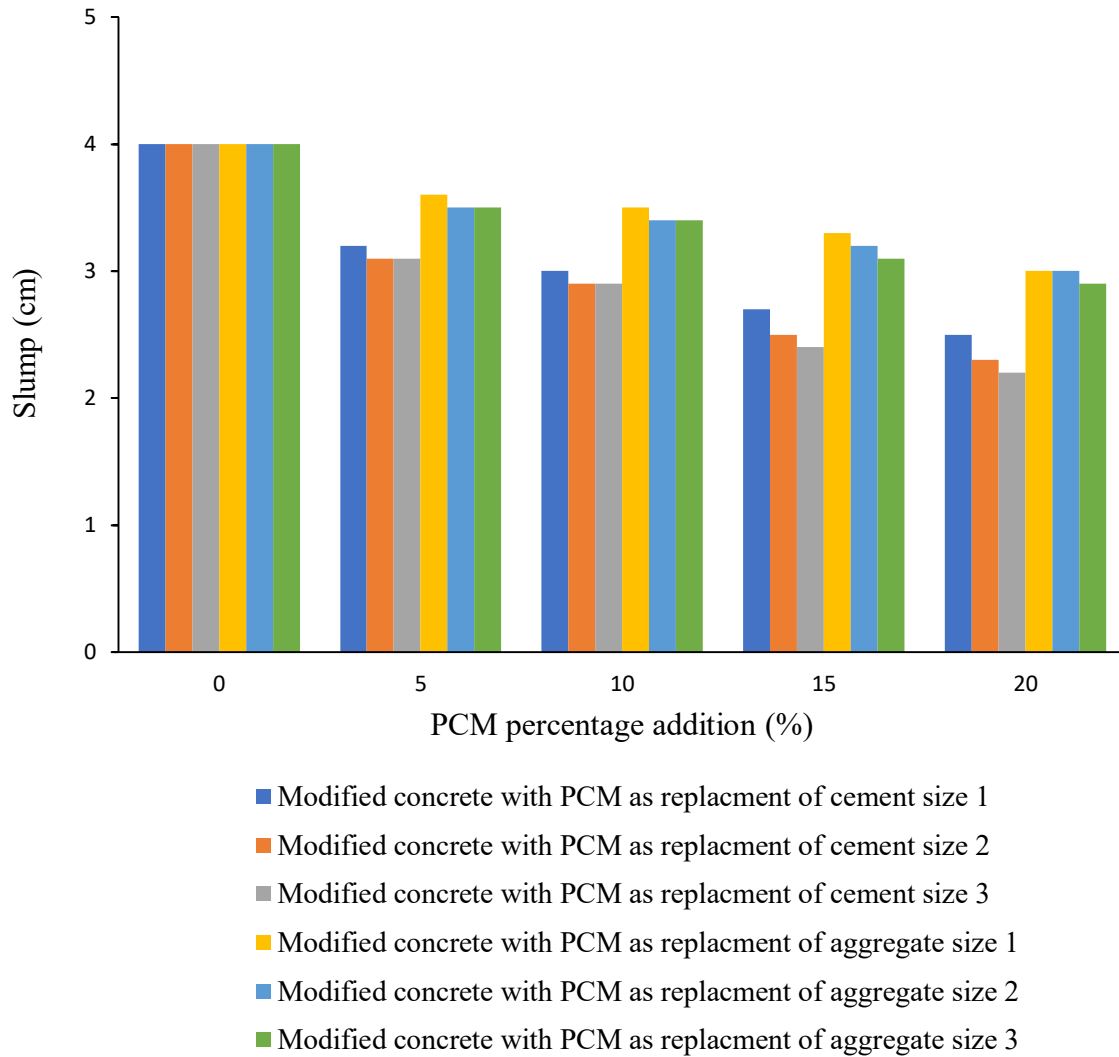


Figure 4.7: The workability results of PCM modified concrete as functions of addition percentages of PCM for two cases of cement replacement and aggregates replacement. for fully cured concrete at 28 days (A) for particle size 1= 2.14mm (B) for particle size 2= 4.85mm (C) for particle size 3= 10.1mm.

The irregular shape of PCM and the rough texture of angular aggregate require more water than round shaped aggregate. For fixed volume or weight, the round or enclosed particles have less surface area, less void, and have less friction resistance as well. Hence, round shaped aggregate shows higher workability than angular, flaky or elongated aggregates.

PCM particles with smooth surfaces are more workable than roughly textured aggregates. Roughly, textured aggregates show high friction and tendency to insulate. Besides, non-absorbent aggregate is more workable because porous and unsaturated aggregate requires more water than aggregate, and it is non-absorbent.

4.5 Water Absorption

Figure 4.8 shows the water absorption results of PCM modified concrete as functions of percentage additions of PCM for two cases of cement replacement and aggregates replacement. It includes three figures a, b and c for three PCM sizes, 2.14mm, 4.85mm and 10.1mm, respectively.

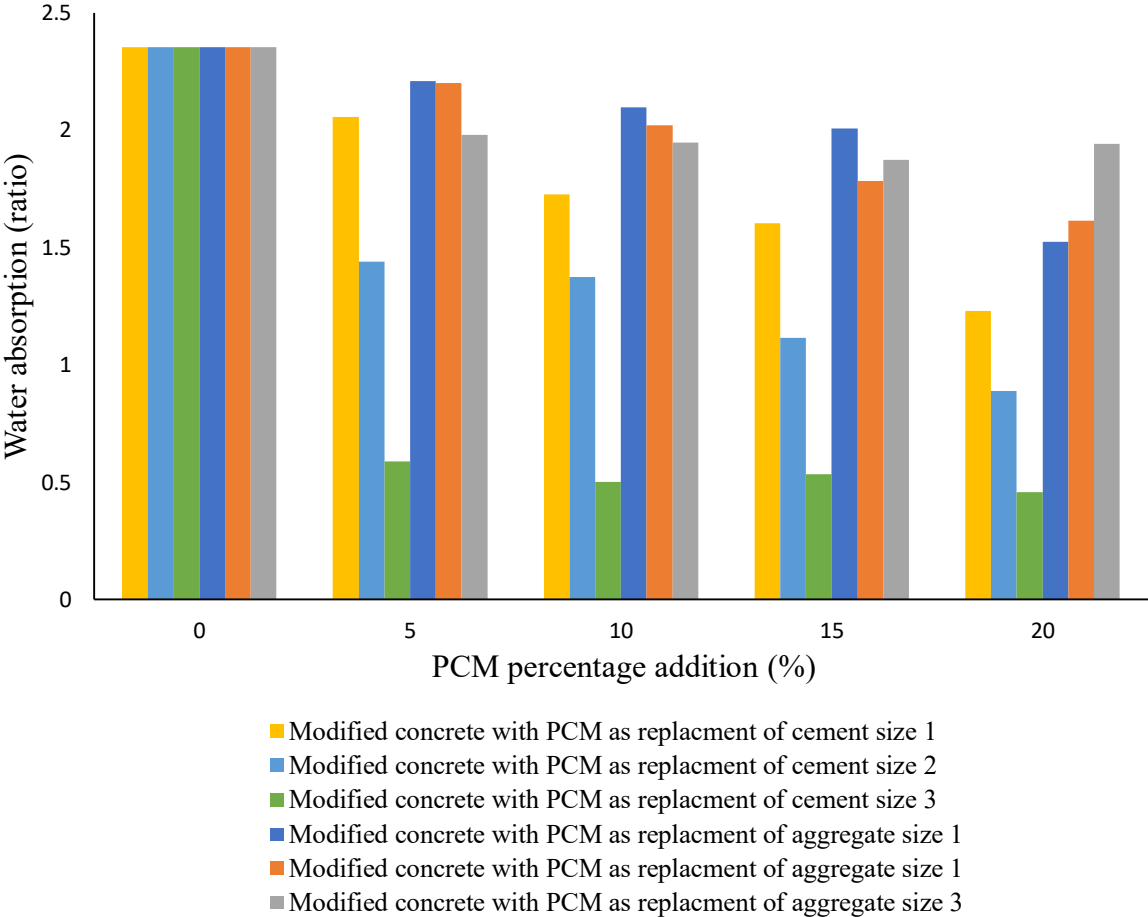


Figure 4.8: The workability results of PCM modified concrete as functions of addition percentages of PCM for two cases of cement replacement and aggregates replacement. It includes three figures a, b and c for three PCM sizes, 2.14mm, 4.85mm, and 10.1mm, respectively.

In figure 4.8, the water absorption with PCM added to concrete as a replacement of medium aggregate is more than that when it is as a replacement of cement. Increasing the particle size of PCM added to concrete as a replacement of cement leads to increase the water absorption, specifically at larger PCM percentage replacement. The difference of water absorption as a replacement of aggregate and cement is noticeable. Obviously, when the amount of cement decreases, the water absorption decreases, and when PCM modified concrete using PCM as a

replacement of medium aggregate, the pours inside aggregate decreases due to the water absorption decreases.

4.6 Density Results

Figure 4.9 shows the density results of PCM modified concrete as functions of percentage additions of PCM for two cases of cement replacement and aggregates replacement. It includes three figures a, b and c for three PCM sizes, 2.14mm, 4.85mm and 10.1mm, respectively.

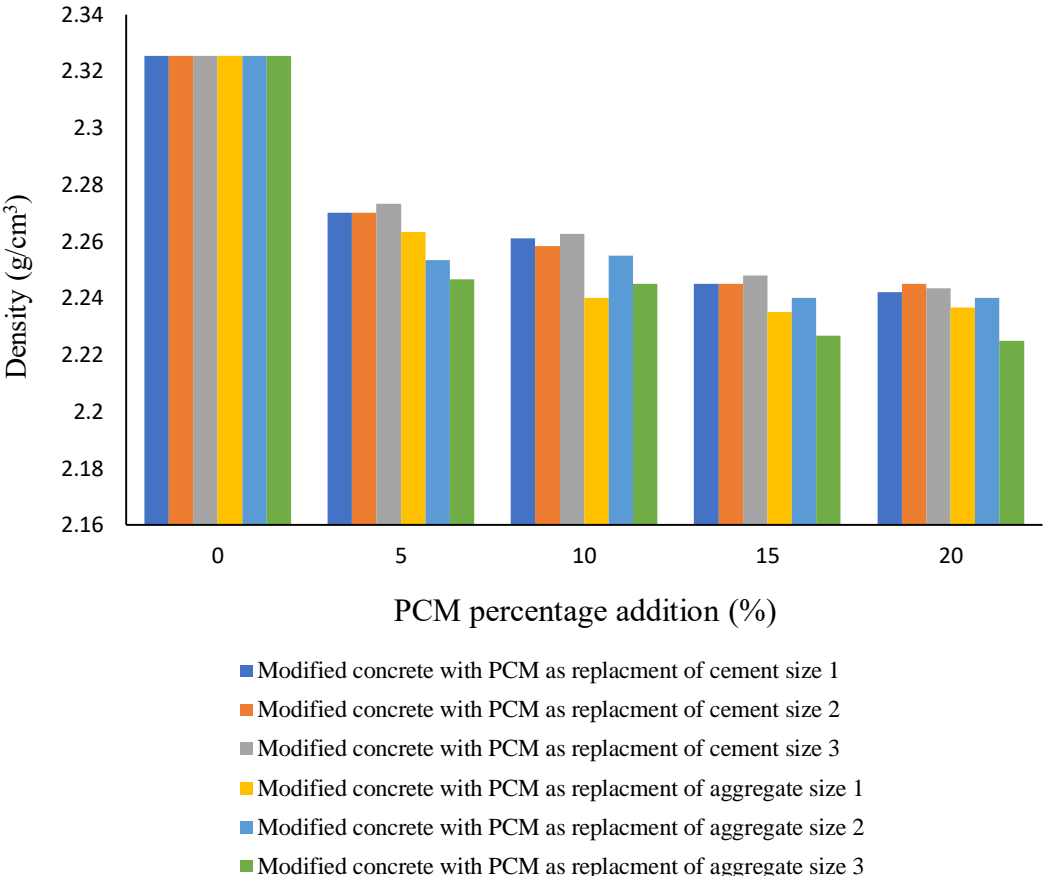


Figure 4.9: The density results of PCM modified concrete as functions of addition percentages of PCM for two cases of cement replacement and aggregates replacement. It includes three figures a, b and c for three PCM sizes, 2.14mm, 4.85mm, and 10.1mm, respectively.

In general, it is noted in figure 4.9 that the greater PCM particles content in the concrete mix, the less the density. However, the ratio of 20% of PCM particles as a replacement to aggregate in the concrete mix has a lower density in comparison with 10% and 15% of PCM content. All these results are logical, and we have seen a reflection on the results of compressive strength tests, and the result matched with results of Cui study [40], which said that when the mass percentages of PCM are 5%, 10%,15%, 20% and 25%, the decreases in density are 8%, 13%, 17%, 20% and 23%, respectively.

4.7 Surface Treatment of PCM Modified Concrete with Sodium Silicate

Figure 4.10 shows the effect of added sodium silicate (40% solution) with 250 ml/m² coverage rate on the compressive strength of concrete as coating silicate mineral paint and the results are taken seven days after the paint of sodium silicate. Concrete treated with a sodium silicate solution helps to reduce porosity in concrete surface. This effect aids in increasing compressive strength. These coatings are known as silicate mineral paint. The sodium silicate is a low cost multifunctional product.

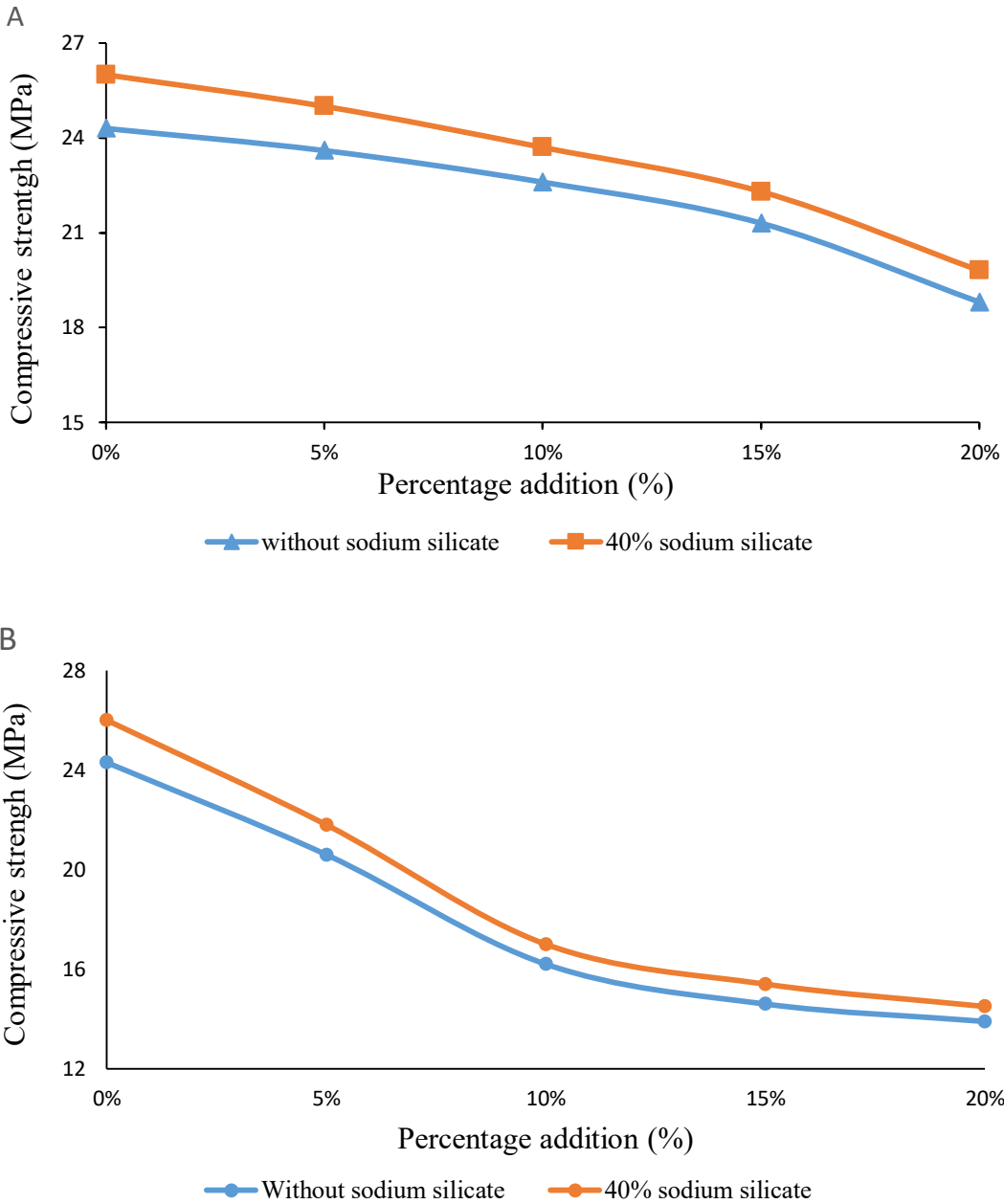


Figure 4.10: Compressive strength of 20% PCM modified concrete with sodium silicate treatment by paint, for fully cured concrete at 28 days: (A) PCM modified concrete as a replacement to medium aggregate size2 (B) PCM modified concrete as a replacement to cement size 2.

By using the surface treatment of PCM modified concrete, we can increase the mechanical strength by 4 to 7%.

4.8 Physical Modeling of Thermal Insulation

Figure 4.11 shows the change of internal temperature of the two concrete physical modeling with PCM modified concrete using 20% PCM as a replacement of medium aggregate and B250 concrete.

The internal temperature of PCM modified concrete using 20% PCM as a replacement of medium aggregate has a 2.5 °C higher than a B250 concrete, and the temperature remain stable at 14 °C about 25 minute.

When the temperature rises (during the day), the PCM absorbs heat in an endothermic process and changes the phase from solid to liquid. As the temperature decreases (at night), the PCM releases heat in an exothermic process and returns to its solid phase. More energy is required to heat and cool the building, which increases energy consumption (heating and cooling energy). The results give better wall insulation, thus reducing energy consumption and energy cost and providing more comfort in temperature.

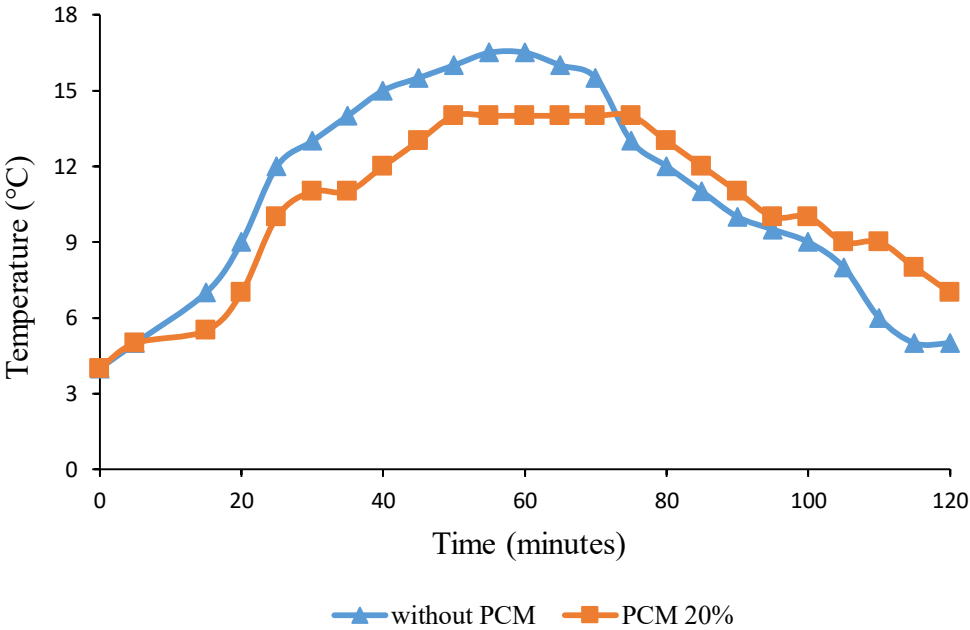


Figure 4.11: The change of internal temperature of the two concrete physical modeling when 20% PCM modified concrete as a replacement to medium aggregate and B250 concrete, along heating and cooling cycle from 0 to 60 minute is heating cycle, from 60 to 120 is cooling cycle.

Chapter Five

Conclusion and Recommendation

Chapter Five

Conclusion and Recommendation

5.1 Introduction

This chapter aims to summarize the most important conclusions reached by working on this thesis. On the other hand, it also aims to summarize the most important recommendations that were concluded by working on this scientific thesis. This chapter provides a thesis summary and lists the findings of this research; some general conclusions are made to summarize the work. Potential additional areas of research that would complement this thesis are also included in this chapter.

5.2 Conclusion

The potential use of phase change materials (PCM) to store thermal heat in concrete is promising. Improved thermal storage of PCM concrete may lead to its widespread use in building and construction applications; but PCM concrete also has some undesirable properties such as low strength, uncertain long-term stability, and low fire resistance. However, these unwanted properties can be minimized if appropriate PCM types and means are used.

Thermal conductivity decreases as the percent of PCM from cement or aggregate replacement increases, in various PCM sizes. In general thermal conductivity when PCM modified concrete as a replacement to medium aggregate is more than as a replacement to cement. The lowest thermal conductivity value at 20% PCM as a replacement to medium aggregate. When the size of PCM particles increases the k-value decreases.

The specific heat increases as the percent of PCM from cement replacement increases, this the result for high latent heat of PCM, its need more energy to absorb and release heat. The specific heat increases proportionally as the size of PCM increases. The specific heat is highest at PCM 20% as a replacement to cement at size3. In general, specific heat at PCM modified concrete as a replacement to medium aggregate is more than as a replacement to cement.

Compressive strength decreases as the percent of PCM from cement replacement increases for all PCM sizes. Compressive strength decreases as the percent of PCM from aggregate replacement increases for various PCM sizes. Compressive strength decreases when the size of PCM particles increases. In general compressive strength when PCM modified concrete as a replacement to cement replacement is more than as a replacement to medium aggregate.

Hydration process of 10% PCM modified concrete as a replacement to cement is slower than control mix. The hydration process decreases when increase the PCM percentage, because the less cement quantity, also the latent heat of PCM is very high.

Compressive strength range acceptable in 5% PCM modified concrete as a replacement to cement with size1=2.14mm. Compressive strength range acceptable in 5% PCM modified concrete as a replacement to medium aggregate with size1=2.14mm. Compressive strength range acceptable in (10%.15%) PCM modified concrete as a replacement to medium aggregate with size1 and size2.

The water absorption decreases as the present of PCM from cement replacement increases. The water absorption decreases as the size of PCM particles increases respectively. The water absorption decreases proportionally as the amount of PCM increases. In general, water absorption at PCM modified concrete as a replacement to medium aggregate is more than as a replacement to cement.

The workability of mix decreases as the present of PCM from cement replacement increases because less cement to compound to each mixture. The workability of mixture decreases as the size of PCM particles increases respectively. In general, workability for PCM modified concrete as a replacement to medium aggregate is more than as a replacement to cement.

The density of PCM modified concrete decreases as the amount of PCM particles increases respectively. In general, density for PCM modified concrete as a replacement to cement is more than as a replacement to medium aggregate.

Adding sodium silicate by coating it on concrete leads to an increases in mechanical strength by 4 to 7%.

In physical modeling: the test room without PCM has a maximum temperature 2.5 °C higher than that with phase change material, and the temperature remain stable at 14 °C about 25 minute when using 20% PCM.

In general, the heat storage capacity of the PCM-concrete is significantly improved with the addition of the wasted phase change material.

5.2 Recommendation

Based on the conclusions drawn above and the laboratory observations, the following are recommended:

1. Since the addition of high ratio of phase change materials decreases compressive strength, it is recommended to use 5% PCM ratio size1.
2. It is recommended to further test the physical characteristics of concrete through shrinkage limit, permeability.
3. It is recommended to explore the influence of other raw materials on these mixtures and to study changes in physical properties.
4. This study did not include any test of the durability, soundness and permeability the long term of the concrete. The above mentioned tests of the concrete are important to evaluate the performance of the sludge mixed concrete in the long run which might be included in the scope of the future study.
5. It is recommended to study the possibility of using more than one additive together as substitutes for cement and its effect on the different properties of concrete.
6. It is recommended to use transient method to faster.
7. It is recommended to use advance thermal conductivity testing device.
8. It is recommended to study the Freeze thaw cycle of PCM.
9. For future research, it is recommended to study the 3D Particle process of phase change material.
10. It is recommended to use the Encapsulation PCM for future study.

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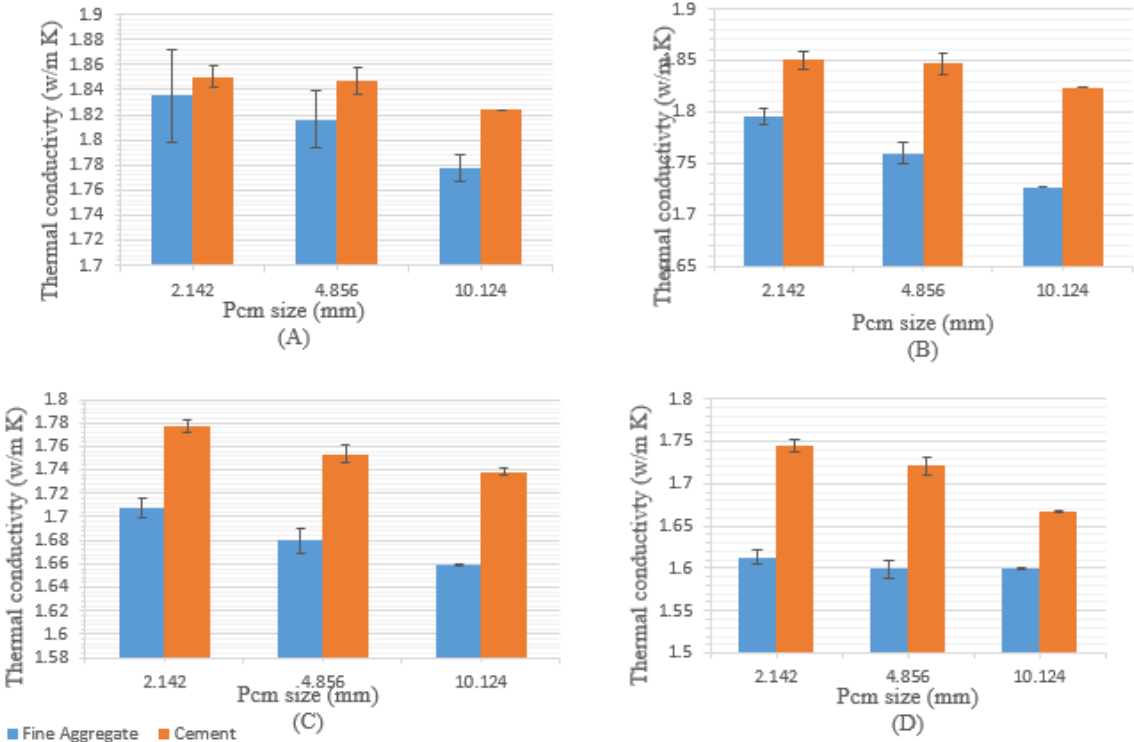
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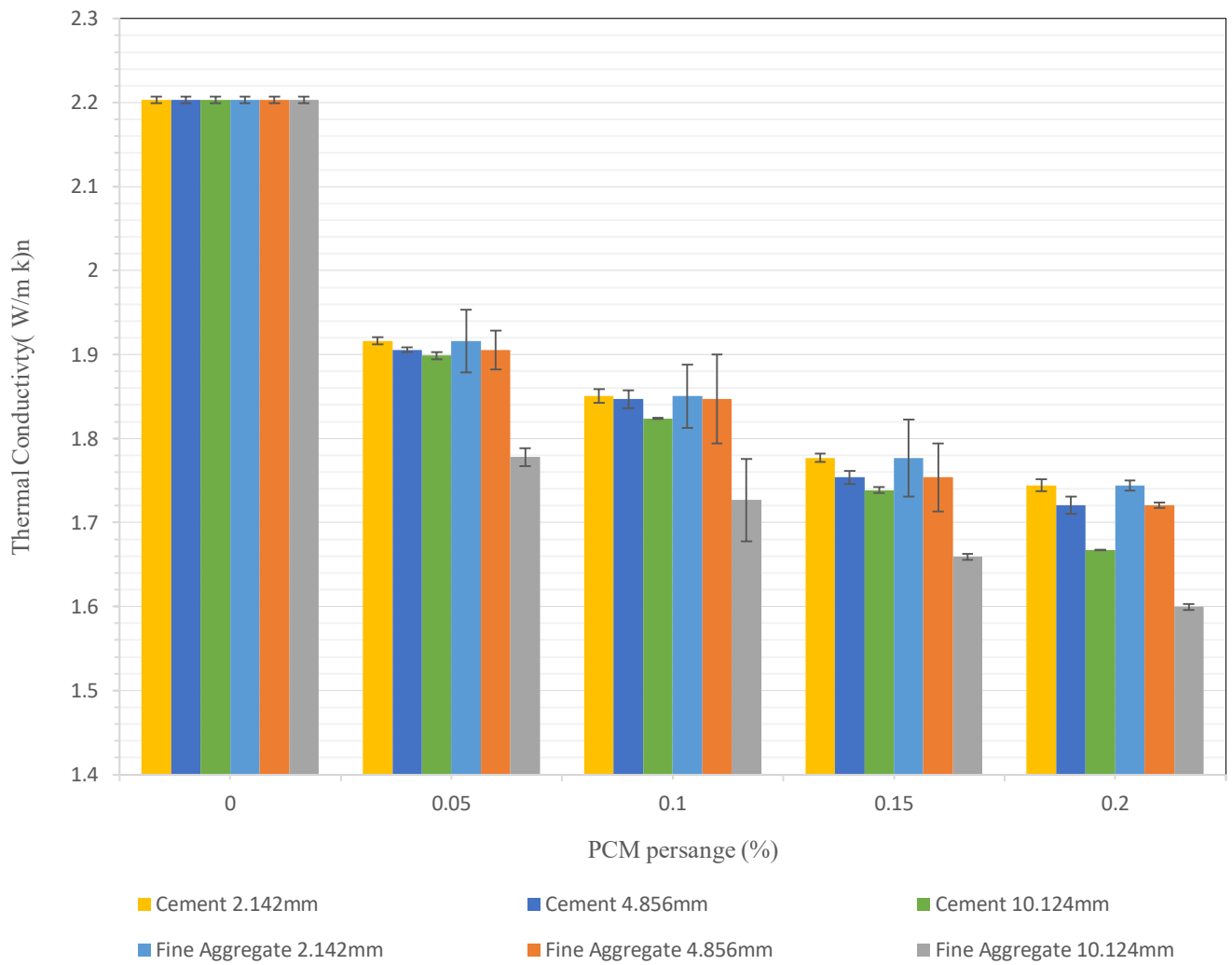
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Appendix A

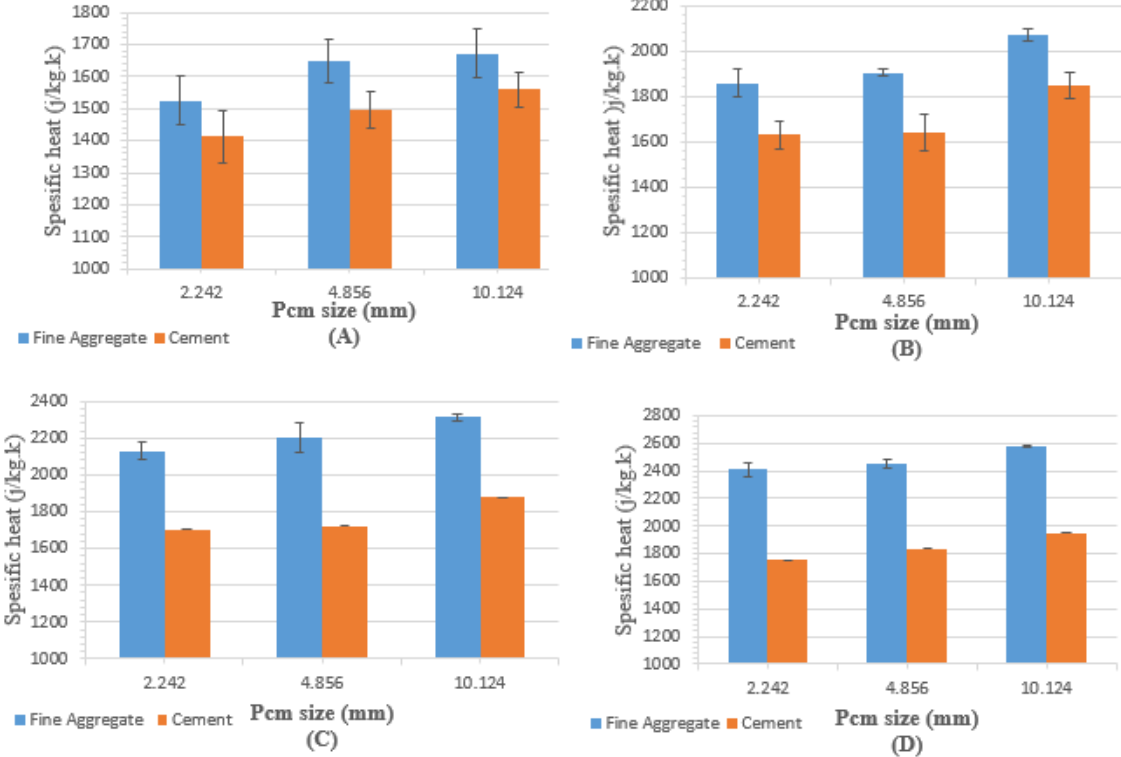
Appendix A.1. Thermal conductivity for three particle sizes for various phase change materials percentage: (A) Thermal conductivity for 5% PCM added by weight of cement and by weight of medium aggregate. (B) Thermal conductivity for 10% PCM added by weight of cement and by weight of medium aggregate. (C) Thermal conductivity for 15% PCM added by weight of cement and by weight of medium aggregate. (D) Thermal conductivity for 20% PCM added by weight of cement and by weight of medium aggregate.



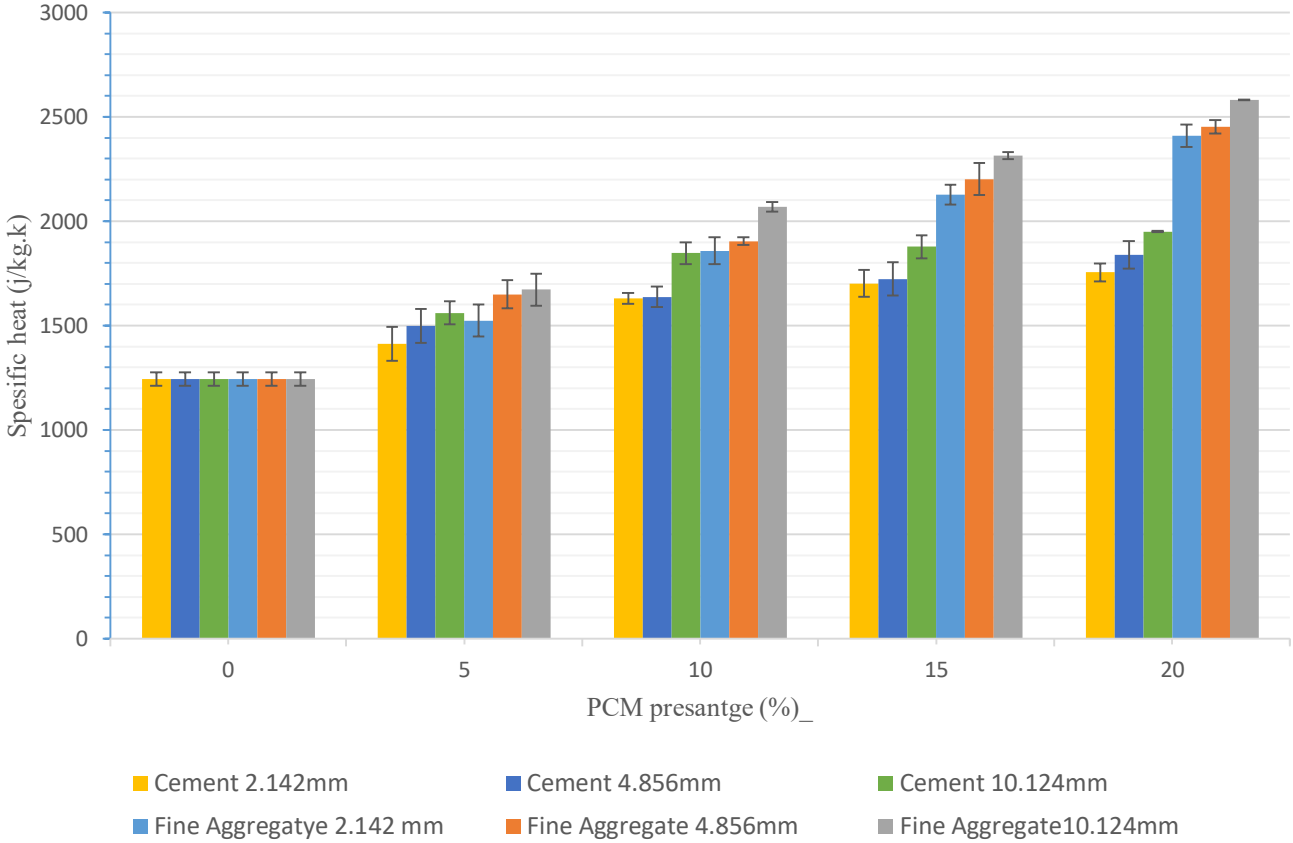
Appendix A.2: The comparison between thermal conductivity for three phase change material particle sizes for different percentage PCM added by weight of cement and by weight of medium aggregate in 28 days.



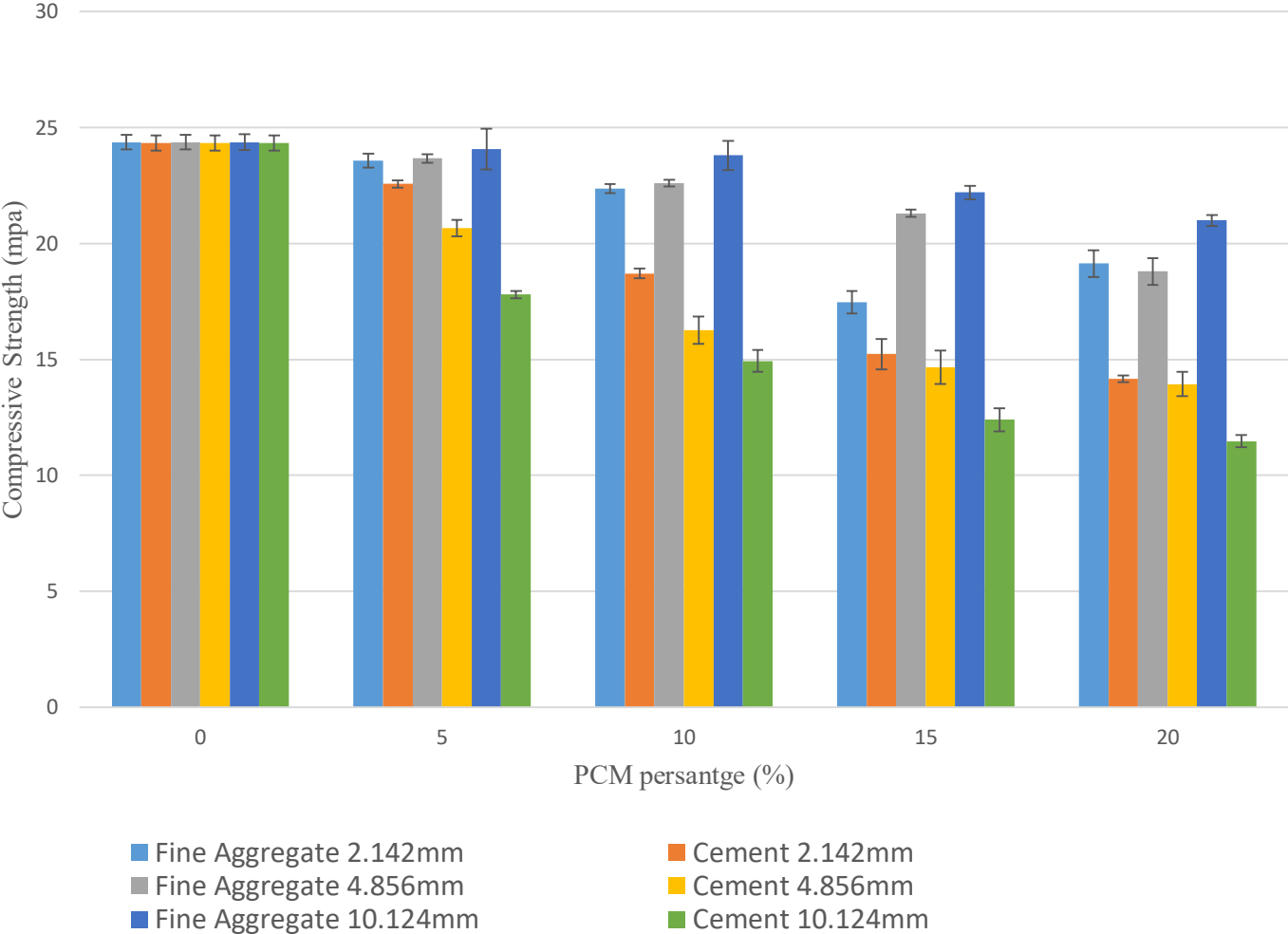
Appendix A.3 Heat capacity for three particle sizes for various phase change materials percentage: (A) heat capacity for 5% PCM added by weight of cement (B) heat capacity for 10% PCM added by weight of cement (C) heat capacity for 15% PCM added by weight of cement (D) heat capacity for 20% PCM added by weight of cement.



Appendix A.4: the comparison between heat capacity for three phase change material particle sizes for different percentage PCM added by weight of cement and by weight of medium aggregate in 28 days.



Appendix A.5: Compressive Strength for three phase change material particle size for different percentages of PCM added by weight of cement and by weight of medium aggregate in 28 days.



Appendix A.6: The density of PCM modified concrete cube, replacement by cement.mass1: before water absorption.mass2: after water absorption.

Density kg/m ³												
Mixture	Size1				Size 2				Size 3			
	Sample1	Sample2	Sample3	Avg	Sample1	Sample2	Sample3	Avg	Sample1	Sample2	Sample3	Avg
	kg/m ³				kg/m ³				kg/m ³			
B250 m1	2357	2341	2278	2325.33333	2357	2341	2278	2325.33333	2357	2341	2278	2325.33333
B250m2	2415	2390	2335	2380	2415	2390	2335	2380	2415	2390	2335	2380
PCM 5 m1	2250	2300	2260	2270	2250	2300	2260	2270	2260	2300	2260	2273.33333
PCM 5 m2	2300	2345	2305	2316.66667	2280	2333	2295	2302.66667	2270	2310	2280	2286.66667
PCM 10 m1	2255	2250	2278	2261	2250	2260	2265	2258.33333	2250	2260	2278	2262.66667
PCM 10m2	2300	2290	2310	2300	2280	2290	2298	2289.33333	2260	2272	2290	2274
PCM 15 m1	2245	2260	2230	2245	2245	2260	2230	2245	2250	2262	2232	2248
PCM 15m2	2280	2295	2268	2281	2270	2285	2255	2270	2260	2271	2249	2260
PCM 20m1	2250	2263	2246	2253	2250	2263	2245	2252.66667	2250	2263	2246	2253
PCM 20 m2	2287	2281	2274	2280.66667	2275	2275	2268	2272.66667	2260	2274	2256	2263.33333

Appendix A.7: The density of PCM modified concrete cube, replacement by cement.mass1: before water absorption.mass2: after water absorption.

Density kg/m ³												
Mixture	Size1				Size 2				Size 3			
	Sample1	Sample2	Sample3	Avg	Sample1	Sample2	Sample3	Avg	Sample1	Sample2	Sample3	Avg
	kg/m ³				kg/m ³				kg/m ³			
B250 mass1	2357	2341	2278	2325.33333	2357	2341	2278	2325.33333	2357	2341	2278	2325.33333
B250mass2	2415	2390	2335	2380	2415	2390	2335	2380	2415	2390	2335	2380
PCM 5 mass1	2250	2300	2260	2270	2250	2300	2260	2270	2260	2300	2260	2273.33333
PCM 5 mass2	2320	2330	2310	2320	2285	2355	2320	2320	2315	2350	2290	2318.33333
PCM 10 mass1	2255	2250	2278	2261	2250	2260	2265	2258.33333	2250	2260	2278	2262.66667
PCM 10mass2	2325	2290	2310	2308.33333	2285	2312	2315	2304	2310	2295	2315	2306.66667
PCM 15 mass1	2245	2260	2230	2245	2245	2260	2230	2245	2245	2260	2230	2245
PCM 15mass2	2295	2295	2280	2290	2275	2295	2285	2285	2275	2295	2285	2285
PCM 20mass1	2250	2263	2246	2253	2250	2263	2245	2252.66667	2250	2263	2245	2252.66667
PCM 20 mass2	2285	2287	2290	2287.33333	2287	2295	2285	2289	2287	2295	2285	2289

Appendix A.8: thermal conductivity of PCM concrete as a replacement to medium aggregate and as a replacement to cement in three different particles sizes

Size (mm)		PCM by weight of medium aggregate (%)					PCM by weight of cement (%)				
		0%	5%	10%	15%	20%	0%	5%	10%	15%	20%
2.14	k	2.2	1.84	1.79	1.7	1.61	2.2	1.91	1.85	1.77	1.74
	(%)	0	-16.3	-18.5	-22.7	-26.8	0	-13.1	-15.9	-16.5	-20.9
4.85	k	2.2	1.81	1.75	1.67	1.59	2.2	1.9	1.84	1.75	1.72
	(%)	0	-17.2	-20	-24	-27.7	0	-13.6	-16.3	-20.4	-21.8
10.12	k	2.2	1.77	1.72	1.65	1.59	2.2	1.89	1.82	1.73	1.66
	(%)	0	-19.5	-21	-25	-27.7	0	-13.6	-16.3	-20.4	-21.8

Table 4.2: Summary of the specific heat results as PCM added to concrete as a replacement to medium aggregate and as a replacement to cement in three different particles sizes.

Size (mm)		PCM by weight of medium aggregate (%)					PCM by weight of cement (%)				
		0%	5%	10%	15%	20%	0%	5%	10%	15%	20%
2.14	Cp	1242	1523	1858	2127	2410	1242	1411	1630	1702	1755
	(%)	0	18	33	41.6	48.4	0	11.9	23.8	27	29
4.85	Cp	1242	1649	1904	2202	2454	1242	1497	1637	1723	1839
	(%)	0	24	34	43	49.3	0	17	24	27.9	32.4
10.12	Cp	1242	1672	2069	2315	2580	1242	1561	1847	1877	1951
	(%)	0	25	39	46	51.8	0	20	32.7	33.8	36.4

Table 4.3: Summary of the compressive strength results as function of replacement percentage and particle size and the reduction value of thermal conductivity related to control.

Size (mm)		PCM by weight of medium aggregate (%)					PCM by weight of cement (%)				
		0%	5%	10%	15%	20%	0%	5%	10%	15%	20%
2.14	C.S	24.3	23.5	22.3	19.6	19.1	24.3	22.5	18.7	15.2	14.2
	(%)	0	-3.2	-8.2	-19.3	-21.3	0	-7.4	-23	-37.4	-41.9
4.85	C.S	24.3	23.6	22.6	21.3	18.8	24.3	20	16.2	14.6	13.9
	(%)	0	-2.8	-6.9	-12.3	-22.6	0	-17.6	-33	-39.9	42.7
10.1	C.S	24.3	24	23.8	22.2	21	24.3	17.8	14.9	12.4	11.4
	(%)	0	-1.2	-2	-8.6	-13.5	0	-26.7	-38	48.9	-53

Appendix B

Appendix B.1: Infrared thermometer and thermometer with couple used in thermal conductivity and heat capacity device.



Appendix B.2: Hot plate heater Source for thermal conductivity measurement device.



Appendix B.3: The Cube preparing for testing







Appendix B.4: Build up a tool for test thermal conductivity



