Canadian Journal of Civil Engineering

Thermal and Mechanical Properties of PCM-Incorporated Normal and Lightweight Concretes Containing Silica Fume

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2018-0334.R1
Manuscript Type:	Article
Date Submitted by the Author:	06-Nov-2018
Complete List of Authors:	Moshtaghi Jafarabad, Amin; Isfahan University of Technology, Department of Civil Engineering Madhkhani, Morteza; Isfahan University of Technology, Pourakbar Sharifi, Naser; Michigan Technological University, Department of Civil and Environmental Engineering
Keyword:	Struct.Eng. & Constr.Mate, struc - adv composite mat < Struct.Eng. & Constr.Mate, structure - concrete < Struct.Eng. & Constr.Mate, MP - concrete < Engineering Materials
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

Thermal and Mechanical Properties of PCM-Incorporated Normal and Lightweight Concretes Containing Silica Fume

Amin Moshtaghi Jafarabad¹, Morteza Madhkhan², Naser P. Sharifi^{3,*}

¹ a.moshtaghi@cv.iut.ac.ir, ² madhkhan@cc.iut.ac.ir, ³ npourakb@mtu.edu

^{1,2} Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran 83111

³ Department of Civil and Environmental Engineering, Michigan Technological University
1400 Townsend Dr, Houghton, MI, USA, 49931

Abstract

Improving the thermal performance of concrete, as an important construction and pavement material, by incorporating Phase Change Materials (PCMs) has been the topic of much research. Also, various carrier agents such as Lightweight Aggregate (LWA) have been introduced to incorporate PCMs into concrete. However, incorporation of PCM-impregnated LWA reduces the compressive strength of concrete. In this study, the application of silica fume to improve the compressive strength of PCM-incorporated concrete is investigated. Two types of PCMs, Salt Hydrate PCM and Polyethylene Glycol PCM, were incorporated into concrete via scoria LWA, and different physical and mechanical characteristics of the concrete were studied when silica fume was incorporated into the mix. The results show that incorporation of silica fume increases the compressive strength of PCM-incorporated concrete, and at the same time does not diminish the thermal performance of the incorporated PCM. Therefore, incorporation of silica fume was found to be a promising strategy to improve the compressive strength of PCM-incorporated concrete.

Keywords

Silica fume, Phase Change Materials, Scoria Lightweight Aggregate, Salt Hydrate PCM, Polyethylene Glycol PCM

1- Introduction

Concrete has been widely used as an important construction material in the world (Aitcin 2000), and thus, much research has been conducted to improve different properties of that (Madhkhan, Hamidi *et al.* 2011). In recent decades, many studies have investigated the strategies to better the thermal performance of concrete (Rao and Chandra 1970). In between the all, incorporating Phase Change Materials (PCMs) in concrete has attracted the attention of many researchers during the last two decades, both in the concrete (Sharifi and Mahboub 2018). PCMs are materials that have relatively high latent heat of fusion, which are able to undergo through several phase transition cycles without degradation in their latent heat of fusion (Sharma, Tyagi *et al.* 2009). When PCMs are used in buildings, they increase the occupant comfort, and reduce the required heating and cooling energy (Sharifi, Shaikh *et al.* 2016). Various PCMs with different melting points and different latent heats of fusion are industrially available (Zalba, Marín *et al.* 2003).

Regarding their origin and chemical structure, PCMs are divided into three main categories: organic, inorganic, and eutectic. Organic PCMs include two main groups: paraffin and non-paraffin PCMs. Paraffin waxes consist of a mixture of chains of n-alkanes; however, non-paraffin PCMs have highly varied properties (Sharma, Tyagi *et al.* 2009). Organic PCMs are mostly stable under normal conditions, predictable, chemically inert, and relatively cheap (Hale, Hoover *et al.* 1971).

Inorganic PCMs are divided in two main categories: salt hydrates and metallics. Salt hydrates have relatively high latent heat of fusion, and small volume changes on phase transition (Lane, Warner *et al.* 1978). Metallics have relatively high latent heat of fusion per unit volume, and low specific heat (Sharma, Tyagi *et al.* 2009). Finally, eutectic PCMs are a composition of two or

more different components. In these PCMs, each component melts and freezes congruently, and the PCM nearly always melts and freezes without segregation (George 1989).

In buildings, incorporating PCM in the concrete that is used in the structure's elements, improves the thermal performance of that, and decreases the energy consumption of the building (Zhou, Zhao *et al.* 2012). In concrete pavements, incorporation of PCMs enhances the thermal inertia and reduces the number of freeze/thaw cycles that the pavement experiences, and thus increases the service life of the pavement (Sakulich and Bentz 2011).

However, if PCM is directly added to a cementitious material such as concrete, it coats the cement particles and diminishes the hydration reactions between cement and water (Eddhahak, Drissi *et al.* 2014). This suppresses the production of the C-S-H phase that is the main strength-bearing phase in concrete, and thus decreases the compressive strength of that (Sharifi and Sakulich 2015). Therefore, various carriers such as Lightweight Aggregate (LWA) (Sakulich and Bentz 2012), rice husk ash (Sharifi, Jafferji *et al.* 2016), and high density polyethylene balls (Tyagi, Pandey *et al.* 2014), have been proposed to incorporate PCMs into cementitious materials (Sharifi, Sakulich *et al.* 2013). However, the compressive strength of concrete will be decreased when LWA presoaked in PCM is incorporated in that (Sakulich and Bentz 2012).

In this study, the application of silica fume to improve the compressive strength of PCM-incorporated concrete was evaluated. Silica fume has been widely used to increase the compressive strength of various types of concrete, such as lightweight concrete (Seabrook and Wilson 1988), fiber-reinforced concrete (Wu, Shi *et al.* 2016), ultra-high strength concrete (Kjellsen, Wallevik *et al.* 1999), and shotcrete (Choi, Yeon *et al.* 2016); however, the application of that in PCM-incorporated concrete was not studied before. Two types of PCMs, Salt Hydrate that is an inorganic PCM and Grade 600 Polyethylene Glycol that is an organic PCM, were

47 incorporated in the mix using scoria LWA. Various laboratory experiments such as Differential
48 Scanning Calorimetry, Fourier Transform Infrared Spectroscopy, semi-adiabatic calorimetry,
49 compressive strength, thermal conductivity, thermal performance, and water absorption tests
50 were conducted to better understand the effectiveness of silica fume incorporation on different
51 chemical, physical, and mechanical properties of PCM-incorporated concrete.

52

Draft

2- Materials and Methods

2-1- Materials

Ordinary portland cement (Type 1) manufactured in Isfahan Cement Company was used. Physical and chemical properties of the utilized cement are provided in Table 1.a and Table 1.b, respectively. Ordinary sand and gravel, with sieve size distribution in accordance with the ASTM C33 standard, and scoria Lightweight Aggregate (LWA) were used. Water absorption capacity of the scoria sand and scoria gravel were equal to 16.4 wt.% and 13.22 wt.%, respectively. Silica fume with accordance to ASTM C1240 and manufactured in Iran Ferroalloy Industries Company was used. Physical and chemical properties of the utilized silica fume are provided in Table 2.a and Table 2.b, respectively. Two types of Phase Change Materials (PCMs), Salt Hydrate PCM and Grade 600 Polyethylene Glycol PCM, were used (Figure 1). Properties of the PCMs are provided in Table 3.a and Table 3.b. Also, SPN215 superplasticizer, which is a chloride-free poly-naphthalene sulfonate based superplasticizer, was used in some mixes. This superplasticizer has a density of 1.18 gr/cm^3 at 20°C , and a freezing point of approximately -2°C .

2-2- Mix Proportioning

ACI 211.1-91 and ACI 211.2-98 standards were followed for the mix proportioning of ordinary and lightweight concrete, respectively. Lightweight concrete is referred to a concrete that contains LWA. The slump of the fresh concrete was considered to be between 75 mm to 100 mm, the water content was 226 kg/m^3 , the water to cement ratio was selected to be equal to 54 wt.%, and the air content of the mixes was about 2.9 vol.%. To have a quantitative study, three control mixes were prepared. Mix N contained cement, water, ordinary sand, and ordinary

gravel; Mix LWA(C) contained cement, water, ordinary sand, and scoria gravel; and Mix LWA(CF) contained cement, water, scoria sand, and scoria gravel, which means all the normal aggregate was replaced by scoria LWA. For the mixes that contain silica fume, 15 wt.% of cement was replaced by silica fume. In these mixes and in order to improve the workability of the mix, superplasticizer equal to 0.3 wt.% of concrete was added to the mixture.

Considering the molds' dimensions, the nominal maximum aggregate size was selected to be equal to 12 mm. By using the standard specifications and considering the nominal maximum aggregate size, the fineness modulus of sand, apparent specific gravity, and the gravel content were calculated. Also, the sand content was calculated using Equation 1:

$$FA = 10 \times G_{FA} \times (100 - A) - G_{FA} \times \left(\frac{CA}{G_{CA}} + \frac{C}{G_C} + W \right) \quad (1)$$

where FA is the weight of sand per unit volume in kg/m³, G_{FA} is the specific gravity of sand, A is the air content, CA is the weight of gravel per unit volume in kg/m³, G_{CA} is the specific gravity of gravel, C is the weight of cement per unit volume in kg/m³, G_C is the specific gravity of cement, and W is the weight of water per unit volume in kg/m³. The final mix proportioning was reached after a few times of try and error cycles. The details of the final mix proportioning are provided in Table 4.

To incorporate the PCMs in the mixes, LWA was presoaked in each PCM for 24 h prior to mixing. To have a quantitative study, two different amounts of PCMs were added to the LWA. In some of the mixes, weight of the added PCM was set to be equal to the LWA's total absorption capacity. In some other mixes, weight of the added PCM was equal to half of LWA's absorption capacity. In the latter mixes, the number "0.5" was added to the name of the mix. Also, the letters "H", "P", and "S" were added to the name of mixes that contained Salt Hydrate PCM, Polyethylene Glycol PCM, and silica fume, respectively. This means that the amount of

PCM added to Mix LWA(C)-P and LWA(C)-H was 47.11 kg/m³, and to Mix LWA(C)-0.5P and LWA(C)-0.5H was 23.52 kg/m³. Also, the added PCM to Mix LWA(CF)-P and LWA(CF)-H was 155 kg/m³, and to Mix LWA(CF)-0.5P and LWA(CF)-0.5H was 77.78 kg/m³. Mix N, Mix LWA(C), and Mix LWA(CF) were the control mixes, and thus no PCM was added to them. Finally, the amount of PCM added to Mix N-P and N-H was considered to be equal to the amount of PCM that was added to Mix LWA(C)-P and LWA(C)-H, to investigate the effect of direct incorporation of PCM on different properties of concrete. The same logic was followed for the mixes that contained silica fume.

106

2-3- Differential Scanning Calorimetry (DSC)

DSC test was conducted to calculate some of the thermal properties of the utilized PCMs. For that, the heat flow through PCM sample was compared to the heat flow through a reference. A heating/cooling cycle with the rate of 5°C/min and over a range of -5 °C to +50 °C was applied to each PCM sample, and the heat flow through the sample was measured. Using DSC results, it was possible to calculate PCMs' specific heat and latent heat of fusion when they undergo phase transition. The specific heat can be calculated by dividing the heat flow per unit mass of PCM in the steady state condition by the temperature changes rate. Also, in order to calculate PCMs' latent heat of fusion, the area below the heat flow peak should be divided by the temperature changes rate (Sharifi and Sakulich 2015):

$$L = \frac{\int_{T_s}^{T_e} q \cdot dT}{dT/dt} \quad (2)$$

where L is the latent heat of fusion per unit mass of PCM in J/g, q is the heat flow per unit mass of the PCM in W/g, T_s is the temperature that the phase change starts in °C, T_e is the temperature that the phase change ends in °C, and dT/dt is the rate of changing in temperature in °C/min.

2-4- Fourier Transform Infrared Spectroscopy (FTIR)

FTIR experiment was done on the mixes that contained scoria aggregate, Salt Hydrate PCM, Polyethylene Glycol PCM, and the mixture of these components to inquire if incorporating such materials changes the chemical composition of concrete. To prepare the liquid samples, a small drop of the liquid was placed on a KBr plate, and a second plate was placed on the top of that. The plates were gently pushed to each other to obtain an even film. Solid samples were prepared by grounding the sample to a very fine powder, and making a KBr pellet out of that. The sample were investigated in the range of wavenumber (λ) from 400 cm^{-1} to 4000 cm^{-1} , and the intervals was 2 cm^{-1} .

2-5- Semi-Adiabatic Calorimetry Test

Hydration reaction, which refers to a series of chemical reactions between cement and water, is an exothermic reaction (Kadri, Aggoun *et al.* 2010). This reaction produces calcium-silicate-hydrate phase, which is the strength-bearing phase, in concrete. If incorporation of additives in concrete interfere with this reaction, less reaction takes place, and therefore the reached peak temperature during hydration reaction will be reduced and retarded. Semi-adiabatic calorimetry test was conducted to examine the potential effects of PCM's incorporation on the hydration reaction. For this test, $100\text{ mm} \times 200\text{ mm}$ cylinders were filled with concrete, and the cylinders were placed in an insulated box. A thermocouple was placed in the cylinder's center and was

connected to a data logger. The data logger was connected to a computer, and the temperature was recorded every 10 min for three days (Figure 2).

2-6- Compressive Strength Test

Compressive strength test was conducted based on BS 1881-116:1983. The ingredients were mixed together in an electric mixer. Then 70 mm cube steel molds were used to prepare the samples. In order to cure the samples, they were placed in a fog room with an almost constant humidity and temperature. Samples were tested at ages of 7, 28 and 90 days. The loading rate was selected to be 12 MPa/min, and three specimens were tested for each mix.

2-7- Thermal Conductivity Test

Thermal conductivity test was conducted on samples using KD2 Pro apparatus to evaluate the effect of PCM incorporation on the thermal conductivity of concrete (Figure 3). The thermal sensor of the apparatus was a TR-1 sensor, and had a length of 100 mm and diameter of 2.4 mm, which matches with the ASTM 5334 standard. Based on the experiment specifications, the thickness of concrete all around the sensor should be at least 15 mm. Therefore, 75 mm × 150 mm cylindrical samples were prepared for this test, and the sensor was placed in a 75 mm × 150 mm hole in the center of the cylinder. To better the contact between the sensor and the surface of concrete, a thermal grease was used as the interface.

For each mix, the test was conducted on three samples at the age of 28 days. The operational range of the apparatus to measure the thermal conductivity was 0.1 W/m·K to 4 W/m·K. Thermal conductivity of the samples was measured by the apparatus by applying a specific

temperature profile to the samples, and analyzing the recorded temperature by the sensor over the course of the experiment. The test duration of this experiment for each sample was 10 min. To calibrate the apparatus, a standard specimen with known thermal conductivity was used. Also, to minimize the errors, the samples, the standard specimen, and the apparatus were kept in room temperature for 15 min prior to the experiment to reach thermal equilibrium.

2-8- Thermal Performance Test

A homemade laboratory apparatus was used to examine the efficiency of PCM incorporation to improve the thermal performance of concrete, (Figure 4). The setup contained a 500 mm cube wooden box, a 500-watt light bulb as heat source, a cold plate, a set of thermocouples, and a data logger connected to a computer. A cylindrical aluminum foil was placed around the light bulb to provide a uniform and steady temperature field (Xu and Li 2013) (This cylindrical foil is not shown in Figure 4.b). To insulate the apparatus, the outer sides of the box and the aluminum foil were covered by a 15 mm thick polystyrene layer, and the inner side of the box was covered by a Foamular® 250 Rigid Foam Insulation with the R-value of 10. There was a rectangular opening on the upper face of the box to insert the 160 mm × 120 mm × 40 mm sample in place. One thermocouple was attached to the upper side of the sample to record the input temperature, and a thermocouple was attached to the lower side of the sample to record the output temperature.

The cycle of applied temperature profile had three phases. First, the cold plate was put on the upper face of the sample to bring the temperature of that to 6 °C. Then the light bulb was turned on for 15 min to bring the surface temperature to a high enough temperature to assure that the entire specimen reaches to a temperature above the melting temperature of the utilized PCMs

(about 80 °C). Finally, the light bulb was kept off for one hour to bring the surface temperature to the room temperature (Figure 5).

2-9- Water Absorption Determination

Water absorption is the action of water movement in the concrete pores because of the capillary action. This is an important physical properties of concrete since it plays a major role in the duration of concrete. Especially in aggressive environments, concrete with high water absorption capacity will be attacked by aggressive agents when they are carried to the concrete's pores via water (Maslehuddin, Al-Amoudi *et al.* 1994). Therefore, the effect of PCM incorporation on the water absorption of concrete was evaluated.

BS 1881-122:2011 and ASTM C642-97 standards were followed to calculate the short-term and the final water absorption of the samples, respectively. The water absorption can be calculated by Equation 3:

$$A = \frac{B - C}{C} \times 100 \quad (3)$$

where A is the water absorption percentage, B is the mass of the sample after being submerged in water and with dried surface in g, and C is the mass of oven-dried sample in g. For the short-term water absorption, the sample was submerged in water for 30 min. The test was conducted on three specimens of each mix at age 28 days.

3- Results and Discussion

3-1- Differential Scanning Calorimetry (DSC)

By increasing the temperature above the melting point, the PCM absorbs the heat and turns to liquid state. Similarly, by decreasing the temperature below the solidifying temperature, the PCM releases the heat that was absorbed in the previous step and turns to solid state. Both of these phenomenon cause an increase in the absolute heat flow (Figure 6.a). These results show that considering the rate of heating and cooling, melting and solidifying of PCMs take place over a specific period of time, and the phase of the entire volume of PCM will not be changed simultaneously.

For the case of Salt Hydrate and during melting, changing in phase starts when the temperature approaches 20 °C. However, to melt the entire PCM volume, the temperature was raised to 41 °C (Figure 6.b). Unlike melting, solidifying of the PCM took place over a short temperature range. Solidifying started with a high peak at 16.8 °C and ended at 10 °C. For the case of Polyethylene Glycol, melting started at 8.5 °C and ended at 24.9 °C, and solidifying started at 16.7 °C and ended at 6.2 °C. Also, during solidifying, there was a drop in the heat flow at 11.3 °C. The mechanism and required energy for molecules' rearranging during solidifying will be different than melting, and therefore these two phenomena started at different temperatures, and took place over at different temperature intervals. Also, the difference between the peak temperature of melting and the temperature that the solidifying started was more for Salt Hydrate PCM than for Polyethylene Glycol PCM. This is because Salt Hydrates normally have to be cooled down well below their melting point before they start to solidify (sub-cooling) (Günther, Mehling *et al.* 2007).

The heat fellow per unit mass of the two PCMs when the temperature was not close to the melting point, i.e. the steady state condition, during heating and cooling was almost the same. This shows that the specific heat of the PCMs in the solid state was the same as their specific heat in liquid state. For each of the PCMs, although melting and solidifying started and ended at different temperatures, and took place over a different temperature range, the area below the melting and solidifying peaks were almost same. This shows that the total amount of the heat energy that was stored in each PCM during melting, was released during solidifying. Using the explanations in Section 2-3 and Equation 2, specific heat and latent heat of fusion of the PCMs were calculated (Table 5). It should be mentioned that the heating/cooling cycle was applied to the PCMs for ten times, and the same results were reached for all the cycles. This shows that the properties of the PCMs will not be deteriorate after experiencing multiple melting and solidifying cycles.

3-2- Fourier Transform Infrared Spectroscopy (FTIR)

Using the results of FTIR, it was possible to recognize the important chemical bonds in the materials (Figure 7.a). For scoria LWA, the weak peak at 449 cm^{-1} indicates stretching vibration of Si-O-Al bond, the broad peak at 1037 cm^{-1} indicates stretching bond of Si-O-Si, the peak at 1641 cm^{-1} likely to indicate bending vibration of H-O-H, and the peak at 3442 cm^{-1} presents the stretching vibration of H-O (Seyfi, Azadmehr *et al.* 2015). For Polyethylene Glycol, the weak peak at 1062 cm^{-1} presents stretching vibration of C-O-C bond, the hump at 1251 cm^{-1} presents stretching vibration of C-O bond, the hump at 1352 cm^{-1} likely to indicate bending vibration of C-H, the broad peak at 2868 cm^{-1} indicates stretching vibration of C-H, and the broad peak at 3452 cm^{-1} presents the stretching vibration of O-H bond (Shameli, Bin Ahmad *et al.* 2012).

A summary of the results for scoria LWA, Polyethylene Glycol PCM, and the mixture of these two components are presented in Table 6. Comparing the results shows that the FTIR spectrum of the LWA and PCM composite includes all the characteristic bands of each of the two components. For example, mixture of the components has a hump at 2873 cm^{-1} representing C-H, and a hump at 1645 cm^{-1} representing H-O-H; which match with the hump at 2868 cm^{-1} of Polyethylene Glycol and the hump at 1641 cm^{-1} of scoria LWA, respectively. This means that after mixing with the LWA, the PCM has kept its original chemical structures, and therefore, it is expected that the thermal properties of the PCM is not deteriorated after mixing with aggregate. However, some of the characteristic bands has slightly shifted. This is attributed to the physical interaction between the components. However, the PCM that leaks out of the LWA could chemically react with other present components in the media, which could possibly lead new products with new characteristic bands (Karaman, Karaipekli *et al.* 2011). Same conclusion can be reached for the case that Salt Hydrate PCM was mixed with scoria LWA (Figure 7.b). After mixing the PCM and the aggregate, the mixture contained the main humps and peaks that were present in each of the components. On the other hand, no new hump or peak was generated for the mixture of the components. This shows that no new chemical composition was produced by mixing the aggregate and the PCM. The results of the FTIR suggests that scoria LWA is compatible with both of the PCMs, and mixing PCMs with scoria LWA does not affect the physical and chemical properties of them. Therefore, scoria aggregate can be used as carrier agent for the PCMs for mixing in concrete.

3-3- Semi-Adiabatic Calorimetry Test

270 Semi-adiabatic calorimetry test was conducted on the samples to examine the effect of
271 incorporation of PCM on the hydration reaction. For the normal concrete, Mix N, the mortar
272 reached to 41 °C after 10 h 30 min. However, when coarse LWA presoaked in Polyethylene
273 Glycol PCM was used in the mix, Mix LWA(C)-P, the temperature peak was delayed and
274 suppressed by 25% and 8%, respectively (Figure 8.a). This suppression and retardation in the
275 hydration reaction is because PCM the interference with the chemical reactions during the
276 hydration of cement. The long-chain molecules of Polyethylene Glycol wrap around the cement
277 particles and makes it harder for the particles to react with the mixing water (Bentz, Snyder *et al.*
278 2008).

279 For the case that half of the LWA's capacity was filled with the PCM, Mix LWA(C)-0.5P, the
280 drop and delay in the peak temperature were 3% and 6%, respectively. This is because less PCM
281 was available to inter the bulk cement paste and interfere with the reaction. Water absorption
282 capacity of the scoria sand and scoria gravel were equal to 16.4 wt.% and 13.22 wt.%,
283 respectively. For the cases that coarse and fine LWA were used, Mixes LWA(CF)-0.5P and
284 LWA(CF)-P, the drop and delay were higher. This is because the finer aggregate has a higher
285 specific area, and therefore, more PCM adheres to the surface of LWA and interferes with the
286 chemical reaction (Sharifi and Sakulich 2015).

287 The effect of Salt Hydrate PCM on the hydration reaction was different than the effect of
288 Polyethylene Glycol PCM (Figure 8.b). For the case that coarse LWA was presoaked in Salt
289 Hydrate, Mix LWA(C)-H, the peak temperature was delayed by 10%, however, there was a
290 small drop in that. This is attributed to the difference between the molecular structures of the two
291 PCMs. Polyethylene Glycol PCM is an organic material and contains long chain of C-H

molecules; whereas Salt Hydrate PCM is an inorganic material and contains molecules of water in its molecular structure.

Salt hydrate interferes with the hydration reaction and delays that for the first hours after mixing, but when the water content in the mix is consumed by the hydration reaction and because of the osmotic pressure, the water molecules in the Salt Hydrate structure leak to the bulk cement paste. This provides an extra source of water for the reaction and increases the degree of cement hydration. Therefore, the peak temperature does not drastically drop. The results of a research show that when Sodium Thiosulfate Pentahydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$) PCM was used in concrete, it had a good chemical compatibility with concrete, and improved the heat capacity of that (Hadjieva, Stoykov *et al.* 2000).

The same result was reached for the case that half of the coarse LWA's capacity was filled with PCM, Mix LWA(C)-0.5H. For the cases that coarse and fine LWA were used, Mix LWA(CF)-H and Mix LWA(CF)-0.5H, the delay was increased to about 25%. This is because finer aggregate has higher specific area per unit mass, and thus more PCM sticks to the surface of LWA particles. This introduces more PCM to the cement paste. However, because of the aforementioned reason, the drop in the peak temperature was much smaller than the case that Polyethylene Glycol PCM was used.

Semi-adiabatic calorimetry test was conducted also on the samples that contained silica fume to evaluate the effect of incorporation of this material on the hydration reaction of cement. Compared to the control mix, Mix N, in the mix that contained silica fume, Mix N S, the peak temperature was increased by about 5%, and the time to reach the peak temperature was decreased by about 4% (Figure 8.c). This shows that more reaction has taken place in a shorter time. Compared to cement, silica fume has finer particles. Thus, it has a higher specific surface

area which makes it more reactive compared to cement (Sharifi and Mahboub 2018). Based on the results presented in a study, when utilized in a cementitious media, silica fume undergoes rapid dissolution in the calcium hydroxide solution, and increases the rate and the amount of released heat. Also, the finer particles of silica fume provide nucleation sites for deposition of alumina silica hydrates, and accelerate the hydration reaction (Sharma, Tyagi *et al.* 2009).

Using silica fume in the mixes that contained Polyethylene Glycol PCM, Mix LWA(C) S-P and Mix LWA(CF) S-P, shows that incorporation of this material increases the peak temperature, and accelerates the time to reach to this point. Based on a research, within minutes after mixing, silica fume provides nucleation sites for $\text{Ca}(\text{OH})_2$ that exist in the media, and accelerates the hydration reaction of cement (Cheng-Yi and Feldman 1985). Comparing the graphs of Figure 8.a and Figure 8.c suggests that PCM molecules attach to the surface silica fume's particles and relatively suppress their reactivity; however, the released heat is still higher compared to the mixes that silica fume is not incorporated.

Similar results can be obtained for the mixes that Slat Hydrate PCM and silica fume were incorporated in the media, Mix LWA(C) S-H and LWA(CF) S-H (Figure 8.d). Silica fume increased the peak temperature, 3% to 5%, and slightly accelerated the hydration reaction. This suggests that the presence of silica fume to some degree compensated the effect that the PCMs have on the hydration reaction. These results match with the results presented in other studies that indicate silica fume enhances and accelerates the hydration reaction of cement, especially when enough water is present in the media (Sharifi and Sakulich 2015).

3-4- Compressive Strength Test

In order to examine the effect of PCM incorporation on the strength of concrete, this test was done on the specimens that PCM and/or LWA were incorporated in them, and the results were compared to the control samples, N, LWA(C), and LWA (CF) (Figure 9). For the case that scoria gravel was used in the mix, LWA(C), the compressive strength was less than the case where ordinary aggregate was used, Mix N, by 20%. This is because LWA has a porous structure and is physically weaker than sand. Using further LWA in the mix, LWA(CF), caused further decrease in the compressive strength.

The compressive strength was reduced by about 15% when Polyethylene Glycol PCM was directly incorporated to the media, Mix N-P, (Figure 9.a). This reduction in strength is because the PCM as a chemical component interferes with the hydration reaction, and suppresses the creation of load bearing phase of C-S-H in concrete.

The compressive strength of concrete will be decreased when LWA that was presoaked in PCM was incorporated in that. This is because on one hand, LWA is mechanically weaker than sand, and on the other hand, the existence of PCM diminishes the formation of C-S-H phase. Also, PCM covers the surface of aggregate particles, which reduces the roughness of the particles (Sakulich and Bentz 2012). Finally, for the cases that half of LWA's capacity was filled with PCM, LWA(C)-0.5P and LWA(CF)-0.5P, drop in the compressive strength was less than the cases that the entire LWA's capacity was filled with PCM, LWA(C)-P and LWA(CF)-P, respectively (Figure 9.a). Because less PCM was available to interfere with the hydration reaction.

Roughly the same results can be obtained for the cases that Salt Hydrate PCM was incorporated in concrete (Figure 9.b). Comparing the results of Figure 9.a and Figure 9.b shows that the drop in the compressive strength in the case of Polyethylene Glycol is higher than the case of Salt

Hydrate. This is attributed to the difference between chemical compositions of the PCMs (Wang, Yang *et al.* 2009). The molecular structure of Polyethylene Glycol contains long chains of C-H, whereas Salt Hydrate is an inorganic material with molecules of water in its structure. Therefore, and as it was explained in the previous section, the hydration reaction of cement and the formation of the load bearing phase of C-S-H is less affected by Salt Hydrate than by Polyethylene Glycol.

This test was conducted also on the mixes that contained silica fume. As expected, the compressive strength was considerably increased when silica fume was added to the control mix, Mix N S. The silica content of silica fume is high, and the reaction between silica and calcium hydroxide during the hydration reaction forms more C-S-H, the load bearing phase in the cement bulk, which results a stronger structure (Sharifi, Sakulich *et al.* 2013). Also, based on the results of a study, the incorporation of silica fume forms a calcium poor silica rich phase that can serve as a substrate for formation of C-S-H gel (Gonen and Yazicioglu 2007). Therefore, the compressive strength of Mix N S was higher than Mix N, by about 20% (Figure 9.c).

Also, for the mixes that contain silica fume and Polyethylene Glycol, the compressive strength was improved. For example, comparing the results of Mix N S-P and Mix N-P shows that the compressive strength was increased by about 25%. The same improvement in compressive strength was observed for the mixes that contained LWA. For these mixes, LWA(C) S-P, LWA(CF) S-P, etc. there was an increase of 20% to 45% in compressive strength compared to their corresponding control samples, Mix LWA(C)-P, LWA(CF)-P, etc. Figure 9.a and Figure 9.c. Also, even in the presence of silica fume, the incorporation of higher percentages of PCM as well as finer LWA resulted a lower compressive strength, as explained earlier.

Roughly the same results were reached for the mixes that contained silica fume and Salt Hydrate PCM (Figure 9.d). As two examples, the compressive strength of Mix N S-H was 32% higher than Mix N-H, and Mix LWA(C) S-H was 18% higher than Mix(C)-H. This shows that in the presence of PCM, silica fume can improve the compressive strength and compensate the negative effect incorporation of this material on the compressive strength (The compressive strength of Mix S-P and Mix S-H was almost equal to Mix N).

Based on the ASTM specifications for structural lightweight concrete, ASTM C330/C330M-14, the minimum acceptable compressive strength for a lightweight concrete that contains only LWA and has a density of 1600 kg/m^3 is 17 MPa. Also, for a lightweight concrete that contains a mixture of normal-weight aggregate and LWA and has a density of 1800 kg/m^3 , the minimum acceptable compressive strength is 24.5 MPa.

In the mixes that both the fine and coarse LWA were used in the concrete, and no silica fume was incorporated, the compressive strength dropped below the specified requirement. However, when only coarse LWA was used and silica fume was incorporated in the mix, and for both of the PCMs, Mix LWA(C) S-P and LWA(C) S-H, the compressive strength was well above the minimum requirements. This suggests that the incorporation of silica fume is a promising way to improve the compressive strength of concretes that contain PCMs. In other words, silica fume can be used to amend the effects of PCMs on the compressive strength. It should be mentioned that when no silica fume is used in the mix, the concrete may be used only in non-structural elements such as non-loadbearing walls in buildings.

3-5- Thermal Conductivity Test

404 Thermal conductivity of the samples that contained LWA and/or PCM were compared with the
405 control samples to evaluate the effect of incorporation of these materials on the thermal
406 conductivity of concrete. For normal concrete, Mix N, thermal conductivity was measured to be
407 equal to $1.8 \text{ W/m}\cdot\text{K}$ (Figure 10.a). When coarse LWA was added to the mix, Mix LWA(C),
408 thermal conductivity was decreased to $1.24 \text{ W/m}\cdot\text{K}$ (31% reduction), and when coarse and fine
409 LWA was added, Mix LWA(CF), thermal conductivity was decreased to $0.79 \text{ W/m}\cdot\text{K}$ (56%
410 reduction).

411 The density of Mix N, Mix LWA(C), and LWA(CF) were equal to 2231 kg/m^3 , 1804 kg/m^3 , and
412 1524 kg/m^3 , respectively. LWA has a porous structure and is less dense than ordinary sand and
413 thus, using higher amount of LWA leads to a more porous concrete. The hydration consumes the
414 water in the mix; therefore, the pores will be filled with air, which has a low thermal
415 conductivity. On the other hand, LWA has an amorphous structure that has a smaller thermal
416 conductivity compared to sand with a more crystalline structure. Therefore, concrete with LWA
417 has a lower thermal conductivity compared to normal concrete (Demirboğa 2007). It should be
418 mentioned that based on EN 1745-2002 standard, for lightweight concrete with density in the
419 range of 800 kg/m^3 to 1600 kg/m^3 , the acceptable range for thermal conductivity is $0.35 \text{ W/m}\cdot\text{K}$
420 to $0.85 \text{ W/m}\cdot\text{K}$.

421 When Polyethylene Glycol PCM was directly added to concrete, Mix N-P, thermal conductivity
422 was slightly increased (Figure 10.a). However, the difference is low enough to say that the
423 graphs are identical. But when PCM was added to concrete by coarse LWA, Mix LWA(C)-P and
424 LWA (C)-0.5P, thermal conductivity was much smaller than normal concrete, and was slightly
425 higher than Mix LWA(C). This shows that even when LWA is presoaked in PCM, thermal
426 conductivity of the concrete would be less than the case that LWA is not used in the concrete.

This is because although a portion of the concrete's pores are filled with PCM, a portion of them stay unfilled, and therefore the thermal conductivity of concrete drops.

For the cases that both coarse and fine LWA were presoaked in PCM and added to concrete, Mix LWA(CF)-P and LWA(CF)-0.5P, the thermal conductivity was even less. Using more LWA introduces more porosity to the concrete's structure. Also, thermal conductivity of LWA is less than normal sand. The results also show that thermal conductivity of Mix LWA(CF)-P is slightly higher than LWA(CF)-0.5P. This is because in the latter, less PCM is used and more pores stay empty (Figure 10.a).

Roughly the same results can be reached for the case that Salt Hydrate PCM was added to concrete (Figure 10.b). Thermal conductivity of Salt Hydrate is about $0.15 \text{ W/m}\cdot\text{K}$ to $0.20 \text{ W/m}\cdot\text{K}$ (Lele, Korhammer *et al.* 2013), whereas the thermal conductivity of Polyethylene Glycol and is in the range of $0.2 \text{ W/m}\cdot\text{K}$ to $0.5 \text{ W/m}\cdot\text{K}$ (DiGuilio and Teja 1990). Therefore, thermal conductivity of the concrete that contained Salt Hydrate was less than the concrete that contained Polyethylene Glycol. For the cases that only coarse LWA was used, Mix LWA(C)-H, the thermal conductivity was dropped to $1.25 \text{ W/m}\cdot\text{K}$ (34% reduction), and for the cases that both coarse and fine LWA was used, Mix LWA(CF)-H, the thermal conductivity was dropped to $0.89 \text{ W/m}\cdot\text{K}$ (51% reduction). Similar to Polyethylene Glycol, incorporating less Salt Hydrate PCM in the mix, Mix LWA(C)-0.5H and Mix LWA(CF)-0.5H, slightly decreases the thermal conductivity of concrete (Figure 10.b).

The results of the thermal conductivity test on the mixes that contained silica fume are shown in Figure 10.c and Figure 10.d. Comparing the results of these mixes with their corresponding control mixes show that the thermal conductivity of them was slightly decreased as silica fume was added to the media. For example, the thermal conductivity of Mix N S is about 8% less than

Mix N, and the thermal conductivities of Mix LWA(C) S-P and Mix LWA(C) S-H are about 6% and 8% less than Mix LWA(C)-P and Mix LWA(C)-H, respectively (Figure 10). Silica fume has a lower density compared to cement, thus, when a portion of cement is replaced by silica fume, the density of the mix decreases. The results of different studies show that decrease in the density reduces the thermal conductivity (Blanco, García *et al.* 2000, Ramezani pour, Zolfagharnasab *et al.* 2018). Therefore, the thermal conductivity of concrete decreases when silica fume is incorporated in that.

3-6- Thermal Performance Test

Thermal performance test was conducted on the samples to examine the effect of PCM incorporation on enhancing the thermal performance of concrete. The goal was to examine the effectiveness of PCM to reduce and delay reaching to peak temperature in concrete samples when they were subjected to input temperature profile (Figure 5). The control sample, Mix N, reached its peak temperature, 31.5 °C, after 30 min (Figure 11.a). After 15 min from the start point of test, the heat source was turned off and therefore, the temperature started to drop. For Mix N-P and Mix N-H, no LWA was used and PCM was directly added to concrete. PCM molecules were mixed with the other chemicals in the media and thus they were not able to keep their molecular structure and actively carry out their thermal performance. Therefore, PCMs were not able to improve the thermal performance of concrete (Figure 11.a).

For Mix LWA(C) and LWA(CF), no PCM was used, but since their thermal conductivity was less than the control sample, Mix N, reaching to peak temperature was delayed in them. However, the discrepancy between the reached peak temperatures in these mixes was not

sufficiently large to make a specific conclusion. Also, the reduction in temperature in these mixes over the cooling period took place with a lower rate, which is attributed to their lower thermal conductivity. (Figure 11.a).

Mix LWA(C)-H reached its peak temperature, 29.2 °C, after 39 min, which means 8% reduction and 30% delay (Figure 11.b). This shows that when Salt Hydrate PCM was presoaked in coarse scoria LWA, it was able to effectively go through the phase transition, and carry out its thermal performance. For the case that both coarse and fine LWA was used, Mix LWA(CF)-H, the delay and reduction in peak temperature were 38% and 8%, respectively. This suggests that using more LWA improves the performance of PCM and increases the delay of reaching to peak temperature, however, the sample remained warm for a long enough time to melt all the PCM, and thus, there was not an extra reduction in the peak temperature.

Same results can be reached for mixes that contained Polyethylene Glycol PCM. For these mixes, Mix LWA(C)-P and LWA(CF)-P, the peak temperature was reduced by 8%, and was delayed by 34% and 43%, respectively (Figure 11.b). These results show that the performance of Polyethylene Glycol PCM was slightly better than Salt Hydrate PCM. The latent heat of fusion of Polyethylene Glycol PCM enhances the thermal inertia of the media and thus improves the thermal performance of that. Based on the results of a study, incorporating Polyethylene Glycol PCM with the melting temperature of 23 °C in wallboards can keep the inside temperature of the building 9 °C warmer during winter time (Lee 2014). Also, incorporating more LWA improves the performance of the presoaked PCM. For all of these three samples, the rate of cooling was slower compared to the control sample. This is because the samples had smaller thermal conductivity, and also during cooling, PCMs released the absorbed heat and kept the concrete warmer.

The results of the thermal performance test for the mixes that contained silica fume is presented in Figure 11.c and Figure 11.d. The results suggest that incorporation of silica fume in the media does not have a considerable effect on the thermal performance of the mix. For example, the peak temperature of Mix LWA(C) S-P and LWA(CF) S-P were about 2% and 3% less than the peak temperature of Mix LWA(C)-P and LWA(CF)-P, respectively. For the case of Salt Hydrate PCM, this difference was even smaller, Mix LWA(C) S-H and LWA(CF) S-H. The results show that the incorporation of silica fume did not diminish the thermal properties of the PCMs, and the PCMs maintained their thermal performance during heating and cooling.

Considering the results of sections 3-4, 3-5, and 3-6, it can be concluded that compressive strength of concrete decreases when PCM-impregnated LWA is incorporated in that; however, the thermal performance of that improves. The results also show that adding silica fume improves the compressive strength of PCM-incorporated concrete, and at the same time, does not diminish the thermal performance of that. The mixes that contain silica fume and only coarse LWA was used as the PCM carrier, Mix LWA(C) S-P and LWA(C) S-H, had the optimum mix design. In these mixes, the compressive strength of concrete was high enough to be used for both structural and non-structural application, and the thermal performance of them was considerably improved. Therefore, incorporation of silica fume can be considered as promising strategy to improve the compressive strength of PCM-incorporated concrete.

3-7- Water Absorption Test

Water absorption was the last test that was conducted in order to examine the potential effect of adding LWA and PCM on the short-term and final water absorption capacity of concrete. For Mix N, these values were 2.52% and 4.72%, respectively (Figure 12.a). This shows that because

of its porous structure, concrete absorbs more water when it is submerged in water for a longer period of time. When Polyethylene Glycol PCM was directly added to concrete, Mix N-P, the water absorption was almost the same as the control mix. However, when coarse LWA was added, Mix LWA(C), the short-term and final absorption were increased to 4.61% and 7.8%, which is 45% and 64% increase, respectively. This is because LWA has a porous structure and these interconnected pores not only provide more space available for water, but also make the water movement through the concrete's structure easier. For the case that coarse and fine LWA were incorporated, Mix LWA(CF), more pores were introduced to concrete's structure, and thus the short-term and final setting time were increased to 6.2% and 10.2%, respectively (Figure 12.a). The results of another study shows that the water absorption of concrete that contains LWA is about 10% (Praisler and Frangu 2012). It should be mentioned that the results of the slump test show that the incorporation of PCM did not change the workability of concrete. In other words, the results of slump test of the sample where the LWA was impregnated with water were equal to the results of slump test of the samples where the LWA was impregnated with PCM.

When coarse LWA was presoaked in PCM before adding to concrete, Mix LWA(C)-P, the short-term and final water absorptions were 2.75% and 5.74%, respectively. These are 39% and 26% less than the case that LWA was not presoaked in PCM. This suggests that the presoaked PCM was well absorbed by the LWA and filled the pores. On the other hand, the lower water absorption of this mix makes it to be less vulnerable to aggressive solutes that exists in the water that penetrates the concrete (Ramezaniapour, Zolfagharnasab *et al.* 2018). Comparison of Mix LWA(CF) and Mix LWA(CF)-P shows the same pattern for the cases that both coarse and fine LWA were used. Also, as expected, the water absorption of the concrete that contained LWA

that half of its capacity was filled with PCM, Mix LWA(C)-0.5P and Mix LWA(CF)-0.5P, was in-between the water absorption of the case that no PCM was used and the case that the entire capacity of the LWA was filled with PCM (Figure 12.a).

The same results were obtained for the mixes that Salt Hydrate PCM was incorporated in concrete (Figure 12.b). Salt Hydrate PCM was well absorbed in the scoria LWA's pores, and therefore it decreased the water absorption of concrete compared to the cases that no PCM was added to LWA, Mix LWA(C) and Mix LWA(CF). Also, the drop in water absorption for Mix LWA(C)-H and Mix LWA(CF)-H compared to Mix LWA(C) and Mix LWA(CF) were 23% and 14%, respectively, which are slightly less than that for mixes that contained Polyethylene Glycol PCM. This is attributed to the different chemical structure and origin of the two PCMs.

The results for the mixes that silica fume was incorporated in the media is presented in Figure 12.c and Figure 12.d. Comparing the results show that in all the cases, both the short term and final water absorption of the mix was decreased when silica fume was incorporated. For example, short term and final water absorption of Mix N S were about 18% and 13% less than Mix N, respectively. Also, short term and final water absorption of Mix LWA(C) S-P and Mix LWA(C) S-H were about 12% and 13%, and 7% and 4% less than Mix LWA(C)-P and Mix LWA(C)-H, respectively. This is attributed to the particle size of silica fume. Since silica fume has finer particles compared to cement, it better fills the micro-pores in the structure of the bulk cement paste. On the other hand, the finer particles of silica fume cause a denser and thinner interfacial transition zone around the aggregates (Sharifi, Jafferji *et al.* 2016). Both of these reduce the porosity of the mix, and therefore the water absorption of concrete will be reduced when silica fume is incorporated in that.

4- Conclusion and Future Work

Various laboratory experiments were conducted to examine the effectiveness of silica fume to improve the mechanical properties of PCM-incorporated concrete. Scoria LWA was used as the carrier agent to add Polyethylene Glycol PCM and Salt Hydrate PCM to the mix. Because of its porous structure and compatibility with cementitious media, scoria LWA was found to be an effective carrier agent for PCM. Latent heat of fusion of PCM enhanced the thermal inertia of concrete, and thus, reduced and delayed reaching to the peak temperature when heat was applied to that from an external source. However, adding LWA and PCM reduces the compressive strength of concrete. Incorporation of silica fume was found a promising way to enhance the compressive strength of PCM-incorporated concrete. At the same time, silica fume did not diminish the thermal properties of the incorporated PCM. Therefore, when PCM was used in the concrete along with silica fume, the resultant concrete had an improved thermal performance, and a high enough compressive strength to be used for structural and non-structural applications. This product can be used specifically in the exterior walls of buildings as well as concrete pavements, where the material is exposed to harsh climate conditions. Introducing novel PCM carrier agents and investigating new strategies to improve the mechanical properties of PCM-incorporated concrete are suggested for future work.

583 **5- Compliance with Ethical Standards:**

584 Funding: None of the authors have received any grant for this study. There was no source of
585 funding for this study.

586 Conflict of Interest: The authors declare that they have no conflict of interest.

587

Draft

References

- Aitcin, P.-C. (2000). "Cements of yesterday and today: concrete of tomorrow." *Cement and Concrete research* **30**(9): 1349-1359.
- Bentz, D. P., K. A. Snyder, L. C. Cass and M. A. Peltz (2008). "Doubling the service life of concrete structures. I: Reducing ion mobility using nanoscale viscosity modifiers." *Cement and Concrete Composites* **30**(8): 674-678.
- Blanco, F., P. García, P. Mateos and J. Ayala (2000). "Characteristics and properties of lightweight concrete manufactured with cenospheres." *Cement and Concrete Research* **30**(11): 1715-1722.
- Cheng-Yi, H. and R. F. Feldman (1985). "Hydration reactions in Portland cement-silica fume blends." *Cement and Concrete Research* **15**(4): 585-592.
- Choi, P., J. H. Yeon and K.-K. Yun (2016). "Air-void structure, strength, and permeability of wet-mix shotcrete before and after shotcreting operation: The influences of silica fume and air-entraining agent." *Cement and Concrete Composites* **70**: 69-77.
- Demirboğa, R. (2007). "Thermal conductivity and compressive strength of concrete incorporation with mineral admixtures." *Building and Environment* **42**(7): 2467-2471.
- DiGuilio, R. and A. S. Teja (1990). "Thermal conductivity of poly (ethylene glycols) and their binary mixtures." *Journal of Chemical and Engineering Data* **35**(2): 117-121.
- Eddhahak, A., S. Drissi, J. Colin, S. Caré and J. Neji (2014). "Effect of phase change materials on the hydration reaction and kinetic of PCM-mortars." *Journal of Thermal Analysis and Calorimetry*: 1-9.
- George, A. (1989). *Hand book of thermal design; Phase change thermal storage materials.*, McGraw Hill Book Co.
- Gonen, T. and S. Yazicioglu (2007). "The influence of mineral admixtures on the short and long-term performance of concrete." *Building and Environment* **42**(8): 3080-3085.
- Günther, E., H. Mehling and S. Hiebler (2007). "Modeling of subcooling and solidification of phase change materials." *Modelling and Simulation in Materials Science and Engineering* **15**(8): 879.
- Hadjieva, M., R. Stoykov and T. Filipova (2000). "Composite salt-hydrate concrete system for building energy storage." *Renewable Energy* **19**(1): 111-115.
- Hale, D., M. Hoover and M. O'Neill (1971). "Phase change materials handbook."
- Isfahan Cement Co., <http://www.Isfahancement.com>.
- Kadri, E., S. Aggoun, G. De Schutter and K. Ezziane (2010). "Combined effect of chemical nature and fineness of mineral powders on Portland cement hydration." *Materials and structures* **43**(5): 665-673.
- Kashaneh Co., <http://www.pgscrc.com/>.
- Karaman, S., A. Karaipekli, A. Sari and A. Bicer (2011). "Polyethylene glycol (PEG)/diatomite composite as a novel form-stable phase change material for thermal energy storage." *Solar Energy Materials and Solar Cells* **95**(7): 1647-1653.
- Kim, H., I. Nam and H. Lee (2014). "Enhanced effect of carbon nanotube on mechanical and electrical properties of cement composites by incorporation of silica fume." *Composite Structures* **107**: 60-69.
- Kjellsen, K., O. Wallevik and M. Hallgren (1999). "On the compressive strength development of high-performance concrete and paste—effect of silica fume." *Materials and Structures* **32**(1): 63.

- Lane, G., G. Warner, P. Hartwick and H. Rossow (1978). "Macro-encapsulation of PCM." Report No. oro/5117-8, Dow Chemical Company, Midland, Michigan **152**.
- Lee, K. O. (2014). "Experimental and Simulation Approaches for Optimizing the Thermal Performance of Building Enclosures Containing Phase Change Materials."
- Lele, A. F., K. Korhammer, N. Wegscheider, H. U. Rammelberg, T. Schmidt and W. K. Ruck (2013) "Thermal conductivity measurement of salt hydrates as porous material using calorimetric (dsc) method."
- Madhkhan, M., A. Hamidi and N. Salehi (2011). Study on the effects of natural pozzolan and limestone powder on mechanical properties of roller compacted concrete pavements. *Advanced Materials Research*, Trans Tech Publ.
- Maslehuddin, M., O. Al-Amoudi and A. Al-Mana (1994). "Concrete durability in a very aggressive environment." *Special Publication* **144**: 191-212.
- Praisler, M. and L. Frangu (2012). Exploratory analysis for the automated detection of amphetamines and of their main precursors. *System Theory, Control and Computing (ICSTCC)*, 2012 16th International Conference on, IEEE.
- Ramezani-pour, A. A., A. Zolfagharnasab, F. B. Zadeh, S. H. Estahbanati, R. Boushehri, M. R. Pourebrahimi and A. M. Ramezani-pour (2018). Effect of Supplementary Cementing Materials on Concrete Resistance Against Sulfuric Acid Attack. *High Tech Concrete: Where Technology and Engineering Meet*, Springer: 2290-2298.
- Rao, K. and P. Chandra (1970). "A study of thermal performance of concrete hollow blocks by an electrical analogue method." *Building Science* **5**(1): 31-40.
- Sakulich, A. and D. Bentz (2012). "Incorporation of phase change materials in cementitious systems via fine lightweight aggregate." *Construction and Building Materials* **35**: 483-490.
- Sakulich, A. R. and D. P. Bentz (2011). "Increasing the service life of bridge decks by incorporating phase-change materials to reduce freeze-thaw cycles." *Journal of Materials in Civil Engineering* **24**(8): 1034-1042.
- Seabrook, P. and H. Wilson (1988). "High strength lightweight concrete for use in offshore structures: utilisation of fly ash and silica fume." *International Journal of Cement Composites and Lightweight Concrete* **10**(3): 183-192.
- Seyfi, S., A. R. Azadmehr, M. Gharabaghi and A. Maghsoudi (2015). "Usage of Iranian scoria for copper and cadmium removal from aqueous solutions." *Journal of Central South University* **22**(10): 3760-3769.
- Shameli, K., M. Bin Ahmad, S. D. Jazayeri, S. Sedaghat, P. Shabanzadeh, H. Jahangirian, M. Mahdavi and Y. Abdollahi (2012). "Synthesis and characterization of polyethylene glycol mediated silver nanoparticles by the green method." *International journal of molecular sciences* **13**(6): 6639-6650.
- Shazand Petrochemical Co., <http://www.arpc.ir/>.
- Sharifi, N. P., H. Jafferji, S. E. Reynolds, M. G. Blanchard and A. R. Sakulich (2016). "Application of lightweight aggregate and rice husk ash to incorporate phase change materials into cementitious materials." *Journal of Sustainable Cement-Based Materials* **14**: 1-21.
- Sharifi, N. P. and K. C. Mahboub (2018). "Application of a PCM-rich concrete overlay to control thermal induced curling stresses in concrete pavements." *Construction and Building Materials* **183**: 502-512.
- Sharifi, N. P. and A. Sakulich (2015). "Application of phase change materials to improve the thermal performance of cementitious material." *Energy and Buildings* **103**: 83-95.
- Sharifi, N. P., A. Sakulich and R. Mallick (2013). Experimental apparatuses for the determination of pavement material thermal properties. *Green Streets, Highways, and Development 2013: Advancing the Practice*: 117-124.

- Sharifi, N. P., A. A. N. Shaikh and A. R. Sakulich (2016). "Application of Phase Change Materials in Gypsum Boards to Meet Building Energy Conservation Goals." *Energy and Buildings*.
- Sharma, A., V. Tyagi, C. Chen and D. Buddhi (2009). "Review on thermal energy storage with phase change materials and applications." *Renewable and Sustainable energy reviews* **13**(2): 318-345.
- Sharma, A., V. V. Tyagi, C. Chen and D. Buddhi (2009). "Review on thermal energy storage with phase change materials and applications." *Renewable and Sustainable energy reviews* **13**(2): 318-345.
- Tyagi, V., A. Pandey, R. Kothari and S. Tyagi (2014). "Thermodynamics and performance evaluation of encapsulated PCM-based energy storage systems for heating application in building." *Journal of Thermal Analysis and Calorimetry* **115**(1): 915-924.
- Wang, W., X. Yang, Y. Fang and J. Ding (2009). "Preparation and performance of form-stable polyethylene glycol/silicon dioxide composites as solid-liquid phase change materials." *Applied Energy* **86**(2): 170-174.
- Wu, Z., C. Shi and K. Khayat (2016). "Influence of silica fume content on microstructure development and bond to steel fiber in ultra-high strength cement-based materials (UHSC)." *Cement and Concrete Composites* **71**: 97-109.
- Xu, B. and Z. Li (2013). "Paraffin/diatomite composite phase change material incorporated cement-based composite for thermal energy storage." *Applied Energy* **105**: 229-237.
- Zalba, B., J. M. Marín, L. F. Cabeza and H. Mehling (2003). "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications." *Applied Thermal Engineering* **23**(3): 251-283.
- Zhou, D., C.-Y. Zhao and Y. Tian (2012). "Review on thermal energy storage with phase change materials (PCMs) in building applications." *Applied energy* **92**: 593-605.

Figure Legends

Figure 1. a) Salt Hydrate PCM. b) Grade 600 Polyethylene Glycol PCM

Figure 2. Semi-adiabatic calorimetry test. a) Thermocouple embedded in the center of the concrete specimen. b) Samples placed in the insulated box, and the thermocouples connected to the data logger

Figure 3. Thermal conductivity test. a) KD2 Pro apparatus with the standard specimen. b) Samples prepared for the test

Figure 4. Thermal performance test. a) Homemade laboratory setup. b) Schematic illustration of the apparatus (The cylindrical aluminum foil around the light bulb is not shown)

Figure 5. Applied temperature profile

Figure 6. a) Heat flow per unit mass of PCM vs. time. b) Heat flow per unit mass of PCM vs. temperature; as determined by DSC

Figure 7. FTIR spectra of raw materials and the mixture of them

a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM

Figure 8. Semi-adiabatic calorimetry test.

a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM.
c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Figure 9. Compressive strength test.

- a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM
- c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Figure 10. Thermal conductivity test.

- a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM
- c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Figure 11. Thermal performance test.

- a) Samples that contain either LWA or PCM. b) Samples that contain both LWA and PCM
- c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Figure 12. Water absorption percentage.

- a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM
- c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Draft

Table 1.a. Physical properties of the utilized cement

Specific area (m ² /kg)	Setting Time (min)		Compressive Strength (MPa)		
	Initial	Final	Day 3	Day 7	Day 28
2,900	90	240	13	24	36.5

Table 1.b. Chemical properties of the utilized cement

Chemical component	K ₂ O	Na ₂ O	SO ₃	MgO	CaO	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂
Weight percentage	0.7	0.2	1.7	1.8	36.5	3.2	5.9	21.7

Draft

Table 2.a. Physical properties of the utilized silica fume

Specific area (m ² /g)	Particle size (nm)	Specific gravity	Melting temperature (°C)	45 micron sieve passing
20-25	229	1.9	1230	96.5%-99.1%

Table 2.b. Chemical properties of the utilized silica fume

Chemical component	SiO ₂	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O
Weight percentage	90-95	0.3-1.6	0.5-1.5	0.5-2	0.3-0.5	0.2-0.5
Chemical component	CL	L.O.I	Al ₂ O ₃	Humidity		PH
Weight percentage	0.04-0.08	0.4-3	0.6-1.2	0.01-0.4		6.8-8

Draft

Table 3.a. Properties of Salt Hydrate PCM

Main components	Flammable	Toxic	Corrosive	Specific Gravity	Thermal Conductivity
Inorganic Salt Hydrate, Water, Additive	No	No	No	1.4	1.5% $\pm$ 0.6% (W/m·K)

Table 3.b. Properties of Grade 600 Polyethylene Glycol PCM

Physical appearance at 20 °C	Average molecular weight (g/mol)	Specific gravity at 40 °C	Water percentage	Viscosity at 25 °C (cST)
Transparent liquid	570 - 630	1.125 $\pm$ 0.02	< 2	136 $\pm$ 10

Draft

Table 4. Mix proportioning of control mixes, and the density of each mix (kg/m³)

Mix ID	Cement	Water	Ordinary Sand	Ordinary Gravel	Scoria Sand	Scoria Gravel	Silica Fume	Density
N	437.9	236.9	868.7	756.9	-	-	-	2420
LWA (C)	438.0	236.6	727.4	-	-	356.3	-	2188
LWA (CF)	438.3	236.7	-	-	613.1	411.0	-	1763
N S	372.2	236.9	868.7	756.9	-	-	65.7	2342
LWA (C) S	356.2	226.3	727.4	-	-	356.3	62.9	2088
LWA (CF) S	372.5	236.7	-	-	613.1	411.0	65.7	1658

Draft

Table 5. Thermal properties of the PCMs

PCM	Specific Heat (J/g·K)		Latent Heat of Fusion (J/g)	
	Heating	Cooling	Melting	Solidifying
Salt Hydrate	2.2	2.4	142.3	139.6
Polyethylene Glycol	2.1	2.5	149.7	148.2

Draft

Table 6. List of bonds recognized by FTIR

Bond	C-O-C	C-O	C-H	C-H	O-H	Si-O-Al	Si-O-Si	H-O-H	H-O
Scoria LWA	-	-	-	-	-	449	1037	1641	3442
Polyethylene Glycol PCM	1062	1251	1352	2868	3452	-	-	-	-
LWA + PCM	1110	1249	1352	2873	3427	447	1040	1645	3419

Draft

Figure 1. a) Salt Hydrate PCM. b) Grade 600 Polyethylene Glycol PCM

Draft

Figure 2. Semi-adiabatic calorimetry test. a) Thermocouple embedded in the center of the concrete specimen. b) Samples placed in the insulated box, and the thermocouples connected to the data logger

Draft

Figure 3. Thermal conductivity test. a) KD2 Pro apparatus with the standard specimen. b) Samples prepared for the test

Draft

Figure 4. Thermal performance test. a) Homemade laboratory setup. b) Schematic illustration of the apparatus (The cylindrical aluminum foil around the light bulb is not shown)

Draft

Figure 5. Applied temperature profile

Figure 6. a) Heat flow per unit mass of PCM vs. time. b) Heat flow per unit mass of PCM vs. temperature; as determined by DSC

Figure 7. FTIR spectra of raw materials and the mixture of them
a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM

Figure 8. Semi-adiabatic calorimetry test.

a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM.
c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Figure 9. Compressive strength test.

- a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM
 c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Figure 10. Thermal conductivity test.
a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM
c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Figure 11. Thermal performance test.

- a) Samples that contain either LWA or PCM. b) Samples that contain both LWA and PCM
 c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM

Figure 12. Water absorption percentage.
a) Samples that contain Polyethylene Glycol PCM. b) Samples that contain Salt Hydrate PCM
c) Samples that contain silica fume and Polyethylene Glycol PCM. d) Samples that contain silica fume and Salt Hydrate PCM