Sigma J Eng & Nat Sci 38 (1), 2020, 183-189

Sigma Journal of Engineering and Natural Sciences
Sigma Mühendislik ve Fen Bilimleri Dergisi

Research Article

A COMPARATIVE STUDY ON THE THERMAL PERFORMANCE OF MORTARS WITH DIFFERENT FORMULATIONS

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Received: 15.10.2019 Accepted: 10.12.2019

ABSTRACT

This paper comparatively analyze the mechanical and thermal performance of three different mortar mixes namely; ordinary Portland cement mortar, geopolymer mortar, and phase change material (PCM) incorporated geopolymer mortar. In geopolymer mortar ground pumice was used as the precursor material and combination of NaOH (Sodium hydroxide) and Na_2SiO_3 (Sodium silicate) was used as the activator. In PCM modified mortar mix, sand was substituted by PCM by 25% by volume. Compressive strength and thermal performance of the mortar mixes were determined at 7 days on cubic and prismatic samples. Test results showed that the compressive strength is dramatically reduced in geopolymer mortar and further reduction was observed with PCM inclusion. Thermal performance of the geopolymer mortar and PCM modified mortar are improved with reduced density. PCM inclusion provided the best thermal insulation property by keeping the internal temperature of the test cubicle cooler and warmer during the heating and cooling cycles and furthermore delays the temperature increase or decrease in the internal space during the cycles.

Keywords: Phase change material, geopolymer, pumice, thermal performance.

1. INTRODUCTION

The increasing energy demand results mainly in exhaustion of natural energy resources and environmental pollution. The energy consumption for buildings is considered a major part of the whole energy demand [1]. Therefore, reducing the energy consumption for building services is of great importance to utilize energy efficiency. The application of the insulation mortar that is a cementitious material and generally applied on the exterior walls is being one of the effective methods to enhance the energy efficiency of buildings [2]. In previous studies [3,4], incorporation of the microencapsulated phase change materials (PCMs) in concrete or mortar was proposed to improve the thermal resistance and thermal response of construction members. PCMs are defined as the substances with a high enthalpy of fusion that can be used to increase the thermal energy storage of a system. Mainly, three different methods have been applied for the incorporation of PCMs in mortar, concrete or boards. The first one is the immersion of wallboards into the molten PCMs, the second one is integration of encapsulated PCMs, and the third one is incorporation of a kind of shape-stabilized PCMs into construction materials [1]. PCMs provide energy efficiency

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during space cooling and/or heating via preventing the heat transfer on daytime and releasing the stored heat into the building at night by changing phase [5]. Zamalloa et al. [6] reported that the incorporation of microencapsulated PCMs in plaster minimizes the thermal fluctuations and decreased the required energy up to 15% and 30% during heating and cooling respectively.

On the other hand, ordinary Portland cement (OPC) production is another environmental issue because of the CO_2 emissions during manufacturing. The arising CO_2 emission from OPC manufacture is associated with (i) calcination of the limestone and (ii) high energy consumption during manufacturing. The contribution of the production of OPC has increased up to 0.82 kg emitted CO_2 per kilogram cement [7]. Geopolymers have been proposed as an alternative binder to reduce greenhouse gas emissions. Geopolymers are described as silicon and aluminum rich inorganic materials, generally, reacted with alkali hydroxides and/or alkali silicates [8]. The emitted CO_2 values for geopolymer production was estimated as 80% less than the OPC production [9]. Industrial wastes or byproducts such as slag, fly ash as and natural pozzolanas that contain reactive silica and alumina have been used as raw materials to produce geopolymer.

In this study, the thermal performance of different mortar mixes was comparatively investigated. Considering the significant environmental and economic benefits of the geopolymer, mix of sodium hydroxide and sodium silicate activated pumice powder-based mortar mixes were produced to compare with OPC based mortar. The effect of PCMs on the mechanical and thermal performance of geopolymer mortar was also investigated by substituting microencapsulated PCMs with sand.

2. EXPERIMENTAL PROGRAM

2.1. Materials and Mix Design

This study comparatively investigates three different mortar mixes composed of different material combinations on the mechanical and thermal performance. The reference mortar mix (OPCM) is composed of ordinary Portland cement, sand and water and designed with water to cement ratio and sand to cement ratio of 0.5 and 3.0 respectively. Geopolymer mortar mix (GPM) is composed of pumice powder, sand, water, NaOH (sodium hydroxide) and Na_2SiO_3 (sodium silicate). The water to pumice ratio and sand to pumice ratio was 0.7 and 1.47 respectively. In the PCM modified geopolymer mortar mix (PCM-GPM), 25% of sand is substituted by PCM by volume. PCM with a melting point of 25 °C, heat storage capacity of 95 kJ/kg, specific heat capacity of 2 kJ/kgK, thermal conductivity of 0.1 W/mK was used in the PCM-GPM mix.

In geopolymer mortar mixes (GPM and PCM-GPM) the precursor material was ground pumice, and the activator was a mix of NaOH and Na_2SiO_3. Mix proportions are detailed in Table 1.

Table 1. Mix proportions (in grams) for 1 dm^3 of mortar

Material	OPCM	GPM	PCM-GPM
Cement	512	-	-
Pumice	-	540	540
Sand	1535	1060	795
Water	256	276	276
NaOH	-	39.2	39.2
Na_2SiO_3	-	160	160
PCM	-	-	90

2.2. Curing, Casting and Testing Procedure

The physical properties of the mortar mixes such as density and thermal performance were determined on 300×300×40 mm dimensioned replicate prismatic specimens at 7 days. The density of the prisms belonging to different mixes was determined by proportioning the mass to the volume of the specimens. Compressive strength was determined on three 50×50×50 mm cubic specimens for each mix at 7 days as per ASTM C 109 [10]. The samples belonging to OPCM mix were cured in water with a temperature of 21±2°C until the test day. The samples belonging to GPM and PCM-GPM mixes were cured in an oven at a temperature of 85°C for 5 days and then kept at laboratory conditions for another 2 days until they reach 7 days of age. The exposed temperature and duration was determined after several trials. The thermal performance test was done using an environmental chamber following a similar method proposed by Hassan et al. [11]. A cubic skeleton made of wood with dimensions of 300x300x300 mm^3 in size was designed to simulate an indoor setup and was initially covered with 50 mm thick expanded polystyrene sheet and was then covered with glass wool to prevent heat transfer from all sides except the top side (Figure 1). The top side of the cubicle was kept operable to allow temperature measurement sensors to be installed and for sample replacement. The temperatures were measured with K-type thermocouples in the interior of the cubicle (T1), the internal surface of the specimen (T2), external surface of the specimen (T3) and the exterior of the cubicle (T4). The data were recorded at a time step of 1 min. The experiments were conducted until a steady state was achieved during both the heating and cooling cycles of the samples. The thermal performance test consisted of: a) stabilizing the temperature at 23 °C for 4 hours, b) increasing the temperature to 50 °C and keeping it there for 8 hours and finally c) decreasing the temperature to 10 °C and keeping it there for another 8 hours.

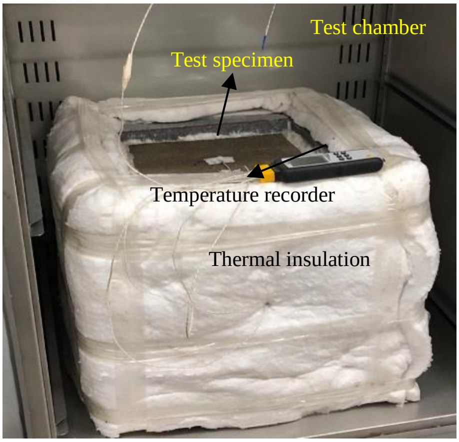

Figure 1. Test setup for thermal performance testing

3. RESULTS AND DISCUSSION

The physical and mechanical test results of the mortar mixes are listed in Table 2. Test results show a consistent reduction in compressive strength of GPM and PCM-GPM mixes compared to the OPCM mix. The 7 days compressive strength of the OPCM mix was 44.2 MPa, however, the compressive strength of GPM and PCM-GPM mixes were determined as 11.6 and 7.2 MPa respectively. The major decline of mechanical properties in geopolymer mortar mixes might be due to the low pozzolanic reactivity of pumice powder. As expected, the compressive strength of

GPM decreased by 38% when PCMs were incorporated. This behavior can be attributed to the low strength and stiffness of microencapsulated PCMs. However the achieved strength values were still satisfactory for basic insulation applications. The density on the other hand reduced in the geopolymer mixes and substitution of PCM with sand provided a lower density value. The average density of OPCM mix was measured as 2052 kg/m^3 and was reduced by 15% in GPM mix and was further reduced by 28% in the PCM-GPM mix compared to OPCM mix. The specific strength values of the mixes are determined by proportioning the strength to density and the results are presented in Table 2. The results again show reduced specific strength values compared to the OPCM mix and further reduction was noted with PCM inclusion.

Table 2. Physical and mechanical properties

Mix ID	Compressive strength (MPa)	Density (g/cm^3)	Specific strength
OPCM	44.2	2.052	21.5
GPM	11.6	1.738	6.7
PCM-GPM	7.2	1.486	4.8

Temperature profiles of the mortar mixes are shown in Figures 2-4. The time to reach specific temperatures during heating and cooling cycles is also presented in Tables 3-5. The test results show that the interior temperature after steady-state was achieved was slightly reduced during the heating cycle. The interior temperature was recorded as 47.3 °C in OPCM mix and was reduced to 46.9 °C and 46.5 °C in GPM and PCM-GPM mixes respectively. Similar results were obtained during the cooling cycle, the interior temperature in OPCM mix was found as 11.8 °C and increased to 12.0 °C and 12.5 °C in GPM and PCM-GPM mixes respectively. In both heating and cooling phases, the PCM-GPM mix demonstrated better properties, i.e. lowered the interior temperature during the heating cycle and increased the interior temperature during the cooling cycle.

Table 3. Steady-state temperatures at the end of the heating cycle

Mix ID	OPCM	GPM	PCM-GPM
T1 (interior)	47.3	46.9	46.5
T2 (interior surface)	48.0	47.7	47.1
T3 (exterior surface)	49.2	49.1	49.1
T4 (exterior)	50.9	50.9	51.0

Table 4. Steady-state temperatures at the end of the cooling cycle

Mix ID	OPCM	GPM	PCM-GPM
T1 (interior)	11.8	12.0	12.5
T2 (interior surface)	11.6	11.8	12.0
T3 (exterior surface	12.5	12.5	12.5
T4 (exterior)	11.2	11.4	11.6

Table 5. Time (in minutes) to reach different interior (T1) temperatures during heating

Interior Temperature	OPCM	GPM	PCM-GPM
25 °C	41.5	43.5	56.0
30 °C	66.5	70.0	91.0
35 °C	101.0	111.5	135.0
40 °C	158.0	174.0	196.0

Table 6. Time (in minutes) to reach different interior temperatures during cooling phase

Interior Temperature	OPCM	GPM	PCM-GPM
40 °C	65.5	68	70
30 °C	116	119	123.5
20 °C	206	207.5	229.0
15 °C	299	299	332.0

The significant difference between the mortar mixes was especially noticed on the time values, in minutes, to reach different interior temperatures during heating and cooling cycles. The thermal properties of PCM-GPM mortar is directly associated with the latent heat storage capacity of PCMs. In the GPM mix, during heating cycle, time to reach 25, 30, 35 and 40 °C interior temperature was found to be clearly delayed, and the effect was more pronounceable at higher temperatures where the temperatures above melting temperature of PCMs. The addition of PCMs further delayed the time to designated interior temperatures and provided better thermal insulation property. Similar results were found during the cooling cycle, PCM-GPM mix, again, achieved better performance compared to the other mixes due to the melting of the PCMs. This effect comes from the ability of PCM to store and release high amount of energy during the phase change in combination with the lower thermal conductivity provided with the PCM inclusion.

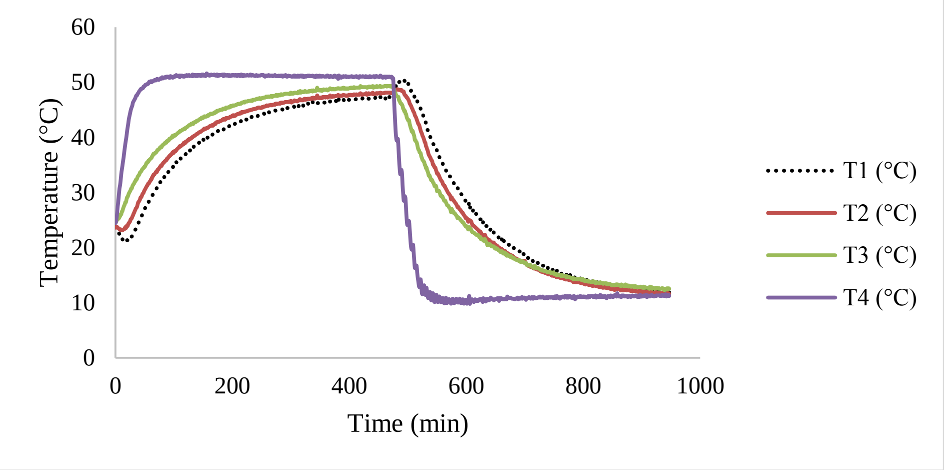

Figure 2. Temperature profile of OPCM mix

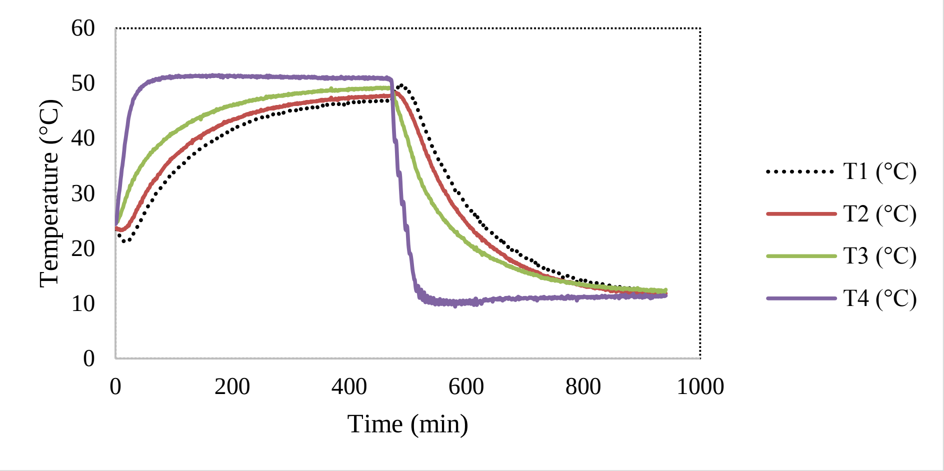

Figure 3. Temperature profile of GPM mix

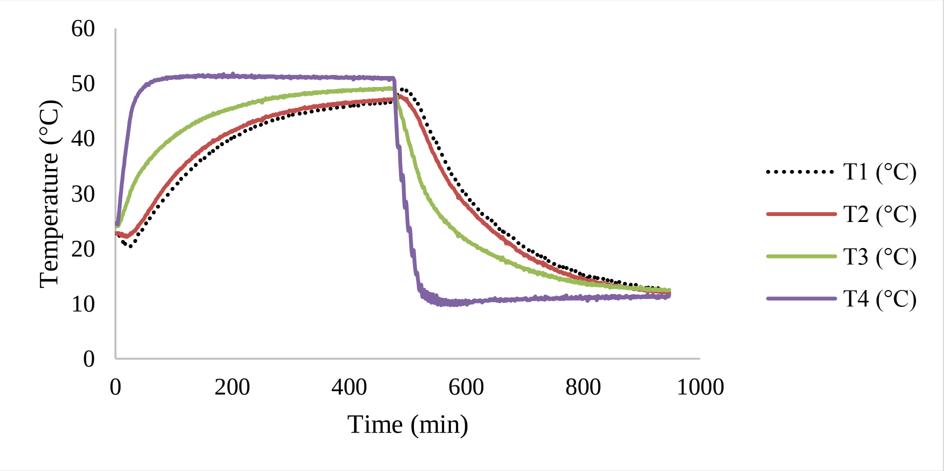

Figure 4. Temperature profile of PCM-GPM mix

4. CONCLUSIONS

This paper aims to develop a mortar which could be applied on the internal part of external walls of a building to achieve energy savings by regulating the temperature fluctuations and delay the temperature variations with in the living space of a building. The current study mainly presents the response of the mortars with and without PCMs in thermal aspects under heating and cooling cycles. From the present study, the following conclusions can be drawn:

- The partial replacement of sand by PCMs decreases the compressive strength and density of the geopolymer mortars. Compared with the reference OPC mortar, the compressive strength reduced from 44.2 MPa to 11.6 MPa in sodium hydroxide activated pumice powder geopolymer mortar and further reduced to 7.2 MPa with PCM inclusion.

- PCM incorporated mortars showed a trend of reduced thermal response. In other words, the addition of PCMs delayed the time to designated interior temperatures and provided better thermal insulation property.
- PCM incorporated mortar provided lower and higher internal temperatures compared to the plain OPC mortar (OPCM) and geopolymer mortar (GPM) during heating and cooling cycles respectively, which offers an opportunity in energy savings.

Acknowledgement

The authors would like to thank the Yildiz Technical University Construction Materials Laboratory staff for their helps during manufacturing and testing the materials.

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