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High temperature resistance of self-compacting lightweight mortar incorporating expanded perlite and pumice

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Abstract. This paper presents the effect of aggregate type on high temperature resistance of self-compacting mortars (SCM) produced with normal and lightweight aggregates like expanded perlite and pumice. Silica fume (SF) and fly ash (FA) were used as mineral additives. Totally 13 different mixtures were designed according to the aggregate rates. Mini slump flow, mini V-funnel and viscometer tests were carried out on the fresh mortar. On the other hand, bulk density, porosity, water absorption and high temperature tests were made on the hardened SCM. After being heated to temperatures of 300, 600 and 900℃, respectively, the tensile strength in bending and compressive strength of mortars determined. As a result of the experiments, the increase in the use of lightweight aggregate increased total water absorption and porosity of mortars. It is observed that, the increment in the usage of lightweight aggregate decreased tensile strength in bending and compressive strengths of mortar specimens exposed to high temperatures but the usage of up to 10% expanded perlite in mortar increased the compressive strength of specimens exposed to 300℃.

Keywords: self-compacting lightweight mortar; lightweight aggregate; high temperature; porosity; water absorption

1. Introduction

Normal weight concrete (NWC) is a composite material which is widely used in the construction industry. NWC has good mechanical strength, but heavy. Structures which is constructed with lightweight concrete (LWC) instead of NWC, have low self-load and are less exposed to lateral forces during an earthquake. Thus, the cross-sections of beams and columns becomes smaller and foundations can be constructed more economically (Topcu 1997, Al-Khaiat and Haque 1998). Also LWC has advantages such as high strength/weight ratio, low coefficient of thermal expansion, high fire resistance and sound insulation compared to NWC (Mouli and Khelafi 2008). The most common method to produce LWC is the use of natural or artificial lightweight aggregates in concrete. Lightweight aggregates obtained from natural sources, mainly is of volcanic origin but artificial aggregates are produced as a result of the heat treatment process (TS EN 206-1 2000, Chandra 2002, Muthusamy and Kolandasamy 2015, Abdulkareem *et al*. 2014, Kew *et al*. 2012). Although, about 1/7 of world's pumice reserve is in Turkey, this potential is not utilized sufficiently. Eastern Anatolia Region has approximately 56% of pumice stone reserves in Turkey and largest pumice stone reserve (about 1.1 billion m^3) is in the region of Bitlis-Tatvan (DPT 2001). The most important reason of durability problem in reinforced concrete structures is the placing of fresh concrete without insufficient compaction process. To increase durability, quality and workability of concrete, self-compacting concrete (SCC) developed in Japan (Ozawa *et al*. 1989) in the late 1980s, is defined as a concrete that has excellent deformability and high resistance to segregation and can be used to fill a heavily reinforced area without applying vibration (Ozawa *et al*. 1989, Okamura 2003, Barbhuiya 2011). Due to the low density of aggregate used in concrete, strength and workability loses increase and segregation occurs in concrete. High strength, durability and segregation resistance properties of SCC can fix mentioned problems of lightweight concretes. Unlike conventional concrete, using of chemical additives, super plasticizer and pozzolanic mineral additive are needed in SCC. New standards and test methods are being developed for the selection and use of these materials in concrete design (Karatas 2010). In this study, standards issued by EFNARC were utilized (Barats *et al*. 2008). According to EFNARC; workability of self-compacting concrete can be provided with filling capability, suitable viscosity determined by the flow rate, the ability to pass through the narrow section and the separation resistance (Karatas 2010, Barats *et al*. 2008). Limiting amount of coarse aggregate is common method to achieve the high fluidity of SCC. Besides, it is necessary to increase the proportion of fine material. For this purpose, mineral additives such as fly ash, limestone powder, slags and silica fume can be used in concrete (Bonavetti *et al*. 2003, Bosiljkov 2003).

Furthermore, the benefits of using mineral additives in

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Table 1 Properties of Portland cement and mineral additives

Chemical components (%)	PC	FA	SF
SiO_2	21,12	42,14	81,4
Al_2O_3	5,62	19,38	4,47
Fe_2O_3	3,24	4,64	1,4
CaO	62,94	26,96	0,82
MgO	2,73	1,78	1,48
SO_3	2,3	2,43	1,35
Na_2O	-	-	-
K_2O	-	1,13	-
CI	-	0,001	-
Loss in ignition	1,78	-	1,84
Physical Properties			
Specific Gravity (g/cm^3)	3,1	2,2	2,2
Specific Surface Area (cm^2/g)	3370	2900	144000

Table 2 Physical properties of aggregates

	Pumice	Natural river sand	Expanded perlite
Specific gravity (g/cm^3)	0.8	2.63	0.055
Water absorption (%)	29	1.96	26.7

Table 3 Composition and labeling of SCLWM mixtures

Label	Amount of ingredient (kg/m^3)							
	PC	FA	SF	W	Sand	EP	P	SP
GP0-P0	455	130	65	255.4	1229.6	0	0	8
GP0-P10	455	130	65	228.06	597.72	0	181.82	8
GP1-P0	455	130	65	249.44	1184.4	1.3	0	8
GP1-P2	455	130	65	240.89	1059.7	1.3	37.92	8
GP1-P6	455	130	65	230.95	799.27	1.29	112.21	8
GP1-P8	455	130	65	229.81	666.89	1.27	147.53	8
GP2-P0	455	130	65	236.69	1152.8	2.68	0	8
GP2-P3	455	130	65	244.47	922.22	2.57	56.11	8
GP2-P4	455	130	65	240.25	860.74	2.57	74.81	8
GP2-P10	455	130	65	229.73	478.18	2.5	181.82	8
GP3-P0	455	130	65	237.59	1088.8	4.02	0	8
GP3-P6	455	130	65	239.82	666.9	3.8	110.65	8
GP3-P10	455	130	65	230.57	418.41	3.75	181.82	8

concrete are protecting nature and providing economy. Mortar serves as one of the basis for the workability properties of SCC and these properties could be assessed by self-compacting mortar (SCM). In fact, assessing the properties of SCM is an integral part of SCC design because SCC contains less coarse aggregate (Karatas 2010).

At elevated temperatures, several of physical and chemical reactions occur in concrete which combined with the thermal incompatibility of their constituents. One of the biggest problems of concrete exposed to high temperature is the loss of compressive strength. The purpose of this study is determining of the high temperature resistance of lightweight self-compacting mortars produced by local materials.

2. Experimental program

In this paper, effect of high temperature on mechanical properties of self-compacting lightweight mortar (SCLWM) was studied. Super plasticizer and two type mineral additives were used in mixtures. The mini slump flow and mini V-funnel flow tests recommended by EFNARC (Barats *et al*. 2008), were carried out to determine the characteristics of fresh properties of SCLWM. In addition, viscosities of fresh mortars were measured. The tensile strength in bending and compressive strength tests were performed on SCLWM mixture exposed to high temperatures. Furthermore, bulk density, porosity, water absorption tests were performed on the hardened mortars.

2.1 Materials

An ordinary Portland cement (CEM I 42.5N) was used to produce the various SCLWM mixtures. Class C fly ash (FA) obtained from Soma Thermal Power Plant and silica fume (SF) obtained from Antalya Electro Metallurgy Enterprise were used as mineral admixture. The chemical components and physical properties of cement and mineral additives are presented in Table 1.

As fine aggregate, expanded perlite (EP) obtained from Konya was used in the range of 0-2 mm and pumice (P) obtained from Bitlis-Tatvan was used in the range of 2-4 mm. Also natural river sand obtained from Murat River in Elazig was used with a maximum size of 4 mm. The physical properties of aggregates are presented in Table 2.

Furthermore, a modified polycarboxylates based polymer type super plasticizer (Sika Hi-Tech 36) with a specific gravity of 1.06 g/cm^3 was used to achieve the workability desired

2.2 Mixture proportions and fresh mortar tests

Mixture proportions for SCLWM are given in Table 3. In this study, 13 different mixtures of mortars were produced. The amount of cement (455 kg/m^3), mineral additives (195 kg/m^3) and maximum grain size (4 mm) were kept constant while the ratio of fine aggregates was taken a variable parameter. In all SCLWM mixtures, fly ash and silica fume was used at the rate 20% and 10% respectively recommended by literature (Aydin 2008, Aydin and Baradan 2007, Delhomme *et al*. 2012). Moreover, the amount of super plasticizer was kept constant at 8 kg/m^3 and water to binder (W/B) ratio was kept around 0.31-0.34. Mortars were labelled according to the aggregate contents.

Tests were performed at a constant temperature 21°C. Mixing process started by mixing all of the powder and sand for one minute using a standard mixer described by ASTM C 305-99'e (ASTM C305 2002). Deformability and viscosity of fresh mortar was evaluated through the measurement of mini slump flow diameter and mini V-funnel flow time described by EFNARC (2002).

Fig. 1 Tensile strength in bending and compressive strength tests

Finally the relative slump was calculated by the following Eq. (1) given in EFNARC (2002)

$$\Gamma_m = [\frac{d}{d_o}]^2 - 1 \qquad (1)$$

Where d_0 is the initial diameter of the cone, and d is the final diameter of mortar. The relative funnel speed was then calculated as

$$R_m = \frac{10}{t} \qquad (2)$$

Where t is the measured time (sec) for mortar to flow through the V-funnel. Viscosity measurements were performed using a Brookfield DV-E model viscometer. The measurements based on the plastic viscosity were realized at the seven rotational speeds (1, 2.5, 5, 10, 20, 50, and 100 rpm) immediately after mixing. Therefore, the viscosity measurements were conducted at different rotational speeds and time dependent viscosity measurements were performed.

After completion of fresh mortar tests, the SCLWM mixtures were poured into prismatic moulds with 40×40×160 mm and cubic moulds with 50×50×50 mm without any compaction or vibration. The specimens were cured in lime saturated water at 21±2℃ for 28 days.

2.3 Density of hardened mortar, porosity and water absorption tests

To determine the physical properties of SCLWM, 3 cubic specimens (50×50×50 mm) for each mixture were produced.

The weight of mortar specimens were measured in air and in water by Archimedes balance after 24 hours curing in water described as TS EN 12390-7 (TS EN 12390-7 2009). Then, the weights of oven-dried (105℃±5) specimens were measured until the mass became constant and also oven-dry density, total water absorption and porosity values of specimens were calculated.

2.4 High temperature test

The high temperature test was performed in accordance with TS EN 1363-1 (TS EN 1363-1 1999) and TS EN 1363-2 (TS EN 1363-2 1999). After 28 days water curing, 3 prismatic specimens for each mixture were heated in an electric furnace (Protherm HLF 150) up to 300℃, 600℃ and 900℃. Each temperature was maintained for 1 h to achieve the thermal steady state. The specimens were

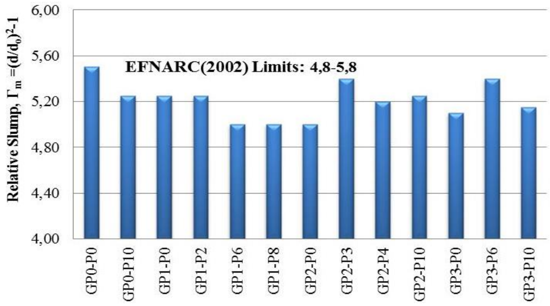

Fig. 2 Relative funnel speed of SCLWMs

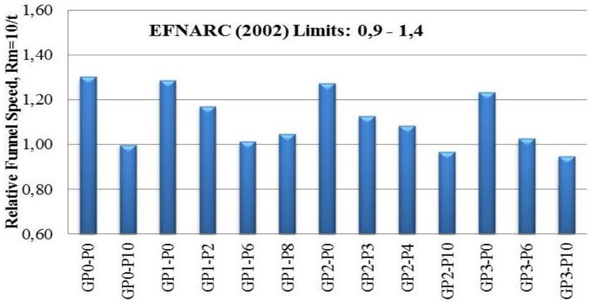

Fig. 3 Relative funnel speed of SCLWMs

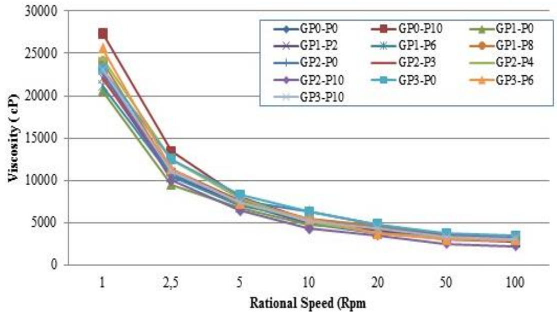

Fig. 4 Viscosity of SCLWMs

allowed to cool naturally to room temperature before testing. Tensile strength in bending and compressive strength tests were performed on specimens exposed to high temperatures (Fig. 1).

3. Results and discussion

3.1 Fresh properties

Relative slump and relative funnel speed values are presented in Figs. 2 and 3. It is obvious that SCLWM mixtures ensured EFNARC (2002) recommendation for relative slump and relative funnel speed.

The material parameters used in concrete can change the self-compacting properties of concrete. For instance, segregation problems can be seen in lightweight aggregate concretes or mortars. In this study, flow ability was achieved with the super plasticizer and stability was achieved with large amount of fine material. Viscosity measurements were also made for all mortars. As seen in (Fig. 4) viscosity curves showed X-axis towards the asymptotic approach. When the results examined in general, viscosity values of all mixture appears to be so close

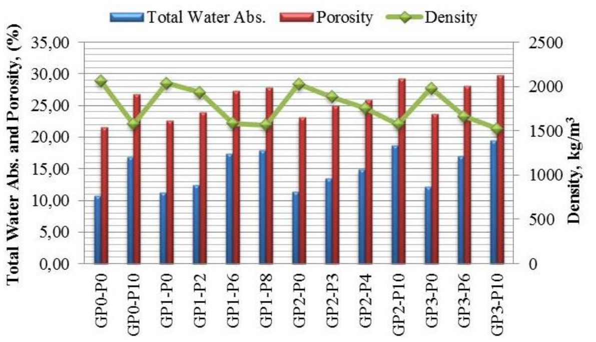

Fig. 5 Density, total water absorption and porosity

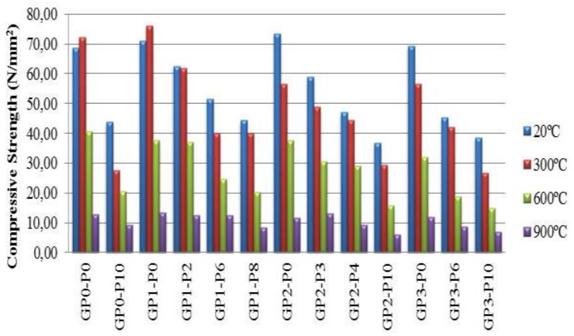

Fig. 7 Compressive strength of SCLWMs

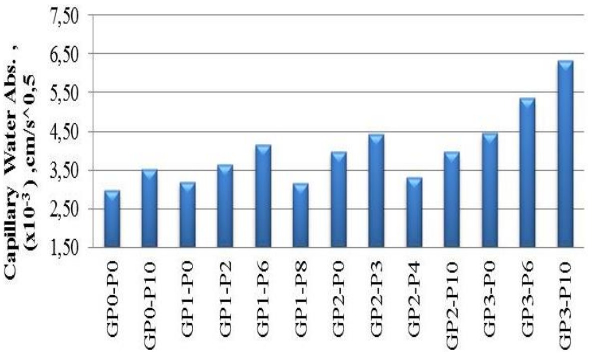

Fig. 6 Coefficients of capillary water absorption

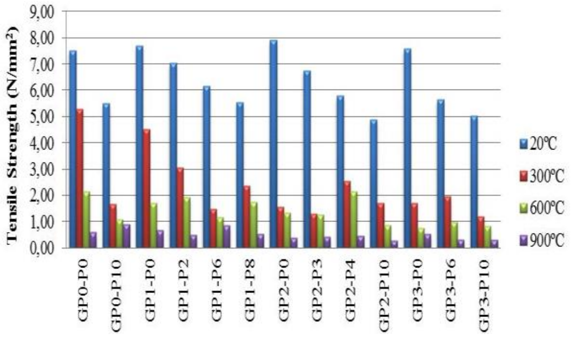

Fig. 8 Tensile strength in bending of SCLWMs

together. Test results show that aggregate type did not change viscosity of SCLWCs too much.

3.2 Density, total water absorption and porosity

The density of all SCLWM mixture were significantly lower because of using lightweight aggregates such as pumice and expanded perlite in experimental studies (Fig. 5). Fig. 5 shows that density of SCLWM specimens varied between 1523 kg/m^3 and 2066 kg/m^3. As the expanded perlite and pumice contents are increased, density off all SCLWM specimens is decreased.

The density of lightweight concrete described by TS EN 206-1 (TS EN 206-1 2000) is between 800 kg/m^3 and 2000 kg/m^3. Therefore, as seen in Fig. 5, nearly all mixtures can be classified as lightweight concrete in accordance with TS EN 206-1'e (TS EN 206-1 2000). The most weight losses were observed in GP3-P10 which containing max lightweight aggregate.

High porosity and high water absorption rate are the biggest problems encountered in production of lightweight aggregate concrete. The relationship between density, porosity and total water absorption values is given in Fig. 5. It shows that, porosity and total water absorption values of SCLWM specimens vary inversely with the density of SCLWM specimens. Maximum porosity value was obtained from GP3-P10 which had minimum density in all mixture whilst minimum porosity and water absorption values were obtained from GP0-P0 which had maximum density in all mixture. Porosity and water absorption of specimens containing expanded perlite and pumice is higher than specimen without lightweight aggregate. Therefore, this study shows that pumice and expanded perlite increases the rate of water absorption of mortars. Topcu and Isikdag (Topcu and Isikdag 2008) found that the use of expanded perlite in concrete improved the values of compressive strength, the splitting tensile strength and the dynamic elasticity modulus when they investigated the effects of expanded perlite on the properties of light-weight concrete.

3.3 Capillary water absorption

Capillary water absorption coefficients of all mixture obtained from capillarity tests are given in Fig. 6.

Capillary water absorption coefficients in all SCM mixtures were influenced by capillary voids within mortar and aggregate pore structure. Capillary water absorption coefficient of specimen including lightweight aggregate was higher than the specimen including natural river sand. Fig. 6 shows that GP3-P10 mixture has the maximum capillary water absorption coefficient whilst GP0-P0 has the minimum. Amount of water absorption of the mortar is related with structure of voids as well as the amount of voids within the aggregates. Mortars with high porosity may not always have a high permeability. Permeability is influenced by the voids volume and connection of voids.

3.4 High temperature

Tensile strength in bending and compressive strength tests were performed on prismatic mortar specimens exposed to high temperatures (300°C, 600°C and 900°C) as well as control specimen (20°C) and the results is given in Figs. 7 and 8.Tensile strength loses were observed for all mortars exposed to high temperature. But, at 300°C, high strength loss in lightweight aggregate mortars was observed compared to mortars without lightweight aggregates.

All mortar specimens' compressive strength decreased at 300℃ except GP1-P0 includes 10% expanded perlite and 0% pumice. It was observed that at 300℃, usage of up to 10% expanded perlite increased the compressive strength of mortars whilst usage of more than 10% expanded perlite decreased. (Bakhtiyari *et al.* 2014) stated that the partial pozzolanic activity of expanded perlite aggregate enhanced at high temperatures and in presence of water vapour which produces an internal autoclave condition, should be responsible for increase of residual compressive strength.

It is noticed that all of the mortar groups lost a significant part of their initial compressive strengths at 600℃, but less strength loss was observed in GP2-P4 include expanded perlite and pumice. The results show that no mortar specimens could withstand 900℃. All of the mortar groups exposed to 900℃ lost approximately 80% of its initial strength. It has been stated that the fire strength of concrete doesn't only depend on the differences of the thermal expansion of the concrete components but also depends on the humidity level and porosity of it (Bingol and Gul 2004). (Khoury 1992, Tanyildizi *et al*. 2008) stated that the concrete is deteriorated around 100℃, however, the strength of concrete is increased up to 300℃. Because, at 300℃ there is the warm curing effect on the concrete and the hydrate structure also isn't deteriorated. At 450ºC and higher temperatures, it is considered that decreasing in the values of strength of concrete was high.

(Karakoc 2013) emphasized that a significant decrease in the compressive strength was observed in all of the mixtures including pumice and expanded perlite after heating to 700℃. Some researchers reported that this strength loss is largely attributed to decomposition of calcium hydroxide, which is known to occur between 450℃ and 500℃ (Bentz 2000, Georgali and Tsakiridis 2005, Zhang and Bicanic 2002). Furthermore, at high temperatures the bond between the aggregate and the paste is weakened, because the paste contracts following loss of water while the aggregate expands.

The researchers also stated that the concrete with different aggregate does not behave the same in its strength degradation under high temperature. The losses in concrete strength can be related to those in weight of samples since the reductions in compressive strength are attributed to the dehydration of concrete due to high temperatures (Arioz 2007, Chan *et al*. 1999, Sakr and El-Hakim 2005, Savva *et al*. 2005).

4. Conclusions

This research focused on the effect of high temperature on mechanical properties of SCLWM. Fresh and hardened properties of SCLWMs were determined. The following conclusions could be drawn from the results obtained in this study;

Expanded perlite and pumice did not have influence upon workability of mortars. In this study, self-compacting mortars can be classified as self-compacting lightweight mortar (SCLM) because of the highest oven dry density (2066 kg/m^3). Also, due to the lowest 28-day compressive strength (34.19 MPa), mortars can be considered as structural lightweight mortars. The density of concrete can be reduced substantially by replacing normal aggregate by expanded perlite and pumice. A relationship between porosity and density was obtained. Porosity of mortars was increased as the content of expanded perlite and pumice increased. Capillary water absorption coefficient of mortars was influenced by pore structure of aggregates and capillaries in mortars. It was found from experimental study that mortars with lightweight aggregates had higher capillary water absorption coefficient value than mortars without lightweight aggregates. As the expanded perlite and pumice contents were increased, total water absorption of mortars was reduced. However, it seems that the water absorption is less affected by the perlite replacement than pumice replacement. Therefore, from a durability point of view, the high water absorption of the expanded perlite and pumice mortars is an important disadvantage and adequate measures should be taken. In general, the tensile strength in bending and compressive strength are decreased as the test temperature is increased. It was observed that usage of up to 10% expanded perlite increased the compressive strength of mortars exposed to 300℃ while usage of more than 10% expanded perlite decreased. Compressive strength of all mortar mixtures are decreased at 600℃ and 900℃ compared to 20℃. It was observed that no mortar specimens could withstand 900℃. The result shows that strength loses were approximately 50% at 600℃ and approximately 80% at 900℃.

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