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Use of pumice fine aggregate as an alternative to standard sand in production of lightweight cement mortar

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The purpose of this study is to evaluate the possibility of using granulated pumice as an alternative to fine aggregate in production of lightweight cement mortar. The cement/pumice fine aggregate ratio is 1:3 for pumice aggregate mortar. The water content is determined by flow table test. Compressive and flexural strength, freeze-thaw resistance, sulfate resistance, water absorption and dry unit weight of the mortars are determined. Mortar using 100% pumice as fine aggregate developed strength in excess 12 MPa and had an oven dry density of 1140-1146 kg/m^3 would satisfy the requirements for lightweight mortar and it can be used as in cast in place walls, load bearing and non-load bearing structures. Pumice aggregate mortar is about 50% lighter than Portland cement control mortar due to the replacement of comparatively heavier standard sand by lighter pumice aggregate. The pumice aggregate mortar exhibits a higher frost resistance due to the existence of voids in pumice aggregate. Pumice aggregate mortar showed better performance showing higher residual strength at high temperatures compared Portland cement mortar. The residual compressive strength reduction of pumice aggregate mortar is higher than that of Portland cement mortar exposed to freeze-thaw cycles. The use of pumice aggregate as sand provides the resistance to sulfate attack.

Keywords*:* Mortar, Pumice, Mechanical properties, High temperatures, Sulfate resistance

Pumice is a natural material of volcanic origin produced by release of gases during the solidification of lava. Pumice can exhibit acidic or basic properties depending on its SiO_2 and CaO/MgO contents. Basaltic pumice sometimes is called as scoria or volcanic cinder. The color of basaltic pumice is dark and its specific weight rather more (1.2-2 g/cm^3) than acidic pumice. The acidic pumice is the most common pumice on the earth. The color of acidic pumice is white to gray white because of its own features as silisium, potassium and sodium. Pumice has very porous structure. The density is 0.5-1.0 g/cm^3.

Due to its toughness and durability pumice has been used as lightweight, thermal and sound insulating, fire resistance construction materials such as concrete blocks and concrete[1-4]. Hossain[5] used volcanic pumice as cement replacement and as a coarser aggregate in lightweight concrete production and it was reported that the concrete with 100% pumice aggregate satisfied the criteria of structural lightweight concrete. However compared to control concrete, volcanic pumice concrete has lower compressive strength and modulus of elasticity. It was also indicated that volcanic pumice concrete has more permeability and initial surface absorption than that of control concrete. Aydin and Gul[6] investigated the influence of pumice and diatomite as additives on the setting time and mechanical properties of concrete. They declared that pumice increased the initial and final setting time more than the same diatomite ratio. The addition of pumice and diatomite caused a sudden decrease at first and then the compressive strength and elasticity modulus increased. According to their test results, variation of compressive strength and the modulus of elasticity were similar to the conventional concrete. The gradation of aggregates and addition of admixtures have significant influence on the strength and density of lightweight pumice concrete. The addition superplasticizer and air-entraining admixtures improve the strength and workability of pumice concrete[7]. Binici *et al*.[8] studied the effect of fineness on the properties of the blended cement containing ground granulated blast furnace slag (GGBFS) and ground basaltic pumice (GBP). It was observed that blended cement had higher strength values than plain Portland cement for the same Blaine values. The finer blended cement specimens had higher compressive strength, sodium sulfate resistance compared to the coarser blended cement and plain Portland cement. The heat of hydration of

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blended cement containing GBFS and GBF was lower than that of Portland cement when the fineness was held constant.

Pumice aggregate is one of main natural materials to be used in concrete mixtures for thermal insulation properties. The porous structure of pumice and the absence of crystalline structures substances give the aggregate excellent heat insulating and sound absorbing qualities. Pumice aggregate (PA) decreased the density and thermal conductivity of concretes up to 40% and 46%, respectively. Thermal conductivity and density of concretes made pumice aggregate increase with the cement dosage[9]. Gunduz and Ugur[10] indicated that thermal conductivity of pumice aggregate concrete is 2.5-4 times lower than those of normal weight concrete.

Turker *et al.*[11] have investigated the role of aggregate type on high temperature resistance of mortars and they found that pumice aggregate mortar does not show compressive strength loss up to 500°C, and it is found to be more resistant to high temperature than quartzite and limestone. Yazici *et al.*[12] also found that pumice aggregate mortar gain a compressive strength value of 41% at 600°C, while natural river sand mortars lost 39% of their strength. The replacement of cement with fly ash improved high resistance temperature of pumice mortar significantly. It was found that the pumice mortar incorporating 60% fly ash revealed the best performance particularly at 900°C[13]. Aydin[14] also studied the effects of high temperature on the mechanical properties of cement based pumice mortars incorporating ground granulated blast furnace slag (GGBFS). The GGBFS incorporated mortars showed no compressive strength loss up to 600°C. GGBFS replacement always positively affects the high temperature resistance significantly of 900°C.

Crushed basaltic pumice had a profound effect on the chloride penetration depth of concrete with basaltic pumice fine aggregates[15]. Hossain[16] studied pumice based blended cement concretes exposed to marine environment for a period of one year. He found that blended type-I cement with 20% pumice produces the best performance showing lower porosity and higher chloride ion resistance under both precast and cast-in-situations. He also claimed that type-I blended pumice cement is potential choice for the construction of marine structures. Ground blast furnace slag and ground basaltic pumice were also used as fine aggregate and it was found that these materials had a beneficial effect on the compressive strength loss due to seawater attack[17]. It was observed that the sulfate resistances of blended cements were significantly higher both against sodium sulfate and magnesium sulfate attacks than control cement[18]. In another study revealed by Hossain[19] reported that blended cement incorporating 30% and 40% volcanic pumice or volcanic ash satisfy the ASTM C618 requirements for alkali-silica reaction.

The purpose of this study is to investigate the possibility of using granulated pumice as fine aggregate substitutes to the standard sand in production of lightweight cement mortar. Lightweight mortars are commonly used in civil engineering applications. Pumice is a very light and porous effusive rock with an extremely vacuumed structure and closed pores. Lightweight pumice aggregate mortar pumice is generally considered as being suitable for more efficient mortar uses in lightweight concrete structures.

Experimental Procedure

Materials and mix proportions

The experimental work was carried out in order to determine the suitability of acidic pumice as standard sand to produce lightweight cement mortar. The cement used in mortar mixture was ordinary Portland cement (CEM I) had a strength class 42.5 N according to TS EN 197-1[20]. The specific weight and specific surface area of Portland cement (PC) was 3.15 and 3516 cm^2/g, respectively.

CEN standard realm sand was used to manufacture Portland cement (PC) control mortar. Pumice fine aggregate was used as sand to produce pumice aggregate (PA) mortar. Pumice aggregates were first crushed by a primer crusher and then were screened into 0-4 mm size fraction as fine pumice aggregate to produce mortar mixtures. A combination of PA was obtained a grading that complied with the requirements of TS EN 197-1[21]. Pumice was obtained from Kocapinar region in Van-Ercis, Turkey. According to chemical analysis, the pumice samples are very rich in silica. Because of the high silica content the pumice samples show acidic characterization. The high silica content also gives this pumice its white color. The chemical composition of pumice aggregate and the chemical composition, physical and mechanical properties of Portland cement are given in Table 1.

The proportions of PC control mortar mixtures were 1:3:0.5 cement, sand and water, respectively. The CEN standard sand according to TS EN 196-1[21]

Table 1–The chemical composition of pumice aggregate and the chemical composition, physical and mechanical properties of Portland cement

Chemical composition (%)	PA	PC	Physical and mechanical properties of PC	
			Specific weight	
SiO_2	71.10	20.04	Initial setting time (min)	3.15
Al_2O_3	13.50	5.81	Final setting time (min)	150
Fe_2O_3	1.68	3.62	Volume expansion (mm)	185
CaO	1.14	61.52	Specific surface (cm^2/g)	2.00
MgO	0.40	1.43		3516
Na_2O	3.40	0.18	Compressive strength (MPa)	
K_2O	4.05	0.94	2-days	22.0
SO_3	-	2.87	7-days	38.7
Free CaO(%)	-	1.41	28-days	46.8

was used to prepare PC control mortar. The cement/ fine pumice aggregate ratio was 1:3 for PA mortar. Pumice aggregate was substituted in weight ratio of 100% of each sand size fraction required for CEN standard sand with the requirements of TS EN 196-1. The grain-size distribution of CEN standard sand and pumice aggregate (PA) was given in Table 2.

The water used in the production of the mortar mixtures was potable water. In the PA mortar mixes, the water was added at different ratios in order to provide a constant fluidity of about 110±5 mm.

Table 2–The grain-size distribution of CEN standard sand and pumice aggregate (PA)

Sieve size) (mm)	Fineness percentage remaining (%)
2.00	0
1.60	7 ± 5
1.00	33 ± 5
0.50	67 ± 5
0.16	87 ± 5
0.08	99 ± 1

Test methods

All trial batches were prepared by using a mechanical mixer confirming to the requirements of TS EN 196-1[21]. The mortar mixtures were cast into three-gang prism molds, each 40×40×160 mm and compacted in accordance with the provisions of TS EN 196-1. After the compaction procedure the specimens were left in the molds for 24 h at room temperature of 20±1°C. Following this period, the specimens were removed from the molds and kept in lime saturated water at a temperature of 20±1°C for 27 days. Compressive strength and flexural strength of pumice aggregate mortars were determined in accordance with the provisions of the TS EN 196-1. Flexural strength of the specimens was determined by using three 40×40×160 mm prismatic specimens. Compressive strength test was applied on six broken portions of flexural test specimens. Compressive strength measurements were carried out using a hydraulic press with a capacity of 3000 kN. Strength tests were carried out at 7, 28 and 56 days. The compressive strength results indicated the average of six values and flexural strength results are the average of three values.

The water absorption test on the 50 mm cubic specimens was conducted after 28 days standard curing. First, the specimens was heated to 105°C until constant weight and then allowed to cool to room temperature. After weighing, specimens were totally immersed in a container of water at 20±1°C until achieved a constant mass. The mortar specimens were weighed with 0.01 g accuracy. Water absorption was calculated as a percentage of dry weight.

For fire resistance, 50 mm cube specimens were used. The specimens were removed from molds after 24 h of casting and then placed in the water tank at 20±1°C for 27 days. After 27 days curing in saturated lime water, the specimens were kept at 105°C for 24 h for drying. The mortar specimens were put into an electric furnace in room temperature (20°C). Then the temperature of furnace reached to desired temperature. The heating rate was set at 10°C/min to reach the desired temperature. When the inner temperature of the furnace was reached to the desired temperature, the specimens were kept for 2 h in the furnace. At the end of heating process, the furnace was turned off and let it cool to room temperature. After cooling process the specimens were weighed and the compressive strengths were conducted on the cooled specimens. The compressive strength of the heated specimens was measured. Fire resistance of mortar mixtures was investigated in terms of residual strength.

The resistance of sulfate attack was investigated on the 50 mm cube specimens. First, the mortar specimens were stored in lime saturated water for 27 days. Then the same specimens were immersed in 5% sodium sulfate (Na_2SO_4) and 5% magnesium sulfate ($MgSO_4$) solution at laboratory temperature (20±1°C). Curing in water and sulfate solution was renewed in periods of every week. The mass of the specimens was measured after 4 weeks. Compressive strength of the specimens was also determined after 4 weeks. Resistance to sulfates was tested by comparing the compressive strength and weight of the specimens exposed to these chemicals with the compressive strength of control mortar specimens. Sulfate resistance was evaluated by determining the weight loss and compressive strength loss of specimens using Eqs. (1) and (2), respectively.

$$\text{Weight loss (\%)} = \frac{w_1 - w_2}{w_1} \quad \ldots (1)$$

$$\text{Compressive strength loss (\%)} = \frac{\sigma_1 - \sigma_2}{\sigma_1} \quad \ldots (2)$$

Where w_1 and w_2 are the weight of the specimens before and after 4-week immersion respectively. σ_1 is the average compressive strength of three mortar cubes moist cured for 4 weeks in lime-saturated water and σ_2 is the average compressive strength of three mortar cubes immersed in 5% sulfate solutions for 4 weeks.

Freeze and thaw resistance was tested on the water saturated 50 mm cube specimens after 28 days of initial moist curing. In this test, the specimens were put in deep freezer at -20°C for 4 h during freezing and in water at room temperature for 4 h during the thawing period. The freeze and thaw test cycle was repeated for 25 times and then compression test was conducted. Also non-exposed control specimens were kept in water at 20±1°C during the freeze-thaw test and all specimens were tested at the same age and the residual compressive strength the mortars were determined.

Results and Discussion

The fine acidic pumice aggregate was used as standard sand in the production of pumice aggregate mortar. The compressive strength of mortars was determined at 2, 7, 28 and 56 days and the test results as a function of time are presented in Fig. 1. As expected the compressive strength increased with time. The compressive strength of the mortars decreased with pumice replacement at all ages. According to test results, the 28-day compressive strength value of 50.37 MPa was obtained for PC mortar. The PA mortar reached a 28-day compressive strength of 12.55 MPa which is lower than that of PC mortar. The using of pumice aggregate as sand in mortar decreases the compressive strength of the mortar. This was due to the replacement of strong standard sand by relatively weak pumice aggregate. ASTM C 270 indicates that the minimum compressive strength for type-N, type-S and type-M mortar is 5.2, 12.4 and 17.2 MPa respectively at 28 days[22]. PA mortar containing 100% pumice aggregate as sand developed strength in excess 12 MPa and had an oven dry density of 1140-1146 kg/m^3 satisfied the compressive strength requirement of type-S mortar. Type S mortar is used in structural load-bearing applications and for exterior applications at or below grade.

The flexural strength test results of mortars are given in Fig. 2. The average flexural strength of PC mortar was found about 7.84 MPa or 16% of the 28-day compressive strength. The flexural strength of PA

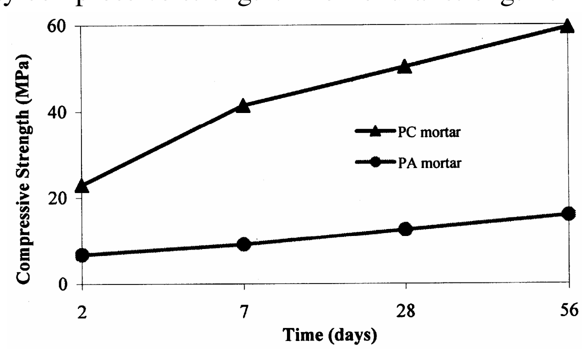

Fig. 1–Compressive strength of mortars versus time

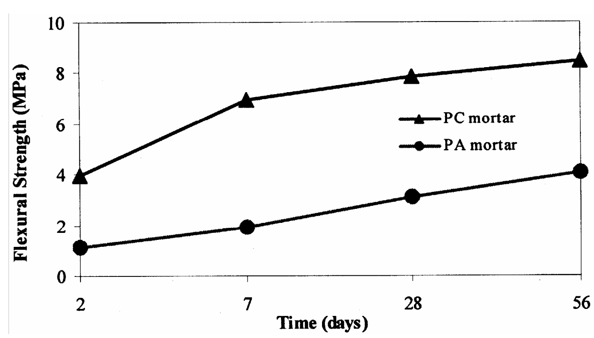

Fig. 2–Flexural strength of mortars versus time

was found as 3.08 MPa or 25% of its compressive strength.

The dry unit weight of mortar specimens is given in Table 3. The dry unit weight of pumice aggregate mortar decreased with the using of pumice aggregate. This is due to the replacement of comparatively heavier standard sand by lighter pumice aggregate. The dry unit weight of pumice mortar varies between 1140 and 1146 kg/m^3 and this value varies between 2054 and 2056 kg/m^3 for PC control mortar. Pumice aggregate mortar was about 50% lighter than PC control mortar.

Water absorption is an important factor due to the porous structure of PA mortar. Table 3 shows the water absorption values of PC mortar and PA mortar. It can be seen that water absorption increased using pumice aggregate. Pumice aggregate shows the highest water absorption as 27-28%. Water absorption of PA mortar is higher four times than that of PC mortar. Gunduz and Ugur[10] have reported the water absorption rates of 14-22% for structural lightweight concrete with pumice aggregate. Generally, pumice aggregates are porous and will have higher water absorption compared to the standard sand.

Fire resistance of mortar mixtures was investigated in terms of residual relative strength. Relative strengths-in percent- at a given temperature with respect to the strength of the mortar specimens at 20^{o}C are given in Fig. 3. The residual relative compressive strength after exposed high temperatures (300^{o}C, 600^{o}C and 900^{o}C) is also given in Fig. 3. The residual strength decreases with increase of temperature for particular fire duration. The compressive strength of mortar specimens drops with temperature starting from 300^{o}C. Residual strength at 300^{o}C for PA mortar is 95.22% and for PC mortar is 88.27%. Residual strength of PA mortar is higher compared with PC mortar when subjected to fire at different temperatures. Rate of loss of strength is significantly higher at 900^{o}C compared with 300 and 600^{o}C for both PA mortar and PC control mortar. Between 600 and 900^{o}C at 2 h of fire duration residual compressive strength is significantly reduced from 86.66% to 49.33% for PA mortar and from 38.04% to 10.52% for PC mortar. At high temperature, the dehydration of cement paste results its gradual disintegration. Because the paste tends to shrink and the aggregate expands at the temperatures of above 600^{o}C, the bond between aggregate and cement pastes weakened resulting in the reduction of strength. Generally the compressive strength loss in PA mortar is lower than PC control mortar when the temperature is varied from 300^{o}C to 900^{o}C. At 900^{o}C, the residual compressive strength of PA mortar is 21.33% higher compared with PC control mortar when subjected to fire for 2 h. This is an indication of better performance of PA mortar in retaining the compressive strength at high temperatures as compared with PC mortar. This can be attributed to the presence of porous structure compared with PC mortar. The Al_2O_3 in structure makes pumice highly resistant to fire and heat. Figure 4 shows the surface character of mortar specimens after exposed to elevated temperatures. Especially for 900^{o}C, PC mortar phases cracked severely and lost their binding properties. Many cracks occurred on PC mortar specimens at 900^{o}C. However, a few cracks happened on PA mortar specimens. The decrease in

Table 3–Physical properties of the PC mortar and PA mortar

Mix	Dry unit weight (kg/m^3)	Water absorption (%)
PC mortar	2054-2056	7-8
PA mortar	1140-1146	27-28

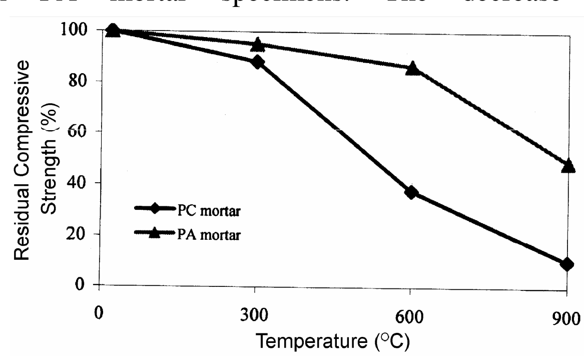

Fig. 3–Residual compressive strength after exposed to high temperatures

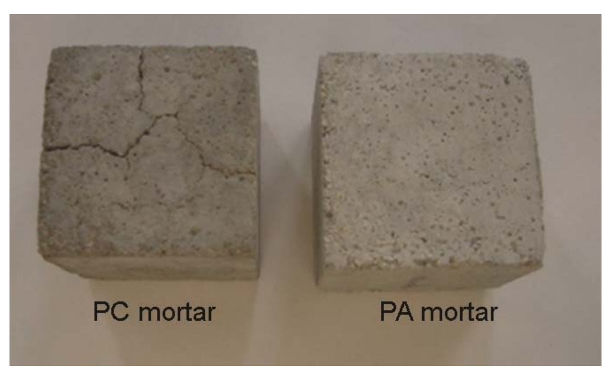

Fig. 4–Mortar specimens after exposure high temperatures (900^{o}C)

compressive strength may be the occurrence of these cracks in mortar because of high temperatures. The cracks decreased with the using pumice aggregate.

As supported by the literature, the compressive strength loss of PC mortar is higher than that of PA mortar up to 900°C. Turker *et al.*[11] have found that the pumice aggregate mortar does not show compressive strength loss up to 500°C and the mortar is more resistant to high temperature than quartzite and limestone. Yazici *et al.*[12] also showed the pumice aggregate mortar gains a compressive strength value of 41% at 600°C while natural river aggregate mortar lost 39% of their strength. Aydin and Baradan[13] have investigated high temperature resistance of pumice mortar and they showed that the pumice mortar incorporating 60% fly ash revealed the best performance particularly at 900°C. Ground granulated blast furnace slag (GGBS) incorporated mortars showed no compressive strength loss up to 600°C and GGBS replacement always positively affects the high temperature resistance significantly at 900°C[14]. Tanyildizi and Coskun[24] also showed that compressive strength and splitting tensile strength decreases were prevented with fly ash mixture. They obtained the highest compressive and splitting tensile strength with 30% fly ash addition. The compressive strength was decreased as temperature was increased. It was found that this decrease was prevented using silica fume mixture. The using 20% silica fume for all temperatures gave the highest compressive and splitting tensile strength[25]. Sancak *et al.*[26] studied the compressive strength and weight losses of lightweight concrete containing pumice aggregate, silica fume and superplasticizer at high temperatures. They found that unit weight of light-weight concrete was 23% lower than that of normal-weight concrete and normal-weight concrete showed higher strength losses than of light-weight concrete.

The weight loss of the mortar samples after elevated temperature exposure is given in Fig. 5. The weight loss of the PC mortar was 6.05%, 7.80% and 8.78% at 300°C, 600°C and 900°C respectively. These losses were 9.57%, 13.53% and 15.03% for PA mortar. The weight loss of PA mortar is higher than that of PC mortar after high temperatures.

The results of sulfate resistance tests carried on PC mortar and PA mortar are shown in Table 4. The compressive strength of PA mortar specimens decreased from 15.74 MPa to 14.91 MPa within 4 weeks of exposure to the 5% Na_2SO_4 solution. The compressive strength also decreased from 15.74 MPa to 15.16 MPa in 5% $MgSO_4$ solution. The compressive strength of PC mortar decreased from 46.63 MPa to 39.67 MPa in 5% Na_2SO_4 solution while decreased from 46.63 MPa to 40.18 MPa in 5% $MgSO_4$ solution. The compressive strength of all mortars decreased with exposure to Na_2SO_4 and $MgSO_4$ solutions. The compressive strength reduction of PC mortar was higher than that of PA mortar. The use of pumice aggregate as sand provides the resistance to sulfate attack. PA mortars showed better resistance to sulfate attack than the PC mortar showed. This may to be due to the dense microstructure of the paste surrounding the pumice aggregate, which makes it difficult for the sulfate ion to ingress into the interior of the mortar. Other researchers have reported that similar observations mentioning that natural additives could contribute to the enhancement of sulfate resistance of mortars. Hossain[15] studied the performance of pumice blended cement concrete in seawater environment a period of one year. According to Hossain, the presence of pumice improves durability due to its pozzolanic

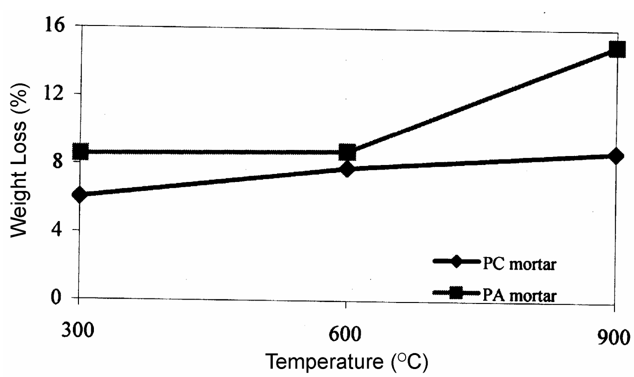

Fig. 5–Weight loss of mortars exposed to high temperatures

Table 4–Compressive strength loss of the mortars exposed to the sulfate solution

Mix	Compressive strength(MPa)			Compressive strength loss (%)	
	in $MgSO_4$	in Na_2SO_4	in water	in $MgSO_4$	in Na_2SO_4
PC mortar	40.18	39.67	46.63	13.83	14.93
PA mortar	15.16	14.91	15.74	3.68	5.27

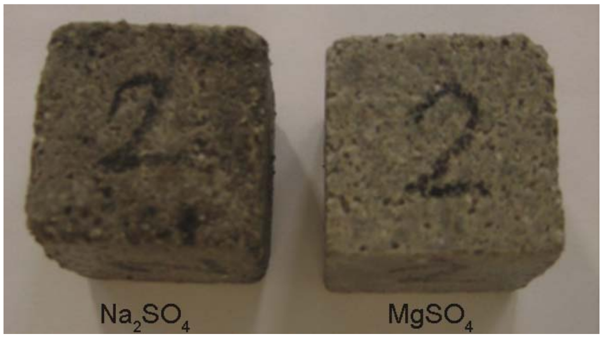

Fig. 6–Mortar specimens after 4-week immersion sulfate solutions

Table 5–The residual compressive strength of the mortarsafter freeze-thaw (FT) test

Mix	Compressive strength after 25 FT cycles (MPa)	Compressive strength without FT cycles (MPa)	Residual compressive strength (%)
PC mortar	40.35	42.76	94
PA mortar	13.39	12.03	111

reaction with $Ca(OH)_2$ to produce a greater solid volume of cementitious calcium silicate gel. The consumption of $Ca(OH)_2$ by pumice prevents the formation ettrengite. As can be seen from Fig. 6 for all specimens, the compressive strength reduction was higher than in sodium sulfate solution compared to magnesium sulfate solution. Binici and Aksogan[18] also showed that final strength reductions of plain and blended cement attacked by magnesium sulfate were lower than those attacked by sodium sulfate. PA mortar using 100% pumice aggregate as standard sand developed the sulfate resistance of cement mortars.

Freeze and thaw resistance results of specimens are given in Table 5. Test results indicate that the residual compressive strength of PC control mortar after 25-freeze-thaw cycles is 94%. The residual compressive strength of PA mortar is 111% which means that freeze-thaw cycle cause increases in compressive strength. Probably freezing-thawing cycles caused an extra curing effect. The PA mortar exhibits a higher frost resistance due to the existence of voids in pumice aggregate. Turkmen[27] studied that the performance of pumice aggregate concretes exposure to thaw-freeze-thaw test and he found that lightweight concrete containing pumice aggregate was resistant to freeze and thaw than normal weight concrete. The PA mortar exhibits a higher frost resistance due to the existence of voids in pumice aggregate.

Conclusions

Based on the experimental results obtained from this investigation the following conclusions are drawn:

(i) The using of pumice aggregate as sand in mortar decreases the strength of the mortar. This was due to the replacement of strong standard sand by relatively weak pumice aggregate. Mortar using 100% pumice as standard sand developed strength in excess 12 MPa and had a dry density of 1140-1146 kg/m^3 satisfied the criteria for light-weight mortar and it can be used as in cast in place walls, load bearing and non-load bearing purposes.

(ii) The dry unit of pumice aggregate mortar decreased with pumice aggregate due to the replacement of comparatively heavier standard sand by lighter pumice aggregate. Pumice aggregate mortar was about 50% lighter than PC control mortar.

(iii) Water absorption of PA mortar is higher four times than that of PC mortar. Generally, pumice aggregates are porous and will have higher water absorption.

(iv) Residual compressive strength of PA mortar is higher compared with PC mortar when subjected to fire at high temperatures. This can be attributed to the less dense pore structure of PA mortar due to the presence of porous sand. The weight loss of PA mortar is higher than that of PC mortar after high temperatures.

(v) PA aggregate developed the sulfate resistance of cement mortars. The compressive strength reduction was higher than in sodium sulfate solution compared to magnesium sulfate solution.

(vi) PA mortar exhibits a higher frost resistance due to the existence of voids in pumice aggregate.

The advantage of this research is that pumice aggregate mortar reduces the weight of structure up to 50% compared to common mortars and at the same time it provides some advantages such as fire resistance, sulphate resistance and freeze-thaw resistance. It was concluded that pumice fine aggregate mortar can be used in the production of lightweight mortar for load bearing or non-load bearing purposes providing less dead load and increasing performance of mortar.

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