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High Strength Lightweight Concrete Made with Ternary Mixtures of Cement-Fly Ash-Silica Fume and Scoria as Aggregate

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Abstract

This paper presents part of the results of an ongoing laboratory study carried out to design a structural lightweight high strength concrete (SLWHSC) made with and without ternary mixtures of cement-fly ash-silica fume. In the mixtures, lightweight basaltic-pumice (scoria) aggregate was used. A concrete mixture made with lightweight scoria, and another lightweight scoria concrete mixture incorporating 20% fly ash and 10% silica fume as a cement replacement, were prepared. Two normal weight concretes were also prepared for comparison purposes. The 28 day compressive strength and air dry unit weight of structural lightweight concrete (SLWC) varied from 28 to 37 MPa and 1800 to 1860 kg/m^3, respectively. Laboratory test results showed that structural lightweight concrete SLWC of 30 MPa at 28 days can be produced by the use of scoria. However, the use of mineral additives seems to be mandatory for the production of SLWHSC of 35 MPa or higher grade.

Key words: Lightweight concrete, Scoria, Fly ash, Silica fume.

Introduction

Earthquake forces, which affect civil engineering structures and buildings, are proportional to the mass of such structures and buildings. Therefore, reducing the mass of the structure or building is of the utmost importance in reducing seismic risk. This can be achieved by the use of lightweight concrete in construction.

Structural lighweight concrete (SLWC) also has obvious advantages of a higher strength/weight ratio, better tensile strain capacity, a lower coefficient of thermal expansion, and superior heat and sound insulation characteristics due to air voids in the lightweight aggregate (Topcu, 1997; Khaiat and Haque, 1998). Furthermore, Topcu (1997) reported that the reduction in the dead weight of a building by the use of lightweight concrete could result in a decrease in the cross section of steel reinforced columns, beams, plates and foundations. It is also possible to reduce steel reinforcement.

Quite a few studies have been done on lightweight concrete. For instance, Khaiat and Haque (1998) studied the effect of initial curing on the early strength and physical properties of lightweight concrete. They produced a lightweight concrete with 50 MPa cube compressive strength and 1800 kg/m^3 fresh unit weight. Alduaij *et al.* (1999) studied the lightweight concrete in coastal areas by using different unit weight aggregates, including lightweight crushed bricks, lightweight expanded clay and normal weight gravel, by the exclusion of natural fine aggregate (no-fines concrete). They obtained a lightweight concrete with 22 MPa cylinder compressive strength and 1520 kg/m^3 dry unit weight at 28 days. In addition, Demirboga *et al.* (2001) reported the results of an extensive laboratory study involving the evaluation of the effect of expanded perlite aggregate and mineral admixtures on the compressive strength of low-density concretes. They concluded that the addition of mineral admixtures increased the compressive strength of concrete produced with lightweight expanded perlite aggregate. Rossignolo *et al.* (2003) reported the results of SLWC made with expanded clay. In their study, the amount of cement varied from 440 to 710 kg/m^3. They reported that the 28 day moist cured compressive strength and the dry unit weight varied from 39.5 to 53.6 MPa and from 1460 to 1605 kg/m^3, respectively. Furthermore, Altun and Haktanir (2001) suggested the use of composite reinforced concrete in structural members. Composite reinforced concrete consists of 2 layers, the lower being cast as normal weight concrete (NWC) and the upper as a layer of SLWC, both of which are placed in the fresh phase, the SLWC overlying the NWC. They reported that composite reinforced concrete elements behave similarly to normal reinforced concrete elements, with the advantage of a reduction in dead weight.

Although there are numerous reports available in the literature on using lightweight aggregate either in SLWC production or lightweight concrete blocks (Alduaij *et al.*, 1999; Demirboğa *et. al.,* 2001; Khaiat and Haque, 1998; Altun and Haktanır; 2001, Rossignolo *et al.*; 2003), there are few published studies on the use of basaltic pumice(scoria) in SLWC. Studies on SLWC made with a ternary mixture of cement-fly ash and silica fume are rare.

The aim of this study is 2-fold. One is to design a SLWC by the use of scoria, which will provide the advantage of reducing dead weight of structures. The second is to obtain a more economical and greener (environmentally friendly) SLWC mixture by the use of mineral admixture fly ash and silica fume.

Materials Used in the Investigation

Cement

The cement used was ASTM Type I normal Portland cement ((NPC) 42.5 N/mm^2). The specific gravity of the cement used was 3.15. Initial and final setting times of the cement were 4 and 5 h, respectively. The Blaine specific surface area was 3140 cm^2/g, and its chemical compositions are given in Table 1.

Fly Ash

The fly ash was obtained from the Afşin-Elbistan Thermal Power Plant in Turkey. It contained high amounts of calcium and sulfate (Erdogan, 1997; Tokyay and Erdogdu, 1998). The fly ash was class C, since it was obtained from lignite coal (ASTM C618, 1991). The total fly ash reserves are about 3.2 million a year. The chemical composition is given in Table 1. The specific gravity was 2.70 and the Blaine specific surface area 2900 cm^2/g. The amount of fly ash remaining on a 45 μm sieve was 14%.

Some standard specifications (ASTM C618, 1991; BSI 3892, 1992; EN 450, 1994; TSI 450, 1998) and properties of the fly ash are given in Table 2, which shows that the Afşin-Elbistan fly ash does not fully comply with the standards.

Table 1. Chemical composition of cement, fly ash and silica fume(%).

Oxide (1)	Cement (2)	Fly Ash (3)	Silica Fume (4)
SiO_2	20.65	18.95	81.40
Al_2O_3	5.60	7.53	4.47
Fe_2O_3	4.13	3.82	1.40
CaO	61.87	51.29	0.82
MgO	2.60	1.58	1.48
SO_3	2.79	12.06	1.35
K_2O	0.83	1.51	NA
Na_2O	0.14	0.32	NA
LOI	1.39	1.94	7.26

Silica fume

Silica fume was supplied from the Antalya-Etibank ferro-chrome factory in Turkey. The chemical oxide composition of the silica fume is given in Table 1. The specific gravity and unit weight were 2.32 and 245 kg/m^3, respectively. The pozzolanic strength activity index was 122% at 28 days. The amount of silica fume remaining on a 45 μm sieve was 4.8%.

Aggregate

Crushed scoria aggregate was used in the production of lightweight concrete. Scoria was obtained from natural deposits in southern Turkey. Its apparent reserves are about 100 million m^3. The dry unit weight, compressive strength and elastic modulus of the scoria measured according to the International Society for Rock Mechanics (ISRM, 1981) were 1518 kg/m^3, 28.3 MPa and 11.3 GPa, respectively. The specific gravity of the pore-free pulverized scoria was 2.59. Crushed scoria aggregate was separated according to size. It was sieved using standard sieves and separated into 6 groups of 0/0.25 mm, 0.25/0.5 mm, 0.5/1 mm, 1/2 mm, 2/4 mm, 4/8 mm and 8/16 mm. A mixture was made from these 6 groups with a grading that complied with the requirements of TSI 706 (1980).

Table 2. Limits of standards for chemical composition and physical properties of fly ash.

	BSI 3892	ASTM C618 Class C	TSI EN 450	Fly Ash
(1)	(2)	(3)	(4)	(5)
Max moisture	0.5	3	-	-
Max LOI	7.0	6	5.0	2.94
Max SO_3	2.5	5	3.0	12.06
Max MgO	4.0	5	-	1.58
Max alkali	-	1.5	-	1.83
Min SiO_2	-	40	-	18.95
Al_2O_3	-	-	-	-
Fe_2O_3	-	-	-	-
Min SAF	-	50	-	30.3
Max free lime	-	-	1.0-2.5	3
PAI min %	-	75	75% at 28 d 85% at 90 d	84% 92%
Max fineness % (remaining on 45 μm sieve)	12.5	34	40	14
Max expansion	-	-	10 mm	41

Natural river aggregate was used in the production of control NWC. The absorption value of the sand was 1.5% and the specific gravity in saturated surface dry (SSD) condition was 2.65. The gravel was 16 mm maximum nominal size with a 1% absorption value, and its specific gravity (SSD) was 2.73. Grading of the natural aggregate was obtained in the same manner as with the scoria lightweight aggregate.

Concrete Mixture Composition and Sample Preparation

The proportions of the control lightweight scoria concrete mixture were 1:2.5 by mass of NPC and mixed scoria aggregate, respectively. The approximate quantity of NPC was 500 kg/m^3. A ternary SLWC mixture was made using 20% fly ash and 10% silica fume as NPC replacement by weight. The water-binder ratio (W/B) was kept constant at 0.55. Two NWCs were also produced for comparison purposes. One of the NWCs was made with a 0.55 W/B ratio, the other with a 0.45 W/B ratio. The first NWC had the same W/B ratio, and the second had similar slump values to SLWC.

Table 3 shows the composition of the concrete mixtures produced and tested. M1 is the corresponding control lightweight concrete made with NPC. M2 is the lightweight concrete made with a ternary mixture containing fly ash and silica fume. CM1 and CM2 are the control NWCs.

Table 3. Approximate concrete mixture composition per cubic meter (kg).

					Aggregate Fractions (Sieve size in mm) (1)						
Mix Code	C	FA	SF	W	8-16	4-8	2-4	1-2	0.5-1	0.25-0.5	0-0.25
(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
M1	500	0	0	275	300	250	175	125	150	150	100
M2	350	100	50	275	300	250	175	125	150	150	100
CM1	500	–	–	275	390	325	225	165	195	195	130
CM2	500	–	–	225	390	325	225	165	195	195	130

Three and two trial mixes were made for SLWC and NWC, respectively. Fresh unit weights and air dry unit weights of the concrete were measured according to ASTM C138 (2002) and ASTM C567 (2002). The average fresh and air dry unit weights of the concrete are presented in Table 4. Slump values measured according to ASTM C143 (2002) were 7 ± 2, 6 ± 1.5, >20 and 8 ± 1.5 cm for the M1, M2, CM1 and CM2 concrete mixtures, respectively.

Table 4. Fresh and air dry unit weight of concrete (kg/m^3).

Mix Name (1)	Fresh Density (2)	Air Dry Unit Weight (3)
M1	1955 ± 29	1860 ± 23
M2	1913 ± 36	1800 ± 31
CM1	2330 ± 56	2260 ± 45
CM2	2380 ± 47	2290 ± 37

Standard cylindrical specimens having 150 mm in diameter and 300 mm in length, and prismatic specimens with dimensions of 100 x 100 x 500 mm, were prepared from fresh concrete mixtures. The “complete” compaction of the samples was performed by means of vibration.

After 24 h, all the test specimens were demoulded and then cured at constant temperature and relative humidity (RH) conditions of 20 °C and 65% RH to simulate a construction site environment. They were kept in the curing chamber until they were tested. Compressive and flexural strength testings were performed according to ASTM C39 (2002) and ASTM C78 (2002), respectively. For each age, 9 and 6 specimens were employed in compression and flexural strength measurements for SLWC and NWC, respectively.

Results and Discussion

Average fresh unit and air dry weights of the M1, M2, CM1 and CM2 concrete mixtures are given in Table 4 with the standard variation. The comparisons between the air dry unit weight of SLWCs (M1 and M2) and NWCs (CM1 and CM2) show that SLWC has the advantage of reducing the dead weight of a structure by some 20%. This also means that earthquake forces would decrease by about 20% when a structure or building is made with SLWC. Furthermore, the ternary mixture (M2) has a lower fresh and air dry unit weight than the control lightweight concrete mixture (M1).

The average compressive strengths of the standard concrete cylinders are presented in Figure 1. The standard variations of the compressive strength varied from 3% to 9%. Figure 1 shows that lightweight scoria concretes (M1 and M2) made with and without mineral admixtures had lower compressive strength than the control mixture CM2. However, they had a higher compressive strength than the CM1 control NWC at 3 days The lightweight scoria ternary mixture of fly ash-silica fume concrete (M2) developed higher compressive strength than the control lightweight scoria concrete (M1) at 7 days and beyond. Furthermore, the compressive strengths of the M1 mixture were similar to the CM1 control NWC mixture at 7 days and beyond. However, these were lower than the compressive strengths of the CM2 control NWC mixture at all ages.

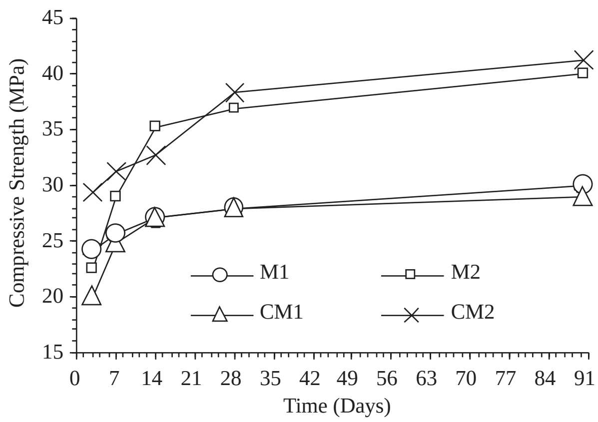

Figure 1. Compressive strength of concrete vs time.

M2 lightweight fly ash-silica fume concrete developed a comparable compressive strength to the CM2 control NWC at 7 days and beyond. The CM2 NWC mixture developed higher compressive strength than its counterpart, the CM1 NWC mixture. This was expected, because the water: cement ratios of CM2 and CM1 were 0.45 and 0.55, respectively.

The average flexural tensile strengths of the concretes are presented in Figure 2. The standard variations of the flexural strength varied from 2% to 7%. It can be seen from Figure 2 that M1 scoria lightweight concrete developed a flexural tensile strength than higher or comparable to the other types of concrete at 3 days.

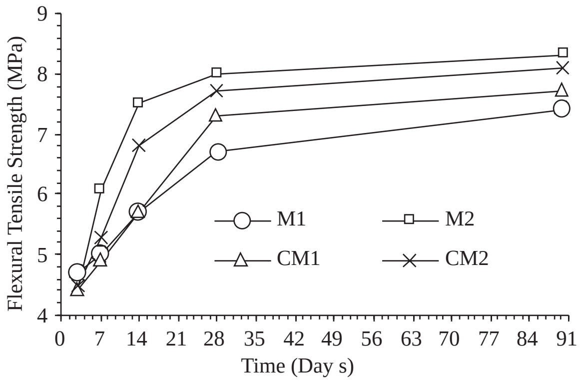

Figure 2. Flexural tensile strength of concrete vs. time.

The M2 scoria lightweight ternary mixture showed higher flexural tensile strength than not only M1 scoria SLWC, but also the CM1 and CM2 control NWCs from 7 days and beyond. This is due to the pozzolanic and filler effects of the ternary mixture binder, as well as better adherence being provided by the porous surface of the scoria lightweight aggregate. In general, all concretes produced developed flexural tensile strengths ranging from 6.5 to 8 MPa at 28 days.

Based on the laboratory test results, it was concluded that scoria lightweight aggregate can be used in the production of SLWC with 30 MPa cylinder compressive strength and about 7 MPa flexural tensile strength at 28 days. It was also concluded that a ternary SLWC mixture made with scoria aggregate promised to produce low cost and environmentally friendly SLWHSC, since it developed 37 MPa 28 day compressive strength that is higher than 35 MPa, which is regarded as the lower limit of compressive strength for SLWHSC (Holm, 1994; Holm and Bremner, 2000). When the lower limit of high strength concrete proposed by ACI 363R-92 (1992) was considered, the present concrete would be SLWC. However, the authors think that the definition of high strength concrete made by ACI 363R-92 also applies to NWC.

It should be noted that in Turkey the use of class C20 concrete, which means a concrete mixture with a cylinder compressive strength of 20 MPa, is common in reinforced concrete due to earthquake specifications (IMO, 1997). It should also be noted that some parts of southern Turkey are in the first seismic danger zone, while other parts are in the second seismic danger zone.

Based on the above results, it can be concluded that a SLWC with a cylinder compressive strength of 30 MPa, meaning C30, can be produced by the use of scoria. In addition, a SLWC with a cylinder compressive strength of 35 MPa (C35) can be produced with a ternary mixture and by the use of lightweight aggregate. The present lightweight concrete can be utilized in southern Turkey to reduce the risks from earthquake acceleration.

Conclusion

Based on the results of the present experimental work, scoria lightweight aggregate can be used in the production of SLWC. The use of a non-standard fly ash, which will reduce costs and environmental pollution, seems to be practicable in ternary lightweight concrete mixtures. The use of ternary mineral additives can reduce the dead weight further and increase strength. Therefore, it is possible to produce scoria ternary SLWHSC with 30 to 40 MPa cylinder compressive strength. Finally, the lightweight scoria aggregate can be utilized to reduce earthquake forces by using it in the production of SLWC and SLWHSC with 1800–1860 kg/m^3 air dry unit weight. Further tests on the strength of the concrete are in progress.

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