Pergamon

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Cement and Concrete Research 33 (2003) 1595–1599

CEMENT AND CONCRETE RESEARCH

High-strength lightweight concrete made with scoria aggregate containing mineral admixtures

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Received 22 August 2002; accepted 31 March 2003

Abstract

This paper presents a part of the results of an ongoing laboratory work carried out to design a structural lightweight high strength concrete (SLWHSC) made with and without mineral admixtures. In the mixtures, basaltic-pumice (scoria) was used as lightweight aggregate. A control lightweight concrete mixture made with lightweight basaltic-pumice (scoria) containing normal Portland cement as the binder was prepared. The control lightweight concrete mixture was modified by replacing 20% of the cement with fly ash. The control lightweight concrete mixture was also modified by replacing 10% of the cement with silica fume. A ternary lightweight concrete mixture was also prepared modifying the control lightweight concrete by replacing 20% of cement with fly ash and 10% of cement with silica fume. Two normal weight concrete (NWC) were also prepared for comparison purpose.

Fly ash and silica fume are used for economical and environmental concerns. Cylinder specimens with 150 mm diameter and 300 mm height and prismatic specimens with dimension 100 × 100 × 500 mm were cast from the fresh mixtures to measure compressive and flexural tensile strength. The concrete samples were cured at 65% relative humidity with 20 °C temperature. The density and slump workability of fresh concrete mixtures were also measured.

Laboratory test results showed that structural lightweight concrete (SLWC) can be produced by the use of scoria. However, the use of mineral additives seems to be mandatory for production of SLWHSC. The use of ternary mixture was recommended due to its satisfactory strength development and environmental friendliness.
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Keywords: High strength lightweight concrete; Normal weight concrete; Scoria aggregate; Mineral admixtures

1. Introduction

Since the earthquake forces that influence the civil engineering structures and buildings are proportional to the mass of those structures and buildings, reducing the mass of the structure or building is of utmost importance. One of the ways to reduce the mass or dead weight of a structure is the use of lightweight concrete in the construction. Lightweight concrete can easily be produced by utilizing natural lightweight aggregate i.e., pumice or perlite aggregate.

Topçu [1] and Al-Khaiat and Haque [2] reported that structural lightweight concrete has its obvious advantages of higher strength/weight ratio, better tensile strain capacity, lower coefficient of thermal expansion, and superior heat and sound insulation characteristic due to air voids in the lightweight aggregate.

Furthermore, Topçu [1] also reported that the reduction in the dead weight of a construction by the use of lightweight aggregate in concrete could result in a decrease in cross section of columns, beams, plates and foundations. It is also possible to reduce steel reinforcement.

Al-Khaiat and Haque [2] worked on the effect of initial curing on early strength and physical properties of lightweight concrete containing 500 kg/m^3 cement and 50 kg/m^3 condensed silica fume. They produced a lightweight concrete with 50 MPa cube compressive strength and 1800 kg/m^3 fresh density. Also, Alduaij et al. [3] studied lightweight concrete using different unit weight aggregate including lightweight crushed bricks, lightweight expanded clay and normal weight gravel without the use 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. Demirboğa et

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doi:10.1016/S0008-8846(03)00131-5

al. [4] reported results of an extensive laboratory study evaluating the influence 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.

Altun and Haktanir [5] suggested that structural lightweight concrete (SLWC) and normal weight concrete (NWC) be used together in composite reinforced concrete members. The composite reinforced concrete consists of two layers—the lower being cast of NWC and the upper of SLWC, both of which are placed in the fresh phase, the SLWC overlying the NWC. They reported that the composite reinforced concrete elements behaved similarly to normal reinforced concrete elements with the advantage of a substantial reduction in dead weight.

The use of mineral additives in concrete such as fly ash, silica fume, natural pozzolan, metakaolin and calcined clay has become widespread due to their pozzolanic reaction and environmental friendliness [6–8].

There are numerous studies on using lightweight aggregate either in SLWC production or lightweight concrete block [2–5]. However, there are few published study on the use of scoria in SLWHSC. Also, there is not much published material on SLWHSC made with mineral admixtures, particularly, a ternary mixture.

The aim of this study is twofold. First is that designing a structural lightweight concrete by the use of scoria that will provide an advantage of reducing dead weight of a structure. Second is that obtaining more economical and greener (environment friendly) SHSLWC mixture by the use of mineral admixture fly ash and silica fume together and separately.

2. Materials used in the investigation

2.1. Cement

The cement used was ASTM Type I normal Portland cement (NPC 42.5 N/mm^2) with a specific gravity of 3.15 g/cm^3. Initial and final setting times of the cement were 4 and 5 h, respectively. Its Blaine specific surface area was 3140 cm^2/g and its chemical compositions are given in Table 1.

2.2. Fly ash

The fly ash (FA) used was obtained from the electricity-generating Afsin-Elbistan Thermal Power Station in Southern Turkey. It is a high-calcium and high-sulphate fly ash [6,9,10]. Its total reserve is about 3.2 million ton a year. Its chemical composition is given in Table 1. Its specific gravity was 2.70 g/cm^3 and Blaine specific surface area was 2900 cm^2/g. Remaining of FA on the 45 μm sieves was 14%. It is class C fly ash, since it is obtained by burning the lignite coal [9–11]. SiO_2 and SO_3 content of the current fly ash are 18.95% and 12.06%, respectively. ASTM C-618 [9] requires that minimum SiO_2 and maximum SO_3 content of fly ash should be 40% and 3%, respectively. These results prove that it is a nonstandard fly ash [9]. Although the fly ash chosen was nonstandard, it was shown in the other studies [11–13] that it could be utilized in NWC of cement replacement up to 20% by weight. Therefore, in this study, it was also chosen for use in this study.

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

Oxide composition	Cement (C)	Fly ash (FA)	Silica fume (SF)
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	n/a
Na_2O	0.14	0.32	n/a
LOI	1.39	1.94	7.26

2.3. Silica fume

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

2.4. Aggregate and its grading

Crushed basaltic-pumice (scoria) was used as the aggregate in the production of lightweight concrete. Scoria was obtained from natural deposits in Osmaniye city (Turkey). Its apparent reserve is about 100 million m^3. Bulk dry unit weight, water absorption value, compressive strength and elastic modulus of scoria were 1518 ± 43 kg/m^3, 17 ± 3%, 28.3 ± 5.7 MPa and 11.3 ± 2.1 GPa, respectively. Specific gravity of scoria is 2.59. Crushed basaltic-pumice (scoria) aggregate was separated according to their size. It was sieved using standard sieves and separated into six group consisting of 0/0.25, 0.25/1, 1/2, 2/4, 4/8 and 8/16 mm. A combination of separated aggregate was obtained with such a grading that complied with the requirements of TSI 706 [14].

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

Crushed basaltic-pumice (scoria) and natural river aggregate were used in dry conditions for the production of the concrete.

3. 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.

Fly ash SLWC mixture was made using 20% fly ash as NPC replacement. Silica fume SLWC was made using 10% silica fume as cement replacement. Ternary SLWC mixture was made using 20% fly ash and 10% silica fume as NPC replacement. Water–binder ratio (W/B) of lightweight concrete was kept constant at 0.55. Two NWCs were also produced for comparison. One of the NWCs was made with 0.55 W/B, the other NWC was made with 0.45. The NWC had the same W/B and the same slump and workability as the SLWC.

Table 2 presents the composition of the concrete mixtures produced and tested. M1 is the corresponding controls lightweight scoria concrete made with NPC. M2 mixture is lightweight concrete made with 20% fly ash replacement. M3 mixture is lightweight concrete made with 10% silica fume replacement. M4 mixture is lightweight concrete made with ternary mixture containing 20% fly ash and 10% silica fume. CM1 and CM2 are the control NWC concretes made with 0.55 and 0.45 W/B, respectively.

Three and two trial mixes were made for SLWC and NWC mixtures, respectively. The average of fresh and air-dry unit weight of the concrete were presented in Table 2. Slump values were 70 ± 20, 60 ± 15, 50 ± 15, 60 ± 25, >200, 80 ± 15 mm for M1, M2, M3, M4, CM1 and CM2 concrete mixtures, respectively.

Cylindrical samples with 150 mm diameter and 300 mm length, and prism samples with dimensions of $100 \times 100 \times 500$ mm were cast from fresh concrete mixtures. The compaction of the samples was obtained by means of vibration.

All the test specimens were demoulded at 1 day and then cured at 20 °C and 65% RH to simulate a real-life environment until tested. For each age, nine and six specimens were employed in compression and flexural strength measurement for SLWC and NWC, respectively.

4. Results and discussions

Average fresh and air dry unit weight of M1, M2, M3, M4, CM1 and CM2 concrete mixtures were given in Table 2 with the standard variations. The comparisons of the air-dry unit weight of SLWCs (M1, M2, M3 and M4) with NWCs (CM1 and CM2) shows that SLWC has a reduced average dead weight of 20%. This also means that the earthquake forces will be reduced by about 20% if a structure was made with SLWC. Furthermore, ternary mixture, M4, has lower fresh and air-dry unit weight than M1, M2 and M3 mixtures.

The average cylinder compressive strengths of the concrete are presented in Fig. 1. The standard variations of the compressive strength varied from 3% to 9%. Compressive strengths at 28 days and 3 months are given in Table 3. Fig. 1 shows that lightweight scoria concrete (M1, M2, M3 and M4) made with and without mineral admixtures (fly ash and silica fume) have lower compressive strength than that of control mixture CM2. These concretes, however, had comparable or higher compressive strength than that of control NWC (CM1) at 3 days of age.

Fly ash SLWC mixture (M2) developed comparable compressive strength to the control lightweight scoria concrete (M1) developed at 3 and 7 days of age. It, however, developed higher strength at 28 days and 3 months of age.

Silica fume SLWC mixture (M3) developed higher compressive strength than that of the control lightweight scoria concrete (M1) and fly ash SLWC mixture (M2) and ternary SLWC mixture (M4) at all ages.

Lightweight scoria ternary mixture of fly ash–silica fume concrete (M4) developed higher compressive strength than the control lightweight scoria concrete (M1) and fly ash SLWC mixture (M2) developed at all ages.

The compressive strength development of lightweight scoria ternary mixture of fly ash–silica fume concrete (M4) was between M1–M2 and M3 mixtures.

Furthermore, compressive strength of M1 and M2 mixture were similar to CM1 control NWC mixture at 7 days and beyond, however, it was lower than that of compressive strength of CM2 control NWC mixture at all ages.

M3 and M4 lightweight silica fume and ternary mixture concrete developed similar or higher compressive strength than that of CM2 control NWC at 7 days and beyond. They developed higher strength than that of CM1 control NWC mixture at all ages.

Table 2
Approximate concrete mixture composition (kg) and densities (kg/m^3) of a cubic meter concrete

Concrete materials					Aggregate fractions (sieve size in mm)							Density (kg/m^3)	
Mix code	C	FA	SF	W	8–16	4–8	2–4	1–2	0.5–1	0.25–0.5	0–0.25	Fresh	Air dry
M1	500	0	0	275	300	250	175	125	150	150	100	1955 ± 29	1860 ± 23
M2	400	100	0	275	300	250	175	125	150	150	100	1932 ± 21	1850 ± 18
M3	450	0	50	275	300	250	175	125	150	150	100	1944 ± 25	1820 ± 28
M4	350	100	50	275	300	250	175	125	150	150	100	1913 ± 36	1800 ± 31
CM1	500	–	–	275	390	325	225	165	195	195	130	2330 ± 56	2260 ± 45
CM2	500	–	–	225	390	325	225	165	195	195	130	2380 ± 47	2290 ± 37

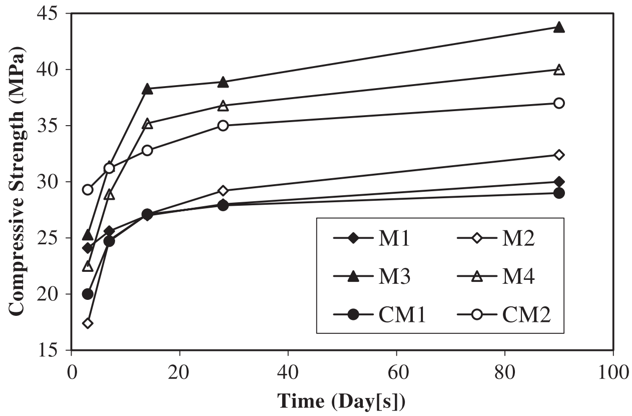

Fig. 1. Compressive strength of concrete.

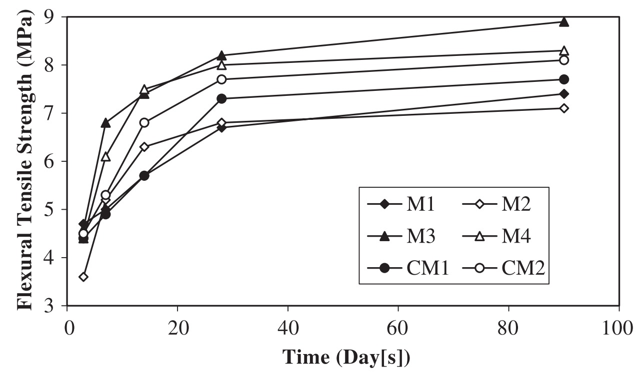

Fig. 2. Flexural tensile strength of concrete.

The average flexural tensile strength of the concrete studied was presented in Fig. 2. The standard variations of the flexural strength were 2% to 7%. Flexural tensile strengths at 28 days and 3 months are given in Table 3. It can be seen from Fig. 2 that M1 scoria lightweight concrete developed higher or comparable flexural tensile strength to other concretes at 3 days of age.

Fly ash SLWC mixture (M2) developed comparable flexural tensile strength to the control lightweight scoria concrete (M1) at all ages.

Furthermore, flexural tensile strength of M1 and M2 mixture were comparable to CM1 control NWC mixture, however, it was lower than that of flexural tensile strength of CM2 control NWC mixture.

M3 and M4 silica fume and ternary mixture concrete showed superior flexural tensile strength to not only M1 and M2 scoria SLWC but also CM1 and CM2 control NWC from 3 days and beyond. M4 ternary mixture concrete developed comparable flexural tensile strength to M3 silica fume lightweight concrete. This is due to pozzolanic and filler effect of silica fume and fly ash mixture binder as well as proper adherence provided by porous scoria lightweight aggregate. In general, all the concretes produced developed satisfactory flexural tensile strength ranging from 6.5 to 8.5 MPa at 28 days of age.

The ternary SLWC mixture (M4) made with scoria aggregate developed 37 MPa compressive strength and 8 MPa flexural tensile strength at 28 days. The strength achieved is higher than 35 MPa, which is accepted as lower limit of compressive strength for SLWHSC [15,16].

It should be noted that, in Turkey, the use of class C20 concrete, which means a concrete with cylinder compressive strength of 20 MPa, is a common practice in reinforced concrete for specifications where earthquakes are expected [17]. It should also be noted that, some parts of Southern Turkey are in the first seismic danger zone, while some parts of it are in the second and less severe seismic danger.

Based on the above laboratory research results, it can be concluded that an SLWC with a cylinder compressive strength of 30 MPa (C30) can be produced by the use of lightweight aggregate. Also, an economical SLWC with a cylinder compressive strength of 30 MPa (C30) can be produced with fly ash. Also, an SLWHSC with a cylinder compressive strength of 40 MPa (C40) can be produced with silica fume. In addition, an SLWHSC with a cylinder compressive strength of higher than 35 MPa (C35) can be produced with ternary mixture.

Performance testing results of the concrete studied, i.e., drying shrinkage, porosity, water and gas permeability, carbonation, abrasion resistance, resistance to carbonation, etc., will be published in due course.

Table 3
Compressive and flexural tensile strength of concrete (MPa) at 28 days and 3 months

Mix code	Compressive strength		Tensile strength	
	28 days	3 months	28 days	3 months
M1	28.0	30.0	6.7	7.4
M2	29.2	32.4	6.8	7.1
M3	38.9	43.8	8.2	8.9
M4	36.8	40.0	8.3	8.3
CM1	27.9	29.0	7.3	7.7
CM2	35.0	37.0	7.7	8.1

5. Conclusion

Based on the results of experimental work, scoria lightweight aggregate can be used in the production of SLWC. The use of a nonstandard fly ash, which will reduce the cost and environmental pollution, is possible for both fly ash SLWC and ternary mixtures. It is possible to produce a lightweight concrete with a 40 MPa cylinder compressive strength by the use of silica fume. The use of mineral additives in structural lightweight concrete can reduce the dead weight further and increase strength. In summary, the lightweight scoria aggregate can be utilized in its locality to reduce the risk of earthquake acceleration by using it in the production of SLWC and SLWHSC.

Acknowledgements

The authors thank Çukurova University Scientific Research Projects Directorate that supported this study (Project No: MMF 2002 BAP 48).

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