Cement & Concrete Composites 25 (2003) 77–82

Cement & Concrete Composites

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Properties of high-performance LWAC for precast structures with Brazilian lightweight aggregates

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Received 10 May 2000; accepted 18 May 2001

Abstract

An experimental study was carried out to examine five mixtures made with selected Brazilian lightweight aggregates in order to produce lightweight aggregate concrete (LWAC) for slim precast components. Flow (initial and after 2 h), air content, compressive strength, tensile strength (flexural and splitting), modulus of elasticity and deformation were studied. The 7-day compressive strength and the dry concrete density varied from 39.7 to 51.9 MPa and from 1460 to 1605 kg/m^3, respectively. The results of this pilot study suggest that there are possibilities of producing slim precast components using high-performance lightweight concrete with Brazilian lightweight aggregates.

Keywords: Lightweight aggregate concrete; High performance; Properties; Expanded clay

1. Introduction

Lightweight aggregate concrete (LWAC) has been used successfully for structural purposes for many years. For structural applications of lightweight concrete, the density is often more important than the strength. A decreased density for the same strength level reduces the self-weight, foundation size and construction costs. With the rapid development of concrete technology in recent years, higher-performance concrete can be produced more easily. Since 1980, several investigations [1–7] on high-performance lightweight concrete have been reported and there are, of course, worldwide environmental, economic and technical impetuses to encourage the structural use of this material [8].

High-performance lightweight concrete is an ideal construction material in Brazil because of weather conditions and low cost. However, very little information is available on mechanical properties of high-performance lightweight concrete with Brazilian lightweight aggregate (expanded clay) [9,10].

Accordingly, a pilot research project has been developed at the University of São Paulo (São Carlos Engineering School) to investigate the possibilities of producing slim precast concrete components using Brazilian lightweight aggregate ($D_{max} = 9.5$ mm) [11,12]. To broaden the scope of this investigation, the properties of five mixes of high-performance lightweight concrete were investigated. The main objective is to provide some basic information on mechanical properties of high-performance concrete using Brazilian lightweight aggregates.

1.1. Research significance

For structural applications of high-performance lightweight concrete, information on the mechanical properties is very important. The research shows that the mechanical properties of high-performance lightweight concrete are very different from those of high-performance normal weight concrete. This paper provides new information on the compressive strength,

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0958-9465/03/$ - see front matter
PII: S0958-9465(01)00046-4

tensile strength, modulus of elasticity and stress–strain behavior of high-performance lightweight concrete with 7-day compressive strength between 39.7 and 51.9 MPa and corresponding density of 1460–1605 kg/m^3.

2. Materials

2.1. Cement and silica fume

The cement used was high-early-strength Portland cement (CPV-ARI according to NBR-5733 and NBR-5737) marketed by Ciminas S.A., Brazil. The silica fume used was marketed by Microssilica, Brazil. Some physical properties of the cement and silica fume are shown in Tables 1 and 2, respectively.

2.2. Aggregate

A natural quartz sand was used in combination with the two types of Brazilian lightweight aggregates (expanded clay) to form the final aggregate. The maximum aggregate size was 9.5 mm. Table 3 and Fig. 1 describe some physical properties of the aggregates.

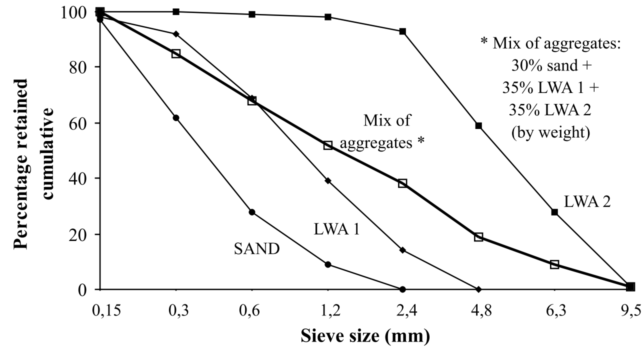

Fig. 1. Aggregates gradation.

2.3. Superplasticizer

The accelerator superplasticizer marketed by MBT Brazil I.C. was used. Table 4 shows the specific density, solid contents and basic ingredients.

Table 1
Some properties of cement used

Type	Specific density (g/cm^3)	Blaine fineness (cm^2/g)	Setting time (min)	
			Initial	Final
High-early-strength Portland cement	3.12	4687	130	210

Table 2
Some properties of silica fume used

Type	Specific density (g/cm^3)	Unit weight (kg/m^3)	Specific surface area (cm^2/g)	% SiO_2
Silica fume	2.21	200	18 000	94.3

3. Experimental program

The method adopted for the design was experimental and the quantities required for approximately 1 m^3 of finished concrete for five mixes are given in Table 5. The cement proportion varied from 440 to 710 kg/m^3 [2]. Silica fume was used in a dosage of 10% [11,12] as a replacement of cement (by weight). The $w/(c+s)$ ratio varied from 0.37 to 0.54, where w is the total water in the mix. For all mixes the aggregate was composed (by weight) of 30% of natural sand, 35% of lightweight aggregate type 1 and 35% of lightweight aggregate type 2. All mixes had 1.5% [11,12] of accelerator superplasticizer by weight of cement. The flow (NBR-7215, flow table) for all mixes was in the range of 200 ± 10 mm.

The materials were mixed in a mixer in the following order:

Table 3
Physical properties of aggregates

Type of aggregate[a]	D_{max} (mm)	Specific density (g/cm^3)	Particle density (g/cm^3)	Water absorption (% by weight)		
				5 min	60 min	24 h
Sand	2.4	2.63	1.49	–	–	–
LWA 1	4.8	1.51	0.86	0.7	2.7	6.0
LWA 2	9.5	1.11	0.59	1.3	3.5	7.0

[a] LWA: lightweight aggregate.

Table 4
Superplasticizer specifications

Type	Basic ingredients	Specific density (g/cm^3)	Solid contents (%)
Accelerator Superplasticizer	Sulfonated melamine formaldehyde	1.11	16.49

Table 5
Mix proportion of the concretes

Mix number	Cement (kg/m^3)	$w/(c+s)$	Mix proportions (weight) C:S:NS:LWA1:LWA2[a]
1	710	0.37	1:0.1:0.27:0.315:0.315
2	613	0.41	1:0.1:0.35:0.403:0.403
3	544	0.45	1:0.1:0.42:0.490:0.490
4	484	0.49	1:0.1:0.50:0.578:0.578
5	440	0.54	1:0.1:0.57:0.665:0.665

[a] Cement:silica fume:natural sand:lightweight aggregate type 1:lightweight aggregate type 2.

1. half of the water, cement and sand (mixed for about 2 min);
2. remaining water, superplasticizer and silica – previously mixed – (mixed for about 2 min);
3. dry lightweight aggregate.

Then the mixing continued until a uniform concrete was obtained, usually after 5 min.

The specimen were cast in steel molds and compacted on a vibration table. After 24 h, they were demolded and stored in a control room maintained at 95% of relative humidity (RH) and 23 ± 2°C, until the day of the test. Immediately before testing, the free surface water was removed with a towel.

The compressive strength and splitting tensile strength were tested using 100×200-mm cylinders, while the flexural strength was tested using $150 \times 150 \times 500$-mm prisms. The modulus of elasticity was obtained from testing 100×200-mm cylinders at a constant loading rate of 0.50 ± 0.05 MPa/s. The modulus of elasticity was calculated based on the stress corresponding to 30% of the ultimate load and the longitudinal strain produced by this stress. The stress–strain diagrams reached 80% of ultimate load. All the tests were conducted in accordance with the Technical Standards Brazilian Association ABNT (NBR). As the lightweight concrete was designed for high early strength, since this material is for precast components, all tests were carried out at 7 days, except for the compressive strength, which was tested at the ages of 1, 3, 7, 28 and 63 days.

4. Results and discussion

4.1. Properties of fresh concrete

Table 6 shows the properties of fresh concrete. The lightweight concrete used in this study was very cohesive and workable. The maximum and minimum values of the density of the fresh concrete were 1717 and 1583 kg/m^3, respectively. Although the aggregates were used in dry state, the lightweight concrete showed, on average, a flow loss of 26 mm in the 2 h after completion of mixing. On average, the air content of the concrete was 2.7%.

4.2. Compressive strength and density

The compressive strength and density of the concrete are summarized in Table 7. The 7-day compressive strength and the dry concrete density varied from 39.7 to

Table 6
Properties in the fresh state

Mix number	Density (kg/m^3)	Flow (mm)	Flow after 2 h (mm)	Air content (%)	$w/(c+s)$
1	1717	198	172	2.3	0.37
2	1658	203	184	3.2	0.41
3	1633	199	182	2.5	0.45
4	1592	198	164	3.3	0.49
5	1583	198	163	2.5	0.54

Table 7
Compressive strength and density

Mix number	Compressive strength (MPa)					Density oven dry (kg/m^3)
	1-day	3-day	7-day	28-day	63-day	
1	40.4	44.6	51.9	53.6	53.7	1605
2	36.5	41.9	48.8	50.0	51.2	1573
3	32.0	38.9	45.2	45.9	48.2	1532
4	28.8	36.7	42.7	43.0	46.2	1482
5	25.0	34.2	39.7	39.5	43.8	1460

51.9 MPa and from 1460 to 1605 kg/m^3, respectively. If one takes the density of normal weight concrete as 2200 kg/m^3, there is a saving in the self-weight between 27% and 36%. Fig. 2 shows the relationship between the density of dry concrete and the 7-day compressive strength also compared to the normal weight concrete (NWC) based on the basalt aggregate reported by Ferreira Júnior [13].

All concrete mixes essentially stopped gaining strength between the ages of 7 and 63 days. This may be attributed to the use of the high-early-strength Portland cement and accelerator superplasticizer. Besides, this indicates that the compressive strength had probably reached an upper level for the aggregate, and the strength does not benefit very much from a further improvement of the mortar strength. The results show that the compressive strength of the lightweight concrete has a larger scatter and becomes more brittle when the strength increases. This may be attributed to the influence of the lightweight aggregate.

Fig. 3 shows the relationship between the 7-day material efficiency [3,14] (compressive-strength/density ratio) and cement proportion for lightweight concrete and NWC [13]. The results clearly demonstrate that this lightweight concrete had high material efficiency.

Fig. 4 shows the 7-day compressive strength as correlated with cement proportion for lightweight concrete and NWC [13]. As it can be seen from the figure, the proportion in cement of the LWAC is larger than that of the normal weight concrete for the same compressive strength.

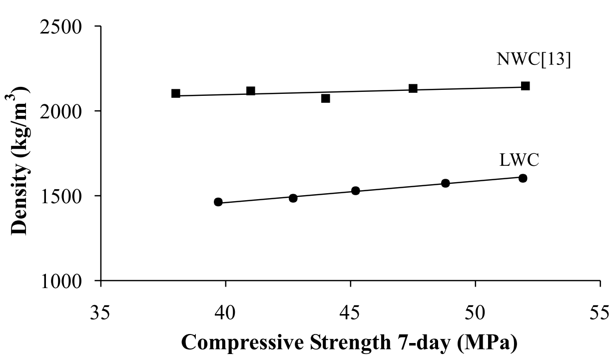

Fig. 2. Relationship between 7-day compressive strength and the density.

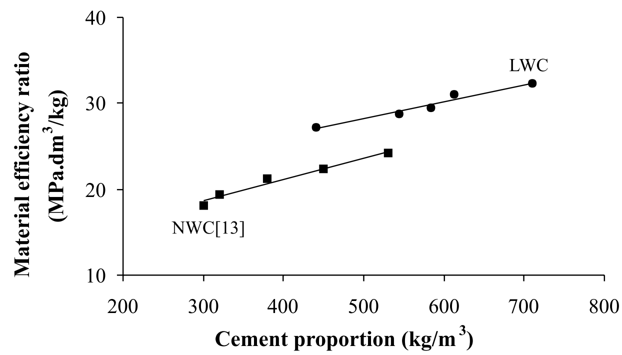

Fig. 3. Relationship between 7-day material efficiency and cement proportion.

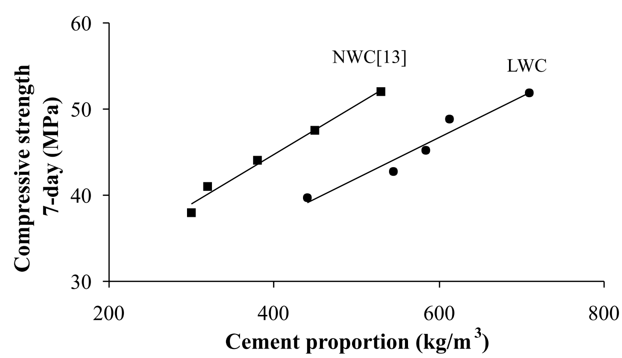

Fig. 4. Relationship between 7-day compressive strength and cement proportion.

4.3. Tensile strength

The flexural and splitting tensile strength varied from 3.1 to 5.3 MPa and from 2.7 to 4.0 MPa, respectively (see Table 8). However, the tensile/compressive strength ratio was lower for high-performance lightweight concrete than that for high-performance normal weight concrete. Fig. 5 shows the observed relationship between the flexural and the 7-day compressive strengths. For comparison, a similar relationship for normal weight concrete based on basalt aggregate [13] is also included

Table 8
7-Day tensile strength

Mix number	7-Day tensile strength (MPa)	
	Flexural	Splitting
1	5.3	4.0
2	5.0	3.7
3	3.5	3.3
4	3.3	3.0
5	3.1	2.7

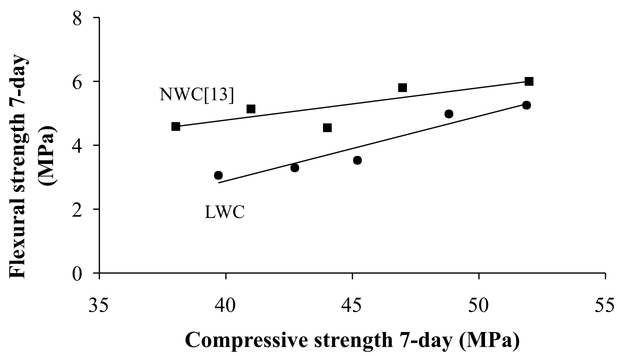

Fig. 5. Relationship between flexural tensile and 7-day compressive strength.

in the diagram. As can be seen from the figure, the flexural tensile strength of the LWAC is less than that of the normal weight concrete for the same compressive strength. For the lightweight concrete, the relationship between the flexural tensile strength and the 7-day compressive strength follows:

$$f_{ctM} = 0.2f_{ck} - 5.0, \quad (1)$$

where f_{ctM} is the flexural tensile strength (MPa) and f_{ck} is the compressive strength (MPa).

Fig. 6 shows the relationship between the splitting tensile strength and the 7-day compressive strength.

The relationship between the splitting tensile strength and the compressive strength is given by

$$f_{tD} = 0.1f_{ck} - 1.2, \quad (2)$$

where f_{tD} is the splitting tensile strength (MPa) and f_{ck} is the compressive strength (MPa).

4.4. Modulus of elasticity and stress–strain behavior

Table 9 shows the results of modulus of elasticity for lightweight concrete. The modulus of elasticity of the lightweight concrete varied from 12.0 to 15.2 GPa, which was very much lower than that of normal weight concrete. Fig. 7 shows the correlation between the modulus of elasticity and the 7-day compressive strength. It can be observed that, for the range of strengths and the types of aggregates investigated, the modulus does not

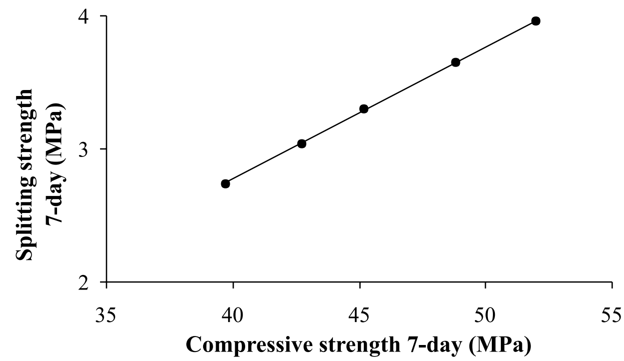

Fig. 6. Relationship between splitting tensile and 7-day compressive strength.

Table 9
Modulus of elasticity

Mix number	Modulus of elasticity (GPa)
1	15.2
2	13.5
3	12.9
4	12.3
5	12.0

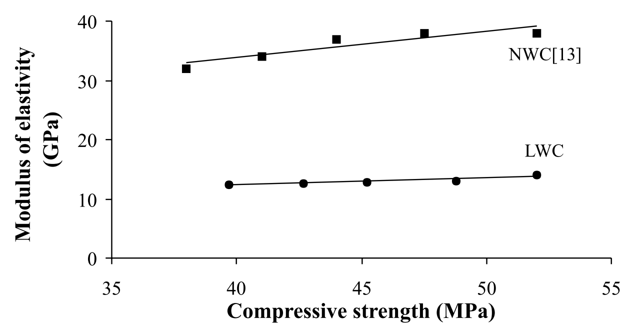

Fig. 7. Relationship between modulus of elasticity and 7-day compressive strength.

increase as the compressive strength increases. For comparison, a similar relationship for normal weight concrete based on basalt aggregate [13] is also included in the diagram.

The relationship between modulus of elasticity and 7-day compressive strength is given by

$$E_0 = 0.12f_{ck} + 7.5, \quad (3)$$

where E_0 is the modulus of elasticity in GPa and f_{ck} is the compressive strength in MPa.

Fig. 8 shows the stress–strain curves for the concrete mixes up to 80% of ultimate. The strain at 80% ultimate load for the lightweight concrete varied from 2.6 to 3.0 mm/m. This is higher than that typically observed for

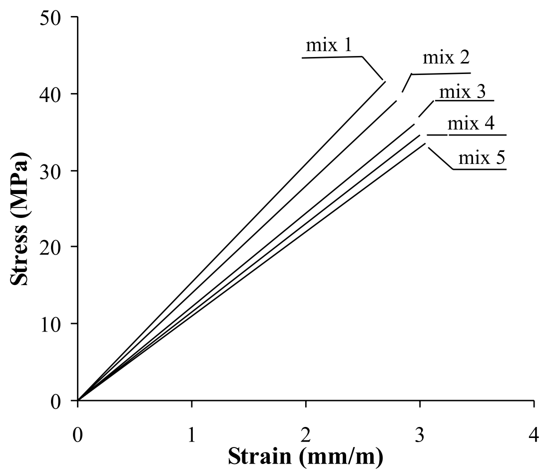

Fig. 8. Stress–strain behavior (80% ultimate load).

normal weight concrete at the same compressive strength level. For the lightweight concrete analyzed, the shape of the ascending part of stress–strain is very linear.

5. Conclusions

In the fresh state the high-performance lightweight concrete with Brazilian lightweight aggregates was very cohesive and workable. Although lightweight aggregates were used in dry state, the lightweight concrete showed very good workability 2 h after completion of mixing.

The results of compressive strength of high-performance lightweight concrete were lower than those of the normal weight concrete. However, the lightweight concrete showed high material efficiency ratio.

The flexural and splitting tensile strength varied from 3.1 to 5.3 MPa and from 2.7 to 4.0 MPa. However, the tensile/compressive strength ratio was lower for high-performance lightweight concrete than for high-performance normal weight concrete.

The modulus of elasticity of the lightweight concrete was much lower than that of normal weight concrete of same strength. The strain at 80% ultimate load for the lightweight concrete was higher than that typically observed for normal weight concrete at the same compressive strength level. This demonstrates that the high-performance lightweight concrete is very ductile. For the lightweight concrete analyzed, the shape of the ascending part of stress–strain is very linear up to 80% of ultimate.

Acknowledgements

The authors would like to acknowledge the financial support received from FAPESP, Fundação de Amparo à Pesquisa do Estado de São Paulo, Brazil.

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