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Some characteristics of high strength fiber reinforced lightweight aggregate concrete

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Abstract

The effect of polypropylene and steel fibers on high strength lightweight aggregate concrete is investigated. Sintered fly ash aggregates were used in the lightweight concrete; the fines were partially replaced by fly ash. The effects on compressive strength, indirect tensile strength, modulus of rupture, modulus of elasticity, stress–strain relationship and compression toughness are reported. Compared to plain sintered fly ash lightweight aggregate concrete, polypropylene fiber addition at 0.56% by volume of the concrete, caused a 90% increase in the indirect tensile strength and a 20% increase in the modulus of rupture. Polypropylene fiber addition did not significantly affect the other mechanical properties that were investigated. Steel fibers at 1.7% by volume of the concrete caused an increase in the indirect tensile strength by about 118% and an increase in the modulus of rupture by about 80%. Steel fiber reinforcement also caused a small decrease in the modulus of elasticity and changed the shape of the stress–strain relationship to become more curvilinear. A large increase in the compression toughness was recorded. This indicated a significant gain in ductility when steel fiber reinforcement is used.

Keywords: High-strength concrete; Lightweight; Aggregate; Fiber reinforcement; Fly ash; Toughness; Strength; Elasticity

1. Introduction

The advantages of structural lightweight concrete over normal weight concrete are numerous and are well recognized [1–4]. Environmentally conscious concrete industry uses lightweight aggregates that are derived from industrial by-products. One of the major by-products is fly ash. It is estimated that the world production of fly ash in the year 2000 was about 600 million tonnes. Of this amount, only about 9% is utilized [5]. In Australia, about 9 million tonnes of fly ash is produced annually, of which <10% is used [1,6]. There is now ample evidence that the concrete industry has become very much aware of the advantages of fly ash use whether as a partial replacement of cement [7], or in the form of lightweight aggregate [8]. Furthermore, producing high-strength lightweight concrete is desirable and has now become practical [9]. Since high strength leads to increased brittleness [10,11], fiber reinforcement should be considered for improving ductility. This is more urgently needed when lightweight aggregate is involved [12–14]. The benefits of fiber reinforcement in lightweight aggregate concrete have been reported more than 25 years now [15]. The vast increase in the use of high-strength concrete, the environmental and economic benefits of lightweight concrete and the ability to produce lightweight high-strength concrete with adequate structural qualities have renewed the interest in using fibers as a necessary reinforcement against brittle failure. Nevertheless, in spite of the advantages that have been reported in this area [16–18], much more research is still needed. This is especially so because of the diversity of the sources from which lightweight aggregates may be obtained. Added to that is the diversity of the types of fibers and the various choices that are available within each type.

The effects of two types of fiber reinforcement on lightweight aggregate concrete is reported in this paper. These are polypropylene and steel fibers. The lightweight aggregate used was sintered fly ash aggregate. The paper reports and discusses the effects of these fibers

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on the compressive, tensile and flexural strength. In addition, it presents and discusses their effects on the modulus of elasticity and on the compression toughness of this type of lightweight aggregate concrete.

2. Experimental details

2.1. Mixes and materials

The following types of mixes were cast and tested:

1. Plain lightweight sintered fly ash aggregate concrete. This mix is referred to as LWplain.
2. Lightweight sintered fly ash aggregate concrete with polypropylene fiber reinforcement, referred to as LWP.
3. Lightweight sintered fly ash aggregate concrete with steel fiber reinforcement, referred to as LWS.
4. Plain normal weight high-strength concrete, referred to as NWHS.

Table 1 shows the manufactured mixes according to the fiber type and content. In the NWHS mix, crushed granite was employed as coarse aggregate and the fine aggregate was river sand. All the lightweight mixes were manufactured using lightweight aggregates only. The lightweight aggregates were sintered fly ash imported from UK and commercially known as Lytag. These aggregates were obtained in different sizes of 2 mm, 6 mm, 3 mm and fine Lytag. 25% of the fines was replaced by fly ash in all mixes except NWHS. This was done to improve the workability and reduce the harshness of the mix that was noticed when the fines consisted of fine Lytag only. The cement was a general purpose Portland cement similar to ASTM type I. Silica fume was applied in all mixes to replace 10% by weight of the cement. A proprietary superplasticizer based on sodium polynaphthalene sulfonate was added at the rate of 1 l per 50 kg of Portland cement. The chemical composition of the cement, fly ash, and silica fume is shown in Table 2. The polypropylene fibers were fibrillated fibers from Fibermesh MD®. Their length is 19 mm and their aspect ratio is 152. The steel fibers were short with slightly enlarged ends from BHP Fibersteel® with the designation 186 EE. They are 18 mm long and have an aspect ratio of 37.5. All mixes were designed such that the fresh concrete had a slump of about 100 mm. Table 3 shows the mix proportions for saturated and surface dry condition of the aggregates. The water absorption of the aggregates within the mixing time was determined and the quantities were adjusted accordingly.

Table 2
Chemical composition of cement, fly ash, and silica fume (% by weight)

Oxide	General purpose cement	Fly ash	Condensed silica fume
SiO_2	21.4	51.8	93
Al_2O_3	4.5	24.4	0.6
Fe_2O_3	3.0	9.62	1.0
CaO	64.4	4.37	0.2
MgO	1.4	1.5	1.2
Na_2O	–	0.34	0.1
K_2O	0.7	1.41	1.0
SO_3	2.4	0.26	0.3
LOI	0.9	–	0.5

2.2. Specimens, curing and testing

For this series of tests, the following specimens were cast from each mix:

- Four 150 × 300 mm cylinders for the modulus of elasticity test. The data obtained from these cylinders were also included in the compressive strength evaluation.
- Further, four 150 × 300 mm cylinders for compressive strength evaluation.
- Four 100 × 200 mm cylinders for the indirect tensile strength testing.
- Three 100 × 100 × 500 mm beams for the modulus of rupture testing.
- Six 100 mm cubes to measure the specific gravity, absorption and water penetrable voids according to ASTM Standard C 642.

The specimens were cured in a fog room maintained at 95 ± 3% RH and 22 ± 2 °C for 28 days before testing. All tests were performed according to the relevant ASTM standards [19] except the one for the modulus of elasticity. The latter was determined by the method conducted by Mor [20] using two linear variable differential transformers (LVDTs) connected to a digital transducer. The data were fed into a personal computer at the rate of forty data points per second. The load was

Table 1
Fiber additions of lightweight aggregate concretes mixtures

	Plain	Polypropylene fibers			Steel fibers		
Fiber (percentage by concrete volume)	–	0.28	0.56	1.0	0.56	1.13	1.7
Concrete	LWplain	LWP1	LWP2	LWP3	LWS1	LWS2	LWS3

Table 3
Mixture proportions (kg/m^3)

Concrete	NWHS	LWplain	LWP1	LWP2	LWP3	LWS1	LWS2	LWS3
Cement	450	550	550	550	550	550	550	550
Silica fume	45	55	55	55	55	55	55	55
Water	122.4	176	176	176	176	176	176	176
Super-plasticizer	9	11	11	11	11	11	11	11
Fibers	0	0	2.6	5.1	9.0	44.0	88.0	132.0
	640.3 (sand) 1205.9 (coarse aggregate)							
12 mm sintered fly ash	0	137.0	136.3	135.6	134.6	135.6	134.3	132.9
6 mm sintered fly ash	0	135.1	134.5	133.8	132.8	133.8	132.4	131.1
3 mm sintered fly ash	0	147.3	146.6	145.8	144.7	145.8	144.4	142.9
Fine sintered fly ash	0	547.4	544.7	541.9	537.8	541.9	536.5	531.0
Fly ash	0	180.2	179.3	178.4	177.0	178.4	176.6	174.8

applied at the rate of 20 MPa per minute using a 3000 kN capacity Avery Denison machine. The data from both LVDTs were averaged and automatically fed into Grapher™ software, which plotted the stress–strain relationship. The same software performed a linear regression analysis on data points starting from a strain of 50 microstrain up to a strain corresponding to 40% of the maximum stress. The slope of this line is the static modulus of elasticity.

3. Results

The bulk density, compressive and indirect tensile strength, modulus of rupture and the modulus of elasticity values of the seven concretes tested are included in Table 4.

The stress–strain curves of the plain high strength lightweight aggregate concrete are shown in Fig. 1. As mentioned earlier, the testing for stress–strain relationship was performed using strain control facility. With plain concrete, the descending curve of only one sample could be successfully recorded. The other three samples were successfully tested and their data automatically recorded until maximum stress was reached. Nevertheless, the four samples shared very similar ascending behaviour as can be seen in Fig. 1. The average stress–strain curves of the LWP2 and LWS3 concretes are plotted in Fig. 2, together with the average of the plain concrete samples for comparison. Similarly, strain energy density of the three concretes, as mentioned above, are included in Fig. 3. Also the variation in the value of

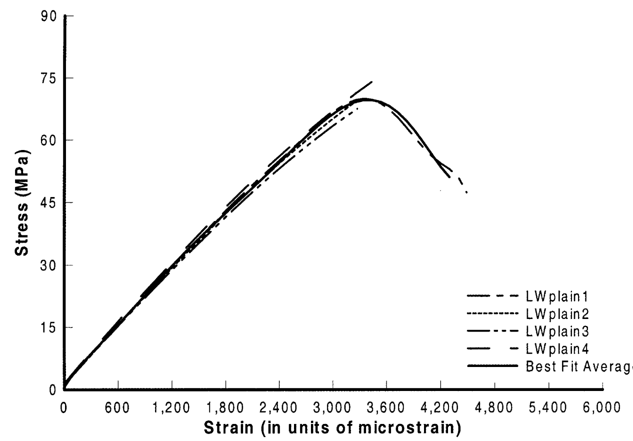

Fig. 1. Stress–strain relationship for samples of plain high strength lightweight aggregate (Lytag) concrete.

Table 4
Physical and mechanical properties of concretes

Concrete	Bulk Density (kg/m^3)		Compressive strength (MPa)	Indirect tensile strength (MPa)	Modulus of rupture (MPa)	Modulus of elasticity (GPa)
	Saturated surface dry	100 °C oven dry				
NWHS	2370	2325	72.5	5.1	6.9	35
LWplain	1890	1590	65.0	3.4	4.4	24
LWP1	1870	1650	65.0	5.4	5.2	22
LWP2	1900	1640	68.0	6.6	5.3	25
LWP3	1860	1620	58.0	5.8	4.6	21
LWS1	1890	1650	61.0	4.1	5.2	21
LWS2	1900	1660	62.0	6.1	6.1	21
LWS3	1940	1700	61.0	7.4	7.9	21

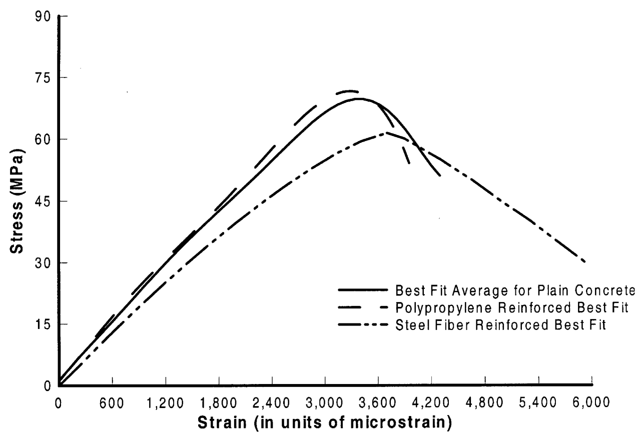

Fig. 2. The average stress–strain relationship for plain, polypropylene and steel fiber reinforced lightweight aggregate concrete.

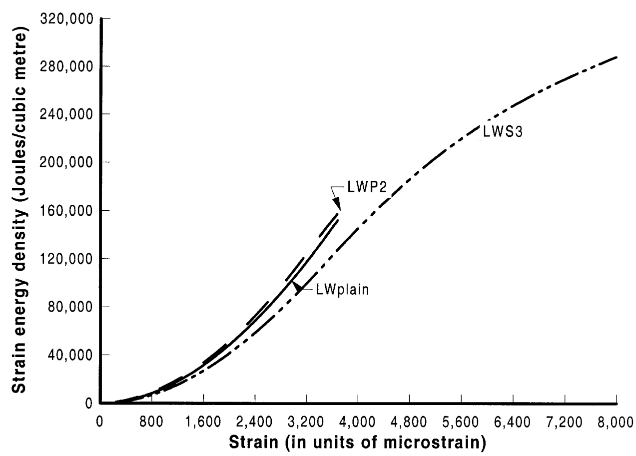

Fig. 3. Effect of fiber reinforcement on the compression toughness of concrete.

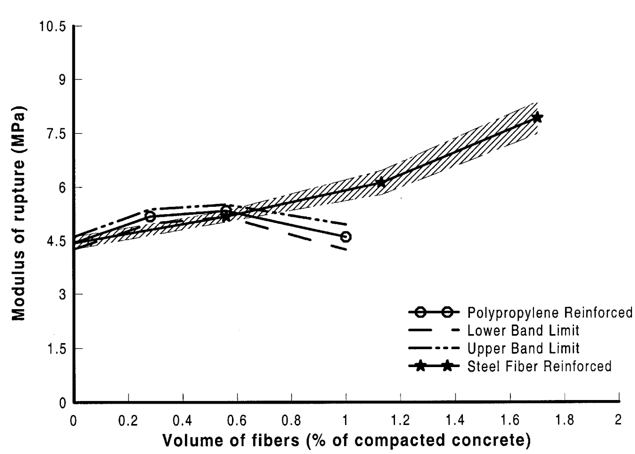

Fig. 4. Effect of fiber reinforcement on the modulus of rupture value.

modulus of rupture with varying volume of fibers is included in Fig. 4.

4. Discussion

As can be seen in Table 4, all the seven lightweight concretes display high strength as a result of the high binder content and low water to binder ratio. On the average, the LWCs tested, with and without fibers, are about 20% lighter than the conventional normal weight concrete. As is well established, the compressive strength of the concretes tested did not result in any improvement on the addition of the fibers [2,15,16]. Of course, the prime objective of adding fibers to the LWC, in this investigation, was to improve its toughness. Accordingly, these effects are discussed in some details.

4.1. Modulus of elasticity (E) and the stress–strain relationship

Again, like the compressive strength, the E value of the LWCs tested does not seem to have changed, in any significant way, on the addition of either of the two fiber types. The E value of the concretes is 22 ± 1 GPa.

Using the law of mixtures approach, the insignificant effect of fiber inclusion in concrete becomes readily explained. In its simplest models, this law as applied to the case of modulus of elasticity may be expressed as follows [21,22]:

$$E = E_1 V_1 + E_2 V_2 + \cdots + E_i V_i$$

where E is the modulus of elasticity of the mixture, while E_i and V_i refer to the modulus of elasticity and volume fraction of the mixture constituents respectively. This law may apply to concrete where plain concrete may be considered constituent 1 while the fibers are constituent 2. With the fibers fraction as low as employed in this investigation, it is not surprising that the value of the modulus of elasticity was hardly affected.

The linearity of stress–strain relationship in normal weight high-strength concrete has been found to extend up to a stress as high as 85% or more of the peak stress [23]. This behaviour is attributed to reduced particle–matrix debonding. In high-strength concrete, the modulus of elasticity of the hardened cement paste is high and the difference between the modulus of elasticity of the aggregates and the hardened paste becomes small enough to result in higher bond strength and monolithic behaviour [24]. Because of the strain control capability of the compression testing machine, it was possible to obtain the stress–strain relationship for lightweight plain and fiber reinforced concretes beyond the point of peak stress. Fig. 2 shows these relationships for the optimum mixes of the three concrete types that were tested. Each curve is the average of at least three cylindrical samples. It is observed that the value of the modulus of elasticity of steel fiber reinforced concrete was lower than that of plain or polypropylene fiber reinforced concrete. This may be a result of incomplete compaction when steel fibers are involved. Nevertheless, the stress–strain relationship (Fig. 1) shows that lightweight plain concrete manifested a brittle failure with brief period of controllable strain. In this and previously reported research [25], the linearity of the stress–strain relationship of sintered fly ash aggregate concrete is observed. This linearity has been attributed to the absence of microcracks at low load levels [26]. Lightweight aggregate concrete is expected to manifest a clearer monolithic behaviour than normal weight aggregate concrete. This is due to the lower modulus of elasticity of the aggregate, resulting in a smaller difference between its value and that of the hardened cement paste, and to the increased aggregate–paste bond due to the rough and porous surfaces of the lightweight aggregates [24]. Subsequent failure in lightweight concrete is rapid because the aggregates do not act as crack arrestors as in normal weight concrete [27]. The sudden failure observed in high-strength concrete is also attributed to the reduced ability to redistribute the stresses in the matrix that has much fewer microcracks [28]. The use of fibers may prevent sudden failure because they function as initiators of microcracks that result in the absorption of energy. Steel fibers prevent the microcracks from joining and thus arrest the sudden loss of strength [29].

In this work, three particular concrete types were chosen to represent the effect of the fibers. The first type is the plain lightweight aggregate concrete LWplain. The second is the lightweight aggregate concrete that contained 0.56% polypropylene fibers by volume. This concrete was the optimum among the polypropylene reinforced type in that it possessed the least water penetrable voids and the highest compressive strength in the series of the same type that was tested. The third was the steel fiber reinforced lightweight aggregate concrete LWS3 where the fibers occupied 1.7% of the concrete volume. Again this concrete displayed the highest compressive strength value together with the lowest value of water penetrable voids in the steel fiber reinforced series. The average stress–strain relationships for the three concrete types is shown in Fig. 2. The modulus of elasticity of polypropylene reinforced concrete did not differ significantly from that for plain concrete. The steel fiber reinforced concrete showed different behavior. Not only was the modulus of elasticity lower than that of the plain concrete, but also the range of linear stress–strain behavior was reduced. In the case of steel fiber concrete, the material could be subjected to very large deformations before total uncontrollable collapse. This may indicate a more efficient role of the steel fibers as crack arrestors. The reduced linearity in the ascending portion is likely to be attributed to increased number of bond microcracks that occur near the steel fibers. These observations emphasize the advantage that steel fibers contribute to the ductility of high-strength concrete in general, and in particular to that of lightweight high-strength concrete which is considered to be even more brittle [30].

4.2. Compression toughness

The importance of achieving a certain degree of ductility in elements of concrete structures has been widely acknowledged by engineers and researchers and codes of practice account for this capacity. The analysis and design of compression as well as flexural members are greatly influenced by the behaviour of concrete in uniaxial compression [31]. Setunge and Mendis concluded that accurate prediction of the tail of the stress–strain curve is important in developing a flexural stress block for the design of beams [32]. However, the shape of the descending stress–strain curve has been shown to largely depend on the test method and the equipment used [33]. With the availability of modern instruments, it has become possible to capture the stress–strain relationship until a considerable strain beyond the point corresponding to peak stress [20].

The term compression toughness has been used to measure the ability of concrete to absorb energy during deformation in compression [2,34]. This parameter is calculated from the area under the stress–strain curve. In other words, it is the strain energy density of the concrete. The problem with the estimation of the value of this property is to define the end point [35]. In this research the equipment was able to record forty data points of stress and strain each second. This capability made it possible to easily distinguish the point of collapse as being that point where a sudden drop in stress occurred at the same strain value for at least three consecutive readings. The value of strain energy density was then estimated by integrating the area under the stress–strain curve up to the point of collapse.

The results for the optimum mixes from the types of lightweight concrete tested here are shown in Fig. 3. The value of the strain energy density of the plain lightweight aggregate concrete at collapse is about 150×10^3 J/m^3 while for polypropylene fiber reinforced lightweight concrete, the value was about 168×10^3. In contrast, the value of the strain energy density of steel fiber reinforced lightweight concrete at collapse was 290×10^3 J/m^3. It is of interest to note that the strain energy density of the steel fiber concrete at a strain of 0.0032, which is near the peak for all the tested types here, is the lowest. This should not indicate a lower ductility because the material is still capable of storing all that energy for more than double this value of strain. On the other hand, the strain energy stored near the peak stress of plain and polypropylene reinforced concrete, is actually a major part of that could be stored before fracture.

4.3. Compressive strength, indirect tensile strength and modulus of rupture

The above strength values are included in Table 4. It has been mentioned earlier that both the compressive strength and the E values of the concrete tested have not been affected, in any significant way, by the inclusion of fibers in the LWCs. There is, of course, a marked increase in the tensile strength and hence the tensile strain capacity of the concretes tested.

The indirect tensile strength has increased by the inclusion of either polypropylene or steel fibers on the average by about 50%. An increase of this magnitude has been reported earlier [2,23]. The effect of polypropylene fibers on the modulus of rupture is less marked, on the average an increase of about 13% was measured. However, as is well established and reported earlier [2,23], steel fibers resulted in an increase in the above value of $\approx$45%. Of course, the main and major advantage of the steel fibers, as is manifested in the results, is the increase of tensile strain capacity of the concrete. This can result in a marked reduction of crack propagation due to thermal and shrinkage effects. The increase in the modulus of rupture value, on the addition of polypropylene and steel fibers, respectively, is plotted in Fig. 4.

Several researchers have tried to come up with empirical relationships between compressive, flexural and indirect tensile strength. The scope of the present experiments is certainly far too limited to use the data for verification purposes. When required, code provisions can be used to get an indicative value of the required characteristics [36,37].

5. Conclusions

1. Addition of steel fibers appreciably increased the ductility of lightweight aggregate concrete but did not significantly affect the value of compressive strength.
2. The value of the indirect tensile strength and that of the modulus of rupture of lightweight high-strength concrete could be approximately doubled with the use of steel fiber reinforcement at 1.7% by volume of the concrete.
3. Addition of polypropylene fibers at 0.56% by volume of concrete resulted in a 90% increase in the value of the indirect tensile strength. The value of the modulus of rupture increased by about 20% as a result of this reinforcement. This type of fibers, however, did not significantly affect the value of the compressive strength or the modulus of elasticity.

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