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Advanced Engineering Informatics

Elixir Adv. Engg. Info. 48 (2012) 9348-9351

ISSN: 2229-712X

The effect of steel fibre inclusion on the mechanical properties and durability of lightweight foam concrete

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ARTICLE INFO

Article history:
Received: 17 May 2012;
Received in revised form: 15 June 2012;
Accepted: 29 June 2012;

Keywords
Lightweight foam concrete,
Steel fiber,
Fly ash,
Mechanical,
Durability.

ABSTRACT

Lightweight foam concrete has been an effective building material product for many years due to its lightness and cost saving characteristics. The present study covers the use of steel fibres to produce Lightweight Foam Concrete (LFC) for use in the construction of non-load bearing elements. The LFC with a density of 1000 kg/m^3 was cast and tested. Compressive, flexural, tensile split, drying shrinkage and water absorption tests were carried out to evaluate the mechanical properties and durability over 28 days. The cement, sand and water used were in the ratio of 1:1.5:0.45. Two percentages of fibre inclusion, 0.25% and 0.4% by total volume fraction, and 30% replacement of cement by fly ash were implemented. The addition of steel fibres in LFC showed a very good contribution in the compressive strength, flexural strength and tensile split strength test results.

Introduction

One of the results of working on green and environmental friendly technologies has been the design and production of concrete products, among which are the use of lightweight aggregate and aerated concrete. Despite it being a good product in building material technology, there are still uncertainties with regard to the behaviour of its mechanical properties and its durability. Compared to normal concrete, lightweight concrete is certainly no match in terms of its mechanical properties, especially in its compressive strength. Furthermore, its shrinkage behaviour has been said to be critically discouraging. But many researchers are trying to come out with more findings to enhance the effectiveness of lightweight concrete. One of the most popular ways to enhance its mechanical properties and durability is fibre inclusion.

Lightweight Foam Concrete (LFC) is derived from aerated concrete to produce a lightweight building material product. Lightweight foamed (or cellular) concrete is normally made from mixing slurry mortars with stable foam.

This action encloses small air bubbles within the mortar which react as the aggregate thereby making it lighter and possessing special properties such as high fire resistance and low thermal conductivity. During the plastic stage, gas-form chemicals are mixed into the cement mortar, resulting in an increase in volume and a decrease in mix density, and when the gas escapes, it leaves a porous structure that forms the aggregate [1].

Foamed concrete may have densities ranging from as low as 500kg/m^3 to as high as 1600kg/m^3. It therefore has widened the range of applications such as material for floor & roof screeds, trench reinstatement, wall blocks or panels, road foundations and also void filling. It has been highlighted by many researches that the specialties of lightweight concrete in comparison to normal concrete is its low density and thermal conductivity. Nowadays, quite a large number of researches have been conducted to enhance the effectiveness of lightweight concrete for building material. For example, fibre lightweight concrete is one of the approaches that have been increasing in recent years.

The knowledge of fibre use in cement composites, mechanisms of durability and mechanical behaviour plus its insulating behaviour has increased. Many research papers have proven the different kinds of advantages of incorporating fibre in cement composites. Raju *et al.* [2] found that the cube compressive strength of concrete increased linearly with the addition of fibres.

Normal concrete reinforced with less than 2% of volume content of steel fibres provides better properties compared to normal concrete, especially in the improvement of toughness [3]. It was also reported by Sanjuan and Moragues [4] that shrinkage and differential settlement can be inhibited or prevented effectively by using fibre reinforcement. Similarly, when applied to foam concrete, it is hoped that the fibre would contribute to the load carrying capacity of the material by shear deformation at the fibre - matrix interface, thereby contributing to increased strength.

Replacements and Additives

There are two different fibres and additives used for the mix proportion in this research which are the additives of steel fibre and fly ash in replacement of the cement.

Both inclusions give different varieties of results in terms of its mechanical properties and durability.

Both tests are covered until the 28th day. Steel fibre is believed to be able to increase the compressive strength due to the solidity of its physical structure. Besides, according to Balendran et al. [5], the improvement of lightweight concrete compared to normal concrete in terms of flexural strength and tensile split strength is much better when steel fibres are used. Tables 1 and 2 show the properties of the steel fibres and fly ash used.

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Table 1: STAHLCON Steel Fibre specification

Description	Hooked-end steel fibre
Fibre type	BS EN 14889-1:2006, Group 1 – cold drawn wire
Coating	None
Fibre Diameter, d (mm)	0.55 (± 0.025)
Fibre length, L (mm)	35 (± 1.75)
Tensile strength (MPa)	1250 (±90)

Table 2: Properties of fly ash (Class F)

Properties	Percentage (%)
Silicon dioxide (SiO_2) plus aluminium oxide (Al_2O_3) plus iron oxide (Fe_2O_3), min. %	70
Sulphur trioxide (SO_3), max. %	5
Moisture Content, max. %	3
Loss on ignition, max. %	6

As for the replacement of cement, 30% of fly ash by cement volume is replaced for optimum results [6]. British Standard 450 Fly Ash (BS 450 EN Fly Ash, [7] has stated the advantages for fly ash inclusion in concrete compositions. The advantages are the creep is significantly less than Portland cement concrete as fly ash concrete continues to gain strength with time. It reduces shrinkage by up to 80% where long term durability is an essential requirement. A minimum fly ash content of at least 30% by weight of the cement content is often specified. Class F fly ash was used in the study due to its availability in Malaysia.

Mix Design

The mixture proportions of the LFC mixtures produced in the laboratory are shown in Table 3. A total of five LFC mixtures were produced. The types of mixtures produced, which were normal foam concrete (NF), 0.25% steel fibre foam concrete (SF25), 0.40% steel fibre foam concrete (SF40), 0.25% steel fibre foam concrete with 30% fly ash cement replacement (SFA25) and 0.40% steel fibre foam concrete with 30% fly ash cement replacement (SFA40). The targeted dry density for the mixes was 1000 kg/m^3. There were two different percentages of 0.25% and 0.4% of fibre additives by total volume fraction. The weight of fibre inclusion for SF25, SF40, SFA25 and SFA40 were 0.2kg, 0.32kg, 0.175kg and 0.32kg, respectively.

The amount of sand included was kept constant except for SFA25, which was changed accordingly to total volume mix used by mix ratio. Meanwhile, the volume of cement was changed for replacement by fly ash by 30% for SFA25 and SFA40. For NF, SF25 and SF40, it followed the designed mix ratio of 1:1.5:0.45 for cement, sand and water respectively. The designed foam density used for its optimum stability was at 80 g/litre. The amount of water used was different for all five mixes. Almost 6.5% more water was used for mixes without fly ash inclusion, exceeding the normal mix, and 5% less water was used for mixes with fly ash inclusion. This shows the 'ball bearing' effect of the fly ash, which being almost totally spherical in shape, decreases the amount of water used. The cement used was ordinary Portland cement.

100 mm^3 cubic specimens were cast for the determination of compressive strength, 25mm x 100mm x 350mm for flexural strength, and specimen size of 100mm x 200mm for tensile split strength. The test specimens were left to stand for 24 hours, after which they were de-moulded and cured in the wrapper until the time of testing. After curing, the samples were tested in dry conditions for compressive, tensile and flexural strength in accordance with BS 1881: Part 116: 1983, BS EN 12390-6:2000 and BS EN 1521:1997 respectively. For the purpose of testing drying shrinkage, 75mm x 75mm x 254mm sized prisms were prepared and tested in accordance with BS 6073-1.

Table 3: Mix proportion

Sample	Sample code	Composition of mixture			
		Cement (kg)	Fly Ash (kg)	Sand (kg)	Water (kg)
Normal foamed concrete	NF	29.59	-	44.38	12.29
0.25% steel fibre foam concrete	SF25	29.59	-	44.38	13.32
0.40% steel fibre foam concrete	SF40	29.59	-	44.38	12.82
0.25% steel fibre foam concrete with 30% fly ash cement replacement	SFA25	18.12	7.77	37.73	11.32
0.40% steel fibre foam concrete with 30% fly ash cement replacement	SFA40	20.71	8.88	44.38	12.06

Results and Discussion

There are some factors to be taken into consideration in defining a good lightweight foamed concrete. In terms of its mechanical properties, compressive strength, flexural strength and tensile split strength have a major impact in proving the advantage of producing a lightweight foamed concrete as a building material.

Compressive Strength

Figure 1 states the compressive strength for the normal foamed concrete (control mix) and steel fibre foam concrete.

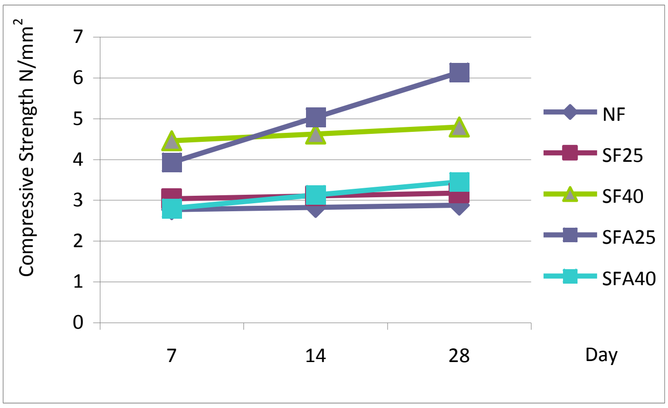

Figure 1: Compressive strength of steel fibre concrete.

Based on the figure above, it has been proven by the numbers that the inclusion of steel fibre as an additive in foam concrete contributes to compressive strength whereas all other mixes have higher compressive strength compared to the control mix, NF. The percentage of increment in compressive strength for all five mixes NF, SF25, SF40, SFA25 and SFA40 have been analysed and resulted in 4.0%, 4.6%, 7.5%, 56% and 23.3% respectively. Compared to all 5 mixes, the NF has the lowest compressive strength and SFA25 has the highest 28 days compressive test result. At the 7th day test, SF40 has the highest compressive strength of all the 5 mixes, but it is believed that due to the inclusion of fly ash, the pozzolan does contribute to the delayed strength of concrete as stated by many researchers. Due to the behaviour of lightweight foam concrete which has a porous structure inside, steel fibre acts as the reinforcement that strongly holds the structure. The physical structure of the steel fibre itself is solid enough to reinforce the lightweight concrete.

Flexural Strength

In analysing the Figure 2, the lowest flexural strength of all the 5 mixes is the SFA40 and the highest is the SF40 for the 28 days test. The percentage increment for all 5 mixes namely NF, SF25, SF40, SFA25 and SFA40 are 58.5%, 14.4%, 4.2%, 39.6%

and 21.2% respectively. It can be observed that even though the NF has the highest percentage increment compared to the others, the flexural strength has not beaten the 3 other specimens. It could be that the fibre was not properly spread in the whole which led to the failure of the fibre to resist the load taken at the very point of load.

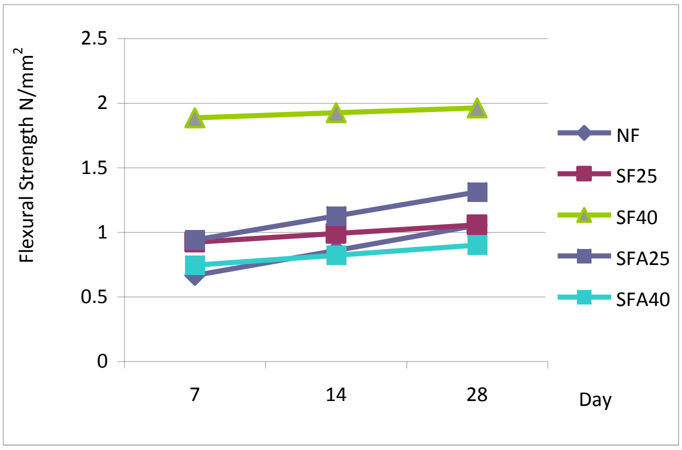

Figure 2: Flexural strength of steel fibre concrete

This could happen due to a low percentage of fibre inclusion in the foam concrete. The second highest percentage increment of all is the SFA25 with 39.6%. According to the British standard [8], the equation that verifies the ratio of compressive strength to flexural strength is $f_{cr}=0.7\sqrt{f_{ck}}$. By referring to Figure 1 of the compressive strength, the SFA25 has the highest compressive strength which follows the rule that flexural and compressive strength are linearly proportionate. However, the specimen was not cracked into two parts. The steel fibre holds the critical part together giving the alert timing before it cracks into two. This is because of the hooked-end structure that holds the two parts together, preventing the structure from cracking into two parts.

Tensile Split Strength

Figure 3 shows the tensile split strength of LFC with steel fibre. Based on Figure 3, SF40 has the highest value of tensile split strength, compared to the other four mixes. On average, all four mixes with steel fibre inclusion had a percentage increment of 92.1% compared to the control mix, NF. This proves the workability of steel fibre towards enhancing better mechanical properties for lightweight foam concrete, especially in the tensile split test.

In terms of fly ash inclusion, the difference was observed to be not much of a contribution compared to those without fly ash replacement. However, according to Balaguru and Foden [9], it is more significant for concrete of higher volume lightweight concrete aggregate to get optimum results in splitting tensile strength. In other words, the greater the percentage of fibre included, the better the tensile split result that will be gained.

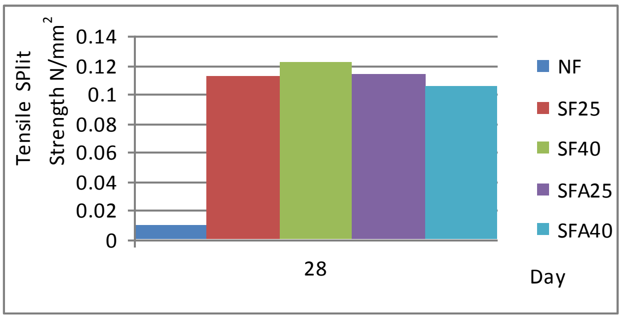

Figure 3: Tensile split strength of steel fibre concrete

Drying Shrinkage

Table 4: Drying shrinkage of steel fibre foam concrete by days of test

Item	Detail	3rd day	7th day	14th day	21st day	28th day	Shrinkage Percentage (%)
1	NF	4.920	5.259	5.290	5.362	5.389	9.53%
2	SF25	4.120	4.299	4.336	4.388	4.379	6.29%
3	SF40	4.357	4.377	4.426	4.457	4.466	2.50%
4	SFA25	4.655	4.722	4.859	4.876	4.879	4.81%
5	SFA40	4.207	4.353	4.421	4.458	4.460	6.01%

Shrinkage is one major problem that has to be faced in using lightweight concrete. Since foam concrete forms bubbles as the aggregate, its shrinkage resistance is lower compared to normal concrete. Referring to the Table 4, the highest drying shrinkage is by the control mix, NF.

This is mainly attributed to the fact that no fibre was added to resist the drying shrinkage. However, steel fibre inclusion as additives has been proven to be effective. Even the second lowest resistance of drying shrinkage namely SF25 has 34% better resistance to drying shrinkage compared to the control mix, NF. The most effective mix design for drying shrinkage goes to SF40 with only 2.5% shrinkage within 28 days of the test.

Water Absorption

Figure 4 shows the results of water absorption. For the water absorption test, the control mix (NF) shows the highest percentage of water absorption.

This is 43% higher than the lowest water absorption by specimen SF25. Previous researches on steel fibre concrete resulted in a positive contribution to the water absorption test and it seems to be consistent with the results of this present study. It is believed that this is the result of the different properties of lightweight foam concrete compared to normal concrete. The result is uncertainly high perhaps due to the absence of fibre. Everything was followed according to the British standard method for water absorption testing.

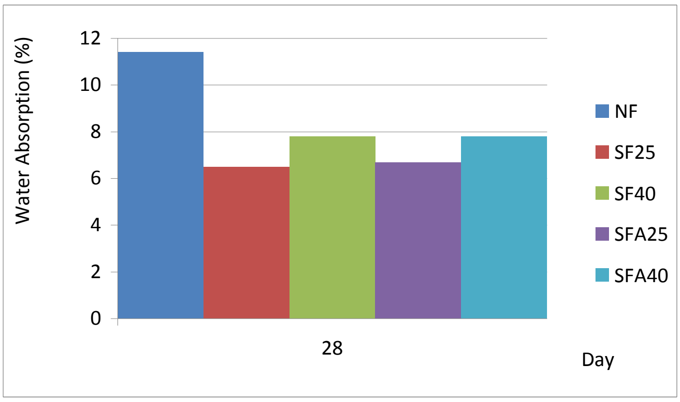

Figure 4: Percentage of water absorption

Conclusions

By referring to the above results, the study has reached the following conclusions:

- The inclusion of steel fibre is amazingly effective towards increasing the compressive and tensile split strength.
- The low percentage of fibre additive shows uncertain results in flexural strength due to uncertain spreading of fibre which leads to failure at the point of load.
- Cement replacement by fly ash is a good approach for a cost saving and greener technology but the percentage of replacement can still be modified for optimum results.

Acknowledgement

The author thankfully for the financial support in this research granted by Universiti Sains Malaysia under USM Short term Grant (Ref. No. 304/ PPBGN/ 6311023)

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