Comparison of Mechanical Properties of Lightweight and Normal Weight Concretes Reinforced with Steel Fibers

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***Abstract*-Compared to conventional concrete, lightweight concrete is more brittle in nature however, in many situations its application is advantageous due to its lower weight. The associated brittleness issue can be, to some extent, addressed by incorporation of discrete fibers. It is now established that fibers modify some fresh and hardened concrete properties. However, evaluation of those properties for lightweight fiber-reinforced concrete (LWFC) against conventional/normal weight concrete of similar strength class has not been done before. Current study not only discusses the change in these properties for lightweight concrete after the addition of steel fibers, but also presents a comparison of these properties with conventional concrete with and without fibers. Both the lightweight and conventional concrete were reinforced with similar types and quantity of fibers. Hooked end steel fibers were added in the quantities of 0, 20, 40 and 60kg/m^3. For similar compressive strength class, results indicate that compared to normal weight fiber-reinforced concrete (NWFC), lightweight fiber-reinforced concrete (LWFC) has better fresh concrete properties, but performs poorly when tested for hardened concrete properties.**

Keywords-lightweight; steel fibers; density; elastic modulus; ductility

I. Introduction

Structural lightweight concrete is defined as the one with minimum 28-days compressive strength of 17MPa and equilibrium density between 1120 and 1920kg/m^3[1], whereas a cubic meter of conventional concrete weighs around 2300kg. Compared to conventional concrete, structural lightweight concrete generally weighs 25% to 35% less [2]. This reduced weight not only imparts favorable effects on foundations, but also lowers the seismic inertial mass [3]. Wide acceptance of the lightweight concrete by the construction industry in the past has been hindered by multiple factors including the lower strength of lightweight aggregates, the aggregate availability, the extra attention required during designing and making of lightweight concrete due to its higher water absorption and most importantly due to its higher brittleness associated with the material compared to the conventional concrete. Nevertheless, current consumption trends show that structural lightweight concrete is getting momentum [4], as an increasing number of industrial plants have been set up for production of artificial aggregates addressing the aggregates' availability issue. Design engineers now have the choice of selecting among varieties of artificial aggregates such as expanded clay and expanded shale etc. Moreover, development of mineral and chemical admixtures and improvement in particle strength of the artificial aggregates over the years have made it possible to produce lightweight aggregate concrete with better mechanical and rheological properties.

As for the concerned brittleness issue, studies suggest that discrete fibers can be used to make concrete a more ductile material. Use of fibers in concrete has been found to affect the properties of fresh and hardened concrete [5-7]. This effect so far has been quantified mostly for the conventional concrete and its test results have been made part of different committee reports and code sections[8, 9]. Our understanding, however, regarding the influence of fibers on fresh and hardened lightweight concrete properties and the material behavior is still in initial stage, for example there are no code guidelines for design of members produced using lightweight fiber-reinforced concrete, whereas a comprehensive committee report by ACI [10] is available for normal weight fiber reinforced concrete. It is therefore essential for the development of any such design guidelines that the behavior of lightweight fiber-reinforced concrete is firstly well understood. Considering this an experimental program was devised for the evaluation of fresh and hardened lightweight concrete properties after the incorporation of steel fibers.

II. EXPERIMENTAL PROGRAM

A. Materials Used

One of the major objectives was to attain comparable compressive strength for both lightweight and conventional concrete, therefore ordinary Portland cement (CEM-1/42.5N) was used as the binding ingredient for both concretes. Natural sand for both concretes was used as a fine aggregate, having particle size in the range of 0–2mm and particle density of 2570kg/m^3. ASTM procedure [11]was used for aggregates' moisture content determination and was adjusted during concrete mixing stage. For lightweight concrete expanded clay was used as a coarse aggregate material, the aggregates were round and regular in shape and had particle size between 2mm to 10mm.These lightweight aggregates absorbed water at 14% of their weight when kept immersed under water for 24 hours. Gravels were used as coarse aggregates for production of NWFC. These aggregates had particle size ranging from 2mm to 8mm. Steel fibers 35mm long with 0.55mm diameter were selected as reinforcement for fibrous mixes. These fibers were hooked-end in shape, with a tensile strength of 1100MPa and aspect ratio $\left(\frac{l_f}{d_f}\right)$. Other material details are given in Table I.

TABLE I. PROPERTIES OF THE MATERIALS USED

Aggregates				
Type	**Particle size range [mm]**	**Bulk density [kg/m^3]**	**Particle density [kg/m^3]**	**Water absorption (24 h)%**
Expanded clay	2-10	650	1190	14.36
Gravel	2-8	1474	2520	1.48
Sand	0-2	1604	2573	1.02
Fibers				
Shape	l_f **[mm]**	d_f **[mm]**	**Fiber dosage [kg/m^3]**	**Tensile strength [MPa]**
Hooked-end	35	0.55	0, 20, 40, 60	1100

B. Experimental Tests

1) Fresh Concrete Tests

Tested fresh concrete properties included workability, and density. Fresh concrete density test were performed using ASTM method [12]. German standard guidelines DIN EN 12350-5 [13] were followed for the determination of workability of all the used mixes (Figure 1). This test method was chosen over other methods due to its simplicity. For example, it becomes easy to quantify the effect of fibers on the workability using German DIN standard, since unlike ASTM standard, the same DIN standard can be used for fibrous and non-fibrous concrete mixes.

(a) (b)

Fig. 1. Mixes at the end of slump flow test (a) NWFC (b) LWFC

C. Hardened Concrete Tests

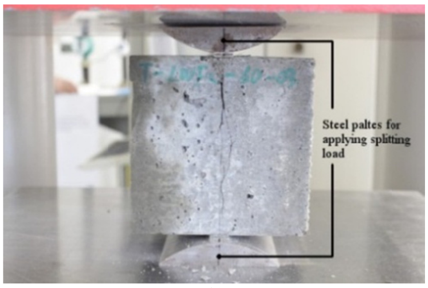
All hardened concrete tests, i.e. compressive strength, elastic modulus and splitting tensile strength tests were carried out in the similar testing machine with maximum load applying capacity of 5000kN. For splitting tensile strength test, additional steel plates were used, placed on top and bottom sides of the test specimens as shown in Figure 2(b). Plates served the purpose of directing the load along the center line of specimens. Cubes of dimensions 150mmx150mmx150mm were used for both compressive strength and split tensile strength tests. Cylinders were used for the measurement of elastic modulus, these had diameter of 100mm and height of 200mm.A mechanical jig was attached to these specimens for the measurement of vertical displacement needed for strain calculation. The recorded displacement was transferred to the processing unit via data cables as shown in Figure 2(c).

III. RESULTS AND DISCUSSION

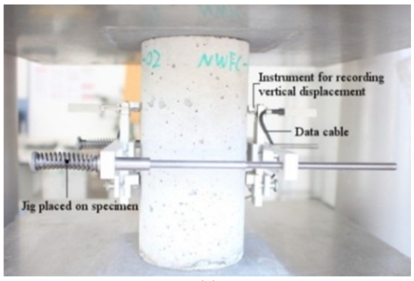
A. Fresh Concrete Density

During measuring concrete properties and concrete handling, it was observed that parameters like the shape of coarse aggregates, particle density and fiber quantity have strong influence on workability and fresh concrete density. Handling of lightweight concrete was easy compared to conventional concrete at all fiber content levels because the aggregates used in the mixes making were twice lighter in weight than gravels and had regular round shape. Fresh concrete density test results show that on an average NWFC was 21% heavier than LWFC. Since steel fibers have higher specific gravity, they have the tendency of increasing the concrete density. At maximum fiber dosage level i.e. 60kg/m^3, an increase of 6.7% in density values of LWFC was recorded, whereas for NWFC this increase was only 2.2%.


(a)



(b)



(c)

Fig. 2. Test setup (a) compressive strength (b) splitting tensile strength (c) elastic modulus

B. Workability

Compared to conventional concrete's, the workability of lightweight concrete was more affected as a result of fiber addition. The mechanism of flow table test is such that the jolting of table helps the gravitational fall of concrete, for this reason conventional concrete is less affected by the presence of fibers. Also, the effect of fibers in reducing the slump flow for normal weight concrete was not observed even up to fiber content of 40kg/m^3. When measured in terms of slump flow, the workability of normal weight concrete reduced by 6.4%, whereas for lightweight concrete this decrease was 12.5% at maximum fiber content level.

C. Compressive Strength

A number of mix trials were performed for bringing closer the compressive strength of lightweight and normal weight concretes. The difference between the strengths at all fiber content levels was brought to less than 5MPa (see Figure 3) for fair evaluation of properties. Specimens containing no fibers failed in a brittle fashion and those with fibers developed a number of cracks before failure. Also, with increasing fiber content, the width of cracks was observed to decrease. Highest compressive strength value was recorded at fiber dosage of 40kg/m3 as shown in Figure 3. The compressive strength at this quantity of fibers was found to increase by 7.7% and 21.1% for specimens of normal weight and lightweight concretes respectively. Further increase in fiber quantity i.e. from 40kg/m3 to 60kg/m3 caused reduction in compressive strength of both lightweight and normal weight concretes possibly due to the difficulty of achieving proper compaction which resulted in voids which led specimens to fail at lower loads.

D. Splitting Tensile Strength

Splitting tensile strength is noted to be on an average 6.6% of the compressive strength for all mixes of LWFC, while this percentage ranges from 6.41% to 6.88% for NWFC. Specimens failed with single major crack in two halves at zero fiber content level, while, at highest fiber dosage, crushing at ends due to transverse compressive stresses and compound cracking at center due to uniform tensile stresses was observed. As shown in Figure 3, variation of tensile strength is independent of fiber volume but follows the compressive test results. These findings indicate that compressive strength has significant impact on concrete splitting tensile strength and it may not be a viable option to bring improvement in first cracking tensile strength through addition of steel fibers.

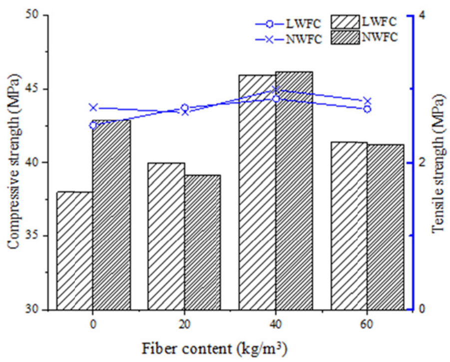


Fig. 3. Dependence of splitting tensile strength on compressive strength

Enhancement in splitting tensile strength due to fiber addition was more distinct in LWFC than in NWFC. Authors in[14] reported similar observations. Enhancement in splitting tensile strength was of no greater significance after the addition of steel fibers. Results show maximum improvement of 9% and 14% for NWFC and LWFC respectively at fiber volume of40 kg/m^3.For this fiber volume (40kg/m^3), authors in [15] reported an increase of 19% in splitting tensile strength of high-strength fiber-reinforced concrete. For normal strength fiber-reinforced concrete [16] reports 11% increase.

E. Elastic Modulus

Results of modulus of elasticity test are illustrated in Figure 4 as a function of fiber content. It can be seen that that there is some reduction in elastic modulus of lightweight concrete as the fiber volume increases and at the highest fiber volume this reduction is about 5.86%.Authors in [17, 18] have also reported similar trends. This behavior is probably due to hindrances created by steel fibers in concrete's consolidation process resulting in less denser material with lower modulus of elasticity. Test results of NWFC follow a well-established relation between compressive strength and modulus of elasticity i.e. any change in compressive strength will affect the elastic modulus exponentially. Despite having similar compressive strength class, elastic modulus values of lightweight concrete at all fiber dosages had an average of 14GPa lower than NWFC values due to lower specific gravity of expanded clay compared to gravel.

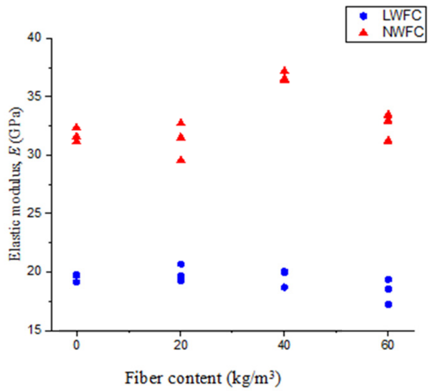


Fig. 4. Modulus of elasticity as a function of fiber content

IV. CONCLUSIONS

No obvious divergence was noticed on the compressive strength of NWFC with maximizing volume, given that the compressive strength of LWFC rises up to 40Kg/m^3 fiber volume. However it begins to lower down at maximum fiber intake. The main reason for this change is the disruption created by fibers which results in failure to attain full compaction by the concrete. It is, therefore, established that concrete's compressive strength does not vary for the selected range of fiber volume. Tensile strength gained by both LWFC and NWFC is on an average of 6.7% of their respective compressive strengths. Dependence of tensile strength on compressive strength is proved by current laboratory test results. Also for the quantity of fibers used in current study, first cracking tensile strength was least affected. Though it has been reported in[19] that this property can be improved by using larger fiber volume fraction (>2% of volume fraction), experience gained from current lab testing and review of literature suggest the limiting of fiber volume maximum up to 2% for different reasons like economy and practicality. However, there is some minimal enhancement in tensile strength as a result of fiber addition and it is more noticeable in lightweight concrete than normal weight concrete, probably because of the greater brittleness of the former. For the range of steel fiber volume used in current study, minimal decrease in modulus of elasticity of concrete, and for NWFC change with compressive strength suggest that steel fibers have no substantial impact on this concrete property.

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