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Experimental Investigation on the Influence of Steel Fiber on the Compressive and Tensile Strength of Recycled Aggregate Concrete

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Abstract: An experimental investigation was carried out to investigate the influence of steel fiber on the compressive and tensile strength of recycled aggregate concrete. The experimental program consisted of testing 100×100 concrete cubes. The experimental variables used were the water/cement ratio, recycled aggregate, fly ash and steel fiber volume fraction of 1.5% M^{-3} of concrete and the cubes were tested at 28 days and results compared with control specimens i.e., cubes made without the addition of steel fibers. Orthogonal table with 4 levels and 3 factors was used to prepare the mixing proportions and analysis of variance and significance test with F statistic were used to check the existence of interaction and level of significance. The effects of these variables on the compressive and tensile strength are presented and discussed. The results indicate that the addition of steel fibers enhanced the 28 day compressive and splitting tensile strengths with increment in the ranges of 10-30% and 27-41%, respectively.

Key words: Concrete, steel fiber, compressive strength, tensile strength, fracture, Nigeria

INTRODUCTION

Recycled concrete aggregate: Recently, the source of raw materials for building industries is clearly changing in many countries and more attention is being paid to the environmental safety regulations. Also, due to the reservation of natural resources, prevention of environmental pollution and cost-saving consideration of construction project, the recycled concrete aggregate has been widely reused for making different construction materials (Hansen, 1992), producing high-strength/high-performance concrete (Hansen, 1996) or serving as the base or sub-base material in the road construction (Collins,1994).

Fiber reinforced concrete: Concrete containing hydraulic cement, water, aggregate and discontinuous discrete fibers is called fiber reinforced concrete. It may also contain pozzolans and other admixtures commonly used with conventional concrete (Mehta and Monteiro, 2006). Fibers are usually produced from different materials ranging from steel, plastic, glass and natural material, however for most structural and none structural purposes, steel fiber is the most commonly used of all the fibers. The type of fiber and its volume fraction has a marked effect on the properties of fiber reinforced concrete. It is convenient to classify the fiber reinforced composites as a function of their volume fraction presented as (Mehta and Monteiro, 2006):

Low volume fraction (<1%): The fibers are used to reduce shrinkage cracking. These fibers are used in slabs and pavements that have a large exposed surface leading to high shrinkage cracking. Disperse fibers offer various advantages over steel bars and wire mesh to reduce the shrinkage cracks as the fibers are uniformly distributed in 3 dimensions making an efficient load distribution, the fibers are less sensitive to corrosion than the reinforcing steel bars and the fibers can reduce the labor cost of placing the bars and wire mesh.

Moderate volume fraction (between 1 and 2%): The presence of fibers at this volume fraction increases the modulus of rupture, fracture toughness and impact resistance. These composites are used in construction methods such as shotcrete and in structures that require energy absorption capability, improved capacity against delamination, spalling and fatigue.

High volume fraction (>2%): The fibers used at this level lead to strain-hardening of the composites. Because of this improved behavior, these composites are often referred to as High Performance Fiber-reinforced Composites (HPFRC).

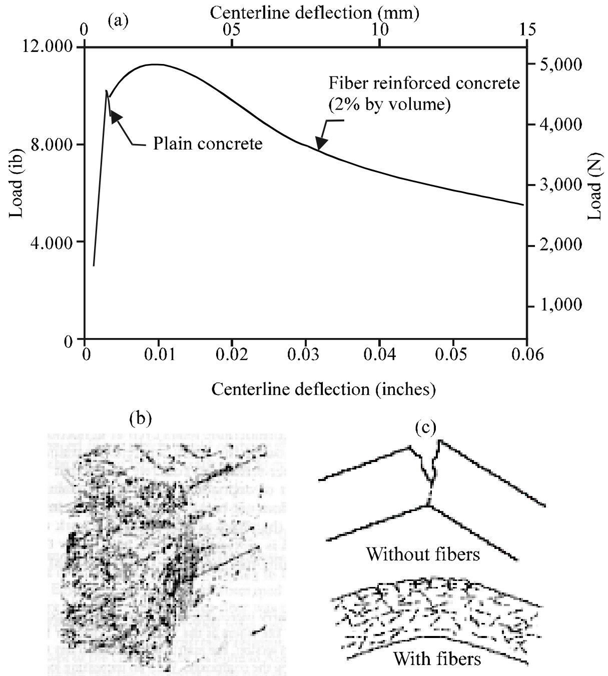

Fig. 1: Load-deflection behavior of plain and fiber-reinforced concrete (b) cross-section of a steel-fiber reinforced beam after fracture showing the failure mode is fiber pullout (c) mechanism of increase in flexure toughness of concrete with fibers

Toughening mechanisms of fiber reinforced concrete: Typical load-deflection curves for plain concrete and fiber reinforced concrete are shown in Fig. 1a. Plain concrete fails suddenly once the deflection corresponding to the ultimate flexural strength is exceeded, on the other hand, fiber-reinforced concrete continues to sustain considerable loads even at the defection considerably in excess of the fracture deflection of the plain concrete.

Figure 1b is an examination of fracture specimens of fiber reinforced concrete, it shows that failure takes place primarily due to fiber pull-out or debonding. Therefore unlike plain concrete, a fiber-reinforced concrete specimen does not break immediately after initiation of the first crack as is shows in Fig. 1c.

Steel Fiber Reinforced Concrete (SFRC): It is now well established that one of the important properties of Steel Fiber Reinforced Concrete (SFRC) is its superior resistance to cracking and crack propagation (Mehta and Monteiro, 2006). As a result of this ability to arrest cracks, fiber composites possess increased extensibility and

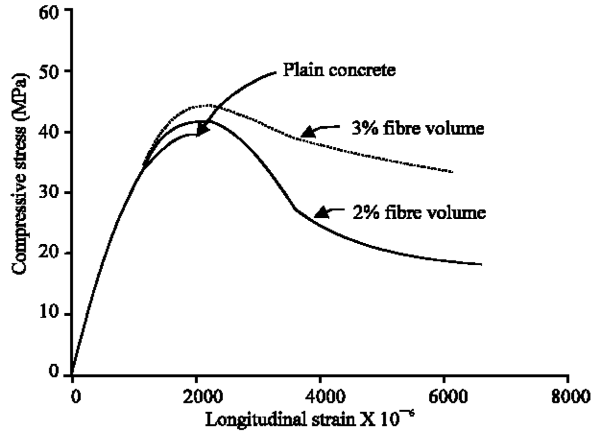

Fig. 2: Stress-strain curves in compression for SFRC

tensile strength both at first crack and at ultimate, particular under flexural loading and the fibers are able to hold the matrix together even after extensive cracking.

Technology for producing SFRC: In general, SFRC can be produced using a conventional concrete practice, though there are obviously some important differences. The basic problem is to introduce a sufficient volume of uniformly dispersed steel fiber to achieve the desired improvements in mechanical behavior while retaining sufficient workability in the fresh mix to permit proper mixing, placing and finishing.

The performance of the hardened concrete is enhanced more by fibers with a higher aspect ratio since this improves the fiber-matrix bond.

On the other hand, a high aspect ratio adversely affects the workability of the fresh mix. In general, the problems of both workability and uniform distribution increase with increasing fiber length and volume (Van Chanh, 2005).

Mechanical properties of SFRC

Compressive strength: Steel fiber has little effect on the compressive strength of concrete with increases in strength ranging from essentially nil to perhaps 25%. Even in members that contain conventional reinforcement in addition to the steel fibers, the fibers have little effect on compressive strength.

However, the fibers do substantially increase the post-cracking ductility or energy absorption of the material. Figure 2 shows the compressive stress-strain curves of SFRC.

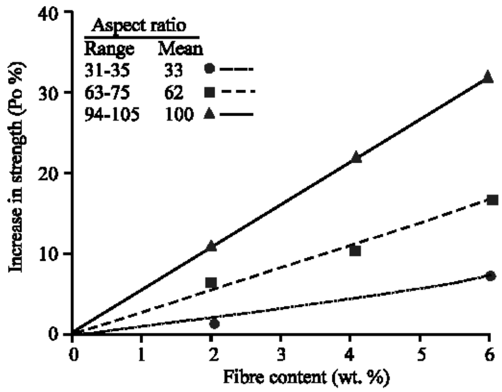

Fig. 3: Influence of fiber content on tensile strength

Tensile strength: When steel fibers are aligned in the direction of the tensile stress it may bring about very large increases in direct tensile strength as high as 133% for 5% of smooth, straight steel fibers. However for more or less randomly distributed fibers, the increase in strength is much smaller, ranging from as little as no increase in some instances to as much as 60% with many investigations indicating intermediate values, as shown in Fig. 3. Splitting-tension tests of SFRC show similar results. Thus, adding fibers merely to increase the direct tensile strength is probably not worthwhile. However, as in compression, steel fibers do lead to major increases in the post-cracking behavior or toughness of the composites.

MATERIALS AND METHODS

Orthogonal arrays: Orthogonal Arrays (OA) are a special set of Latin squares, constructed by Taguchi to lay out the product design experiments. By using this table, an orthogonal array of standard procedure can be used for a number of experimental situations. Taguchi's OA is considered to be more superior than the traditional factorial design method since:

- The factorial design experiment is not efficient in handling large numbers of factor variables
- Taguchi's OA experiments on a product design, yield similar and consistent results although, the experiment can be carried out by different experimenters
- The OA table allows determination of the contribution of each quality influencing factor
- OA allows easy interpretation of experiments with a large number of factors

The Analysis of Variance (ANOVA) is used to analyze the results of the OA experiment in product design and to determine how much variation each quality influencing factor has contributed. By studying the main effects of each of the factors, the general trends of the influence factors, towards the product or process can be characterized. The characteristics can be controlled, such that a lower or a higher, value in a particular quality influencing factor produces the preferred result. Thus, the levels of influencing factors, to produce the best results can be predicted (Taguchi, 1988).

There are 2 different methodologies in carrying out the complete OA analysis. A common approach is to analyze the average result of repetitive runs or a single run, through ANOVA analysis as discussed. After the ANOVA is completed, the F statistic of any specific control factor A, say F_A which is defined as the ratio between the sum of variance square for the A control factor and the sum of error variance square can be obtained. The value of F_A is used for the significance test. The bigger the F_A, the larger the significant influence of control factor A will be. The significance level is divided into two kinds as significant (α = 5%) and very significant (α = 1%) as given by the following Eq. 1 and 2:

$$F_A \geq F_{0.01,v1,v2} : \text{very significant} \quad (1)$$

$$F_{0.01,v1,v2} > F_A \geq F_{0.05,v1,v2} : \text{significant} \quad (2)$$

Design of experiment: In this study Taguchi's approach was adopted in order to reduce the numbers of trails required to gather necessary data. L_{16} (4^5 series) orthogonal arrays as contained (Akinkurolere, 2009) was used to reduce the number of tests. In this type, the four levels considered which form the column of the orthogonal array were the changes in water/cement ratio which are 0.44, 0.50, 0.55 and 0.58, respectively while the test three factors on the orthogonal rows were considered. The three factors were the changes in recycled coarse aggregates content, changes in fly ash addition, steel fiber and amount of water to cement needed for each run. Since, the experiment has only 3 major parameters, the right-most 2 columns were ignored while other parameters that appeared on the table were generated from the major parameters.

Steel fiber: Steel fibers were added to determine the effect on the compressive and flexural strengths. Table 1 shows the properties of the steel fiber used in this research. Figure 4 shows a sample of steel fiber used in this investigation.

Mixing of concrete: All concrete mix designs used in this project were calculated using absolute volume method.

Fig. 4: Steel fiber used in the experiment

Table 1: Properties of steel fiber

Types of property	Values
Dimension (mm)	0.8/2-1.0/38
Split tensile strength (Mpa)	≥410
Youngs's modulus (GPa)	≥4.2
Melting point (°C)	About 167
Density (g cm^{-3})	0.91~ 0.93
Ultimate elongation%	15±5
Burning point (°C)	About 580
Shape	Screw
Color	White

All mixing was conducted under laboratory conditions using 100 kg capacity concrete mixer in accordance with Chinese code. The mixing and casting of concrete were carried out China State Construction Engineering Corporation (CSCEC) while the tests on hardened concrete were done at structure Laboratory of Civil Engineering Department, Wuhan University of Technology. All specimens were cast into plastic moulds and compacted using a vibrating table. In this study, moist room also known as fog room curing was used. For the fog-room cured specimens, the specimens were cured in air in a vibration free environment for a period of 24-48 h before they were demolded. After demolding they were then transferred to fog room having a temperature of 20±3°C and Relative Humidity (RH) of no <95% until test ages were reached.

RESULTS AND DISCUSSION

Table 2-4 give the results of compressive and splitting tensile strengths of steel fiber reinforced

Table 2: L_{16} (4^5 series) orthogonal arrays test results for compressive strength and splitting tensile strength of fiber reinforced concrete

Test no	Average compressive strength f_{cf}(Mpa)	S/N ratio for average compressive strength	Average splitting tensile strength f_{ft}(Mpa)	S/N ratio for average splitting tensile strength	Increment between f_c and f_{cf}	Increment between f_t and f_{ft}
	28 days					
1	38.10	31.62	4.40	12.88	10.12	38.36
2	36.59	31.27	4.39	12.85	24.92	38.49
3	36.09	31.15	4.30	12.68	28.98	36.94
4	34.52	30.76	4.26	12.58	29.39	36.10
5	34.69	30.80	3.95	11.94	28.05	37.15
6	33.64	30.53	3.97	11.97	33.6	37.85
7	32.68	30.27	3.94	11.91	30.04	40.71
8	31.97	30.09	3.95	11.94	32.82	41.58
9	31.45	29.95	3.57	11.05	28.47	34.72
10	30.43	29.66	3.56	11.02	29.65	34.85
11	29.69	29.45	3.58	11.09	33.92	36.12
12	28.85	29.20	3.61	11.15	33.44	36.23
13	29.36	29.35	3.25	10.24	33.39	28.97
14	28.08	28.97	3.18	10.06	32.89	30.86
15	27.09	28.65	3.10	9.830	28.57	30.80
16	26.16	28.35	3.14	9.950	25.29	27.13

Table 3: Analysis of Variance (ANOVA) for fiber reinforced concrete

Parameters	Factor	DOF	SS	Contribution factors of SS(%)	F ratio	Prob >F
28 days compressive strength	W/C	3	169.87	89.44	976.81	<0.0001*
	RA	3	19.640	10.34	112.95	<0.0001*
	FA	3	0.0600	0.03	0.37	0.7768
	Error	6	0.3500	0.18	Prob >F	-
	Total	15	189.92	100.00	-	<0.0001*
28 days splitting tensile strength	W/C	3	3.0100	99.01	347.83	<0.0001*
	RA	3	0.0100	0.33	1.17	0.3956
	FA	3	0.0000	0.00	0.16	0.9178
	Error	6	0.0200	0.66	Prob >F	-
	Total	15	3.0400	100.00	-	<0.0001*

Table 4: L16 (4^5 series) orthogonal analysis for fiber reinforced concrete

Parameters	Factors	E1	E2	E3	E4	R
28 days compressive strength f_c (Mpa)	W/C	36.32	33.24	30.10	27.67	8.65
	RA	33.40	32.18	31.38	30.47	2.94
	FA	31.90	31.80	31.90	31.75	0.15
28 days splitting tensile strength f_t (Mpa)	W/C	4.34	3.95	3.58	3.17	1.17
	RA	3.79	3.77	3.73	3.74	0.06
	FA	3.77	3.76	3.75	3.75	0.02

*E1-E4-Average effect of three factors at levels 1-4. *R-Rank of significance among the factors

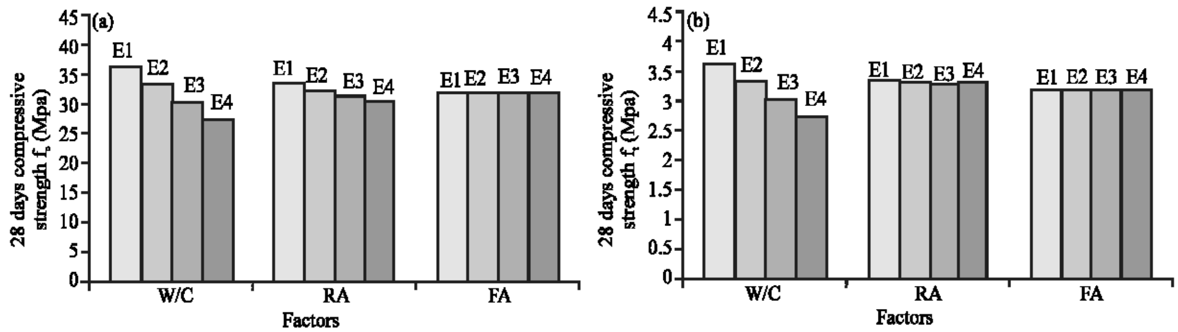

Fig. 5: (a) Mean effects of 3 factors on 28-day compressive strength of fiber reinforced concrete (b) Mean effects of 3 factors on 28 days splitting tensile strength of fiber reinforced concrete samples

concrete at 28 days. From the results (Table 2), there is no remarkable increase in the compressive strength plain concrete and that of SFRC with an overall average increment of 28.97 but the increment is higher for tensile strength. One can therefore conclude that steel fibers do not usually have a major effect on the compressive strength of concrete but can add a little to the splitting tensile strength of concrete. However, the direct splitting tensile strength is probably not worthwhile. The reason for the higher increment in tensile strength might be due to the angular shape of the recycled aggregates because as can be seen from the table, mixes with recycled aggregates also have very close results to the mixes without recycled aggregates. But it is necessary to note that the rate of increase in mixes with recycled aggregate is higher at lower proportion of recycled aggregate which means that recycled aggregates at proportions no >60% of the total aggregate might add to strength increase of SFRC. The above conclusion is also reflected in the S/N ratio the values at each water-cement ratio are very close to each other. The analysis of variance and orthogonal analysis in Table 3 and 4 also followed the same trend with other properties that have been discussed earlier. Figure 5a and b show the mean effects of the three factors on the strength of the SFRC.

CONCLUSION

One can therefore conclude that steel fibers do not usually have a major effect on the compressive strength of concrete but can add a little to the splitting tensile strength of concrete. However, the direct splitting tensile strength is probably not worthwhile.

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