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Experimental Investigation Of Influence Of Steel Fibres On The Properties Of Concretes

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***Abstract*—This paper presents an experimental investigation to study the influence of conventional steel fibres on the mechanical properties of concrete. Unreinforced concrete is weak in tension and requires reinforcement to prevent cracks and enhance tension and flexural capacities. This study evaluated the effects of 1%, 2%, 3%, 4% and 5% fibre contents on the fresh and hardened properties of concrete. The geometric properties of steel fibres were 30 mm length and 0.5 mm diameter. The workability of steel fibre reinforced concrete (SFRC) decreased linearly with increase in fibre content. Compressive strength also increased with curing age and the optimum fibre content was 3% with 11 – 15% increase in compressive strength. The tensile strength also increased with age and increased nonlinearly and attained maximum split tensile strength at the optimum fibre content of 4% with 60 – 70% increase in strength. The flexural strengths of beam specimens examined at 28-day and 56-day curing ages increased non-linearly cubic with fibre content with about 30% maximum strength enhancement at 3% optimum fibre content. It is evident that contrary to previous studies which limited the optimum steel fibre in FRC to 2 %, the tensile and flexural strength can be enhanced at 3% to 4% fibre volume fraction.**

***Keywords*—Fibre-reinforced concrete, waste tyres, recycled fibre, concrete, compressive strength, workability, compressive strength, split tensile strength, flexural strength**

I. INTRODUCTION

Concrete is unarguably the most widely used construction material for buildings and civil infrastructure all over the world. Its history begins since cement was introduced. Mass concrete is a brittle material, with a low tensile strength and a low strain capacity. Unreinforced concrete is strong the compression, but weak both in tension and flexure. Although concrete undergoes a mixture of these stresses, it can only withstand internal compressive forces far much better than tensile stresses. Concrete needs to be reinforced to improve its strength against tensile forces [1]. A major form of strength enhancement of mass or unreinforced concrete is the use of fibres. The concept of using fibres as reinforcement is not new. In ancient times horsehair was used in mortar and straw in mud-bricks. Fibres were used to reinforce brittle materials before cement was known since Egyptian and Babylonian civilisations [2].

The use of fibres in brittle matrix materials has a long history going back at least 3500 years when sun-baked bricks reinforced with straw were used to build the 57 m high hill of Aqar Quf near Baghdad. In more recent times, asbestos fibres have been used to reinforce cement products for about 100 years, cellulose fibres for at least 50 years, and steel, polypropylene and glass fibres have been used for the same purpose for the past 30 years [1–3]. In 1900s, asbestos fibres were used in concrete but was later discouraged due to detection of health risk [4-5].

Fibre-reinforced concrete is a technique where fibrous materials are incorporated in the concrete matrix to improve its crack resistance, ductility, energy absorption, impact-resistance characteristics and a long-term post-crack tensile strength [2]. Fibers increase the strain at peak load, and provide additional energy absorption ability of RC elements and structures. It was recently reported that they also considerably improve static flexural strength of concrete as well as its impact strength, tensile strength, ductility and flexural toughness [3]. There are many different types of fibres such as glass, propylene, carbon and steel fibres. These fibres differ in performance because of their mechanical properties and other factors [5].

Fibers made from steel, plastic, glass, and natural materials (such as wood cellulose) are available in a variety of shapes, sizes, and thicknesses; they may be round, flat, crimped, and deformed with typical lengths of 6 - 150 mm and thicknesses ranging from 5 - 750 µm. These fibres are added to concrete during mixing [6]. Although the basic governing principles are the same for the conventional reinforcement and fiber systems in concrete, there are three basic characteristic differences. First, fibers are generally randomly distributed throughout a given cross section whereas reinforcing bars or wires are placed only at the tension zones. Second, most fibers are relatively short and closely spaced as compared with continuous reinforcing bars or wires. Lastly, it is practically impossible to achieve the same area of reinforcement to area of concrete using fibers as compared to using a network of reinforcing bars or wire mesh [7].

Fibres typically added to concrete in low volume dosages (often less than 1%) have been shown to be effective in reducing plastic shrinkage cracking of concrete. On the other hand, whereas fibres do not significantly alter free shrinkage of concrete, but high fibre content (much greater than 1%) have been found to increase concrete resistance to cracking and decrease in crack width [8].

The oldest forms of fibre-reinforced composites were made with naturally occurring fibre such as straw and horsehair [1-4]. Modern technology has made it possible to extract fibres economically from various plants, such as jute and bamboo to use in cement composites. Fibres produced by plants (vegetable, leaves and wood), animals and geological processes are known as natural fibres. Primary sources of these fibres include akwara bamboo, coconut, flax, jute, sisal, sugarcane bagasse and wood [9].

Kavitha & Kala [9] found that fibres generated from agricultural activities modify the properties of the cement matrix in concrete and therefore arrest the cracking behaviour of concrete. These produce stronger, safer and more economical especially for low-income housing and buildings in rural areas where these fibre are locally available, cheap and easily accessible and affordable. Hence, these natural fibres are much cheaper as a composite construction material than other types of fibres. However, the environmental impacts of such fibres require extensive investigation for long-term performance and sustainability.

Synthetic fibres are the result of an extensive research to improve the properties naturally occurring fibre. Synthetic fibres help to improve pumpability and keep concrete from spalling during impacts [10]. They help to prevent cracking under varying environmental conditions as such fibres do not expand in heat and contract in cold and hence more durable. However, sustainability and cost are major factors that discourage their utilization in FRC. Examples of synthetic fibres include carbon, nylon, polyester, polypropylene and polyethylene. Further comprehensive studies are required to ascertain the cost-benefit analysis and long-term effectiveness under mild, moderate and extreme loading.

Steel fibres, usually of many types, are used to reinforce concrete in construction. These include straight, paddled, deformed, crimped, irregular and hooked steel fibres. They are classified according to the manufacturing processes and shapes. Steel fibres are short, discrete lengths of steel with an aspect ratio (ratio of length to diameter) from about 20 to 100, and with any of several cross sections. Some steel fibres have hooked ends to improve resistance to pullout from a cement-based matrix [1-5]. ASTM A 820 [13] classifies four different types based on their manufacture. Type I – Cold-drawn wire fibres are the most commercially available, manufactured from drawn steel wire. Type II – Cut sheet fibres are steel fibres laterally sheared off steel sheets. Type III – Melt-extracted fibres are manufactured as crescent-shaped fibres from liquid metal from a molten metal surface by capillary action and subsequently extracted from rapidly frozen into fibres and thrown off the wheel by centrifugal force. Type IV are fibres from other sources manufactured from processed different from the above three types [2-4]. Hooked end stainless steel has the best performance [14,15].

This paper presents an experimental investigation to study the influence of 1%, 2%, 3%, 4% and 5% conventional steel fibre content on fresh and hardened properties of concrete. The geometric properties of steel fibres were 30 mm length, 0.5 mm diameter and an aspect ratio of 60. The influence on workability, compressive, split tensile and flexural strength of concrete due to varying dosages of steel fibre content on FRC were assessed and the optimum fibre dosage were determined for strength enhancement of concrete structures.

II. Experimental Programme

A. *Materials*

Portland composite cement type II of grade 32.5 R with specific gravity of 3.15 was used in this study. Coarse aggregate was crushed granite of maximum nominal size of 19 mm with water absorption of 0.26%. Fine aggregate was well-graded crusher sand of maximum nominal size of 4.75 mm and water absorption of 1.55% and fineness modulus of 3.13. The particle size distribution curves of the aggregates are plotted in Fig. 1. The properties of cement such as consistency, setting times, soundness and compressive strength are summarized in Table 1. The aggregates were free from deleterious materials and the physical properties were carried out in accordance with BS 812 [16]. The properties of fine and coarse aggregates are presented in Table 2. It is obvious that the fine and coarse aggregates employed as constituents of the concrete in the study are well-graded. Potable water of pH of 7.1 which conformed to the requirements of BS 3148 [17] was used in mixing the aggregates and cement. Steel fibres of length 30 mm and 0.5 mm diameter (of aspect ratio 60), sourced from South Africa as shown in Fig. 2, were utilized for FRC experimentation in this study. The mix was designed for a target compressive strength of 38.5 MPa.

TABLE 1: PHYSICAL PROPERTIES OF CEMENT

Standard Consistency (%)	30
Specific gravity	3.15
Initial setting time (min)	290
Final setting time (min)	450
Soundness (mm)	1.0
Compressive strength (N/mm^2)	
3 days	24.5
7 days	30.8

Crushed granite as coarse aggregate

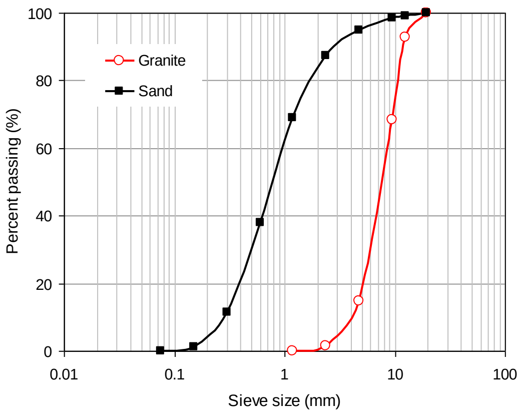

Fig. 1: Samples of particle size distribution of fine and coarse aggregates

TABLE 2: PROPERTIES OF AGGREGATES

Properties	Crusher sand	Crushed granite
Specific Gravity	2.34	2.64
Bulk Density (kg/m^3)	1240	1464
Moisture content (%)	4.24	1.61
Fineness modulus	3.13	2.59
Aggregate Crushing Value (%)		12.9
Impact Value (%)		7.13

Fig. 2: Steel fibre

B. *Mix proportioning and casting of concrete specimens*

A fixed concrete mix proportions with a fixed water-cement ratio of 0.47 considered for the study. The cementitious materials, fine and coarse aggregates were kept constant at 430 kg/m^3, 686 kg/m^3 and 1024 kg/m^3 respectively representing a concrete mix ratio of 1:1.6:2.4 in proportion of cement, fine and coarse aggregates. Steel fibres of 30 mm length, 0.5 mm diameter and an aspect ratio of 60 were uniformly introduced in the concrete mixture in volume fractions of 1%, 2%, 3%, 4% and 5% to determine the influence on fresh and hardened properties of concrete. Concrete specimens with zero fibre content were considered as the control. No plasticizer was added into the mix in this study. Each concrete mix proportion was prepared in a rotating drum mixer. The aggregates and cement were placed in the drum and mixed in parts with water to ensure a better bond between the cement paste and the aggregates. All mixing and sampling of concrete were carried out in accordance with the procedures given in BS 1881[18].

The workability of fresh concrete of varying fiber contents was determined via slump test in accordance with ASTM C143 [19]. The apparatus used included tamping rod, cone and a measuring rule. The slump test setup is shown in Fig. 3. The ideal slump was expected in the range 25 mm to 75 mm.

Fig. 3: Slump test set-up

Test specimen were prepared and cast into moulds of different sizes. Fifty-four (54) cubes of size 100 mm were cast, cured and tested for compressive strengths according to BS 1881 [18] at curing ages 7 days, 14 days and 28 days. Compression testing machine, employed for crushing of cubes and splitting of cylinders as per the requirements of EN 12390-4[20] as shown in Fig. 4. Compression load was applied without shock and continuously increased at a uniform rate of between 0.3 ± 0.1 MPa/s until the specimen failed. The maximum crushing or spliting load, the appearance of the specimen and any unusual feature in the type of failure was recorded for analysis. The compressive strength was determined by calculating the ratio of the crushing load to the cross-sectional area of the cube specimens.

Fig. 4: Test setup of concrete cubes for compressive strengths.

Thirty-six (36) cylinders of 150 mm diameter and 300 mm length were cast, cured and tested at 7 days and 28 days for the split tensile strength of concrete of varying fibre volume fractions. The split tensile strength was carried out as per BS EN 12390:6[21]. After curing, water was wiped out from the surface of specimen and diametrical lines were drawn on the two ends of the specimen using a marker to verify that they are on the same axial place. Plywood strips were placed on the lower plate followed by the concrete cylinder specimens and the upper plate was brought down to touch the plywood strip. The load was applied continuously without shock at an approximate rate of 14-21 kg/cm^2/min and the breaking load was recorded for each test specimens.

Thirty-six (36) beam specimens of size 100 × 100 × 400 mm were cast, cured and tested at 28 days and 56 days curing ages for flexural strength assessment. All the concrete specimens were cast and then covered with thin polythene membrane to minimize moisture loss. The concretes were stored and tested in the laboratory under mean air temperature of 26 ± 1˚C. The specimens were demoulded after 24 ± ½ hours and then transferred into a water-curing tank for the test periods. Flexural test was carried to measure the bending strength of concrete in accordance with ASTM C78 [22]. The beams were tested under a three-point loading procedure as shown in Fig. 5 at the Concrete/Construction Material Laboratory of the University of Botswana. The load was applied continuously at a rate that constantly increases the extreme fiber stress from 0.85 MPa to 1.2 MPa/min, until rupture occurs. When the approximate failure load was known, the load may be rapidly applied to approximately 50 % of the breaking load.

Fig. 5: Test setup for flexural strength of beam specimens.

III. Results and Discussion

A. Properties of fresh concrete

Concrete must always be made with a workability, consistency, and plasticity suitable for job conditions. Workability is a measure of how easy or difficult it is to place, consolidate, and finish concrete.

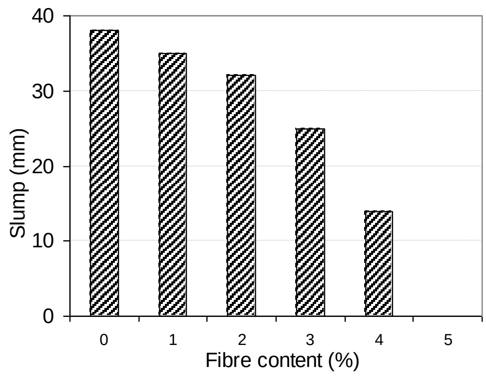

Fig. 6: Slump test results

This study assessed the workability of the mix proportions using slump and compaction factor tests. Fig. 6 shows the test results of workability of the six concrete mixes with fiber contents from 0% (control specimens) to 5% at interval of 1%. The slump of the concrete mixes decreased linearly with increase in steel fibre content. The control specimen had the highest slump of 38 mm, and concrete mixes with fiber contents up to 3% produced acceptable slump values, However, 4% and 5% fiber contents would require plasticizer to produce acceptable workability for concrete works. The relationship between slump and fiber content was almost perfectly linear with $s = -7.429v + 42.571$ ($R^2 = 0.913$), where s and v are the slump value and fiber volume fraction (i.e fibre content) respectively.

The percentage reduction in the slump of fiber contents 1%, 2%, 3%, 4% and 5% were 7.9%, 15.8%, 34.2%, 63.2% and 100% of the control value. This shows that there was a remarkable loss of workability for 4% and 5% fibre contents.

B. Split tensile strength of steel fibre reinforced concrete (SFRC)

The tensile strength of concrete is conventionally about one-tenth of the compressive strength. It is determined by loading a concrete cylinder across a diameter in accordance with BS EN 12390:6 [21]. The relationship between the split tensile strength of the concrete mixes and the fibre content was perfectly cubic as shown in Fig. 7. The tensile strength of the SFRC increased with curing age. In this study, the percentage rise in the tensile strength at 28th day test with respect to the 7th day test were 11.1%, 10%, 19%, 30.4%, 25.4% and 28% for the control (zero fiber), 1%, 2%, 3%, 4% and 5% steel fibre contents. The optimum fibre content was 3%.

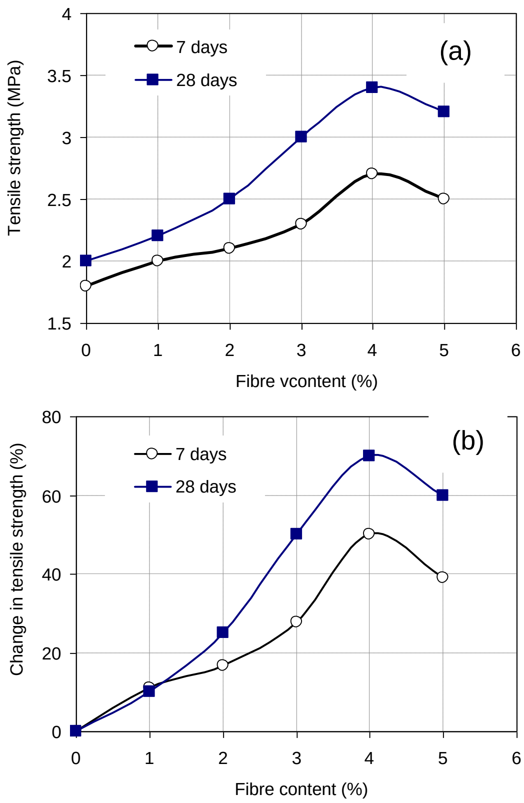

Fig. 7: Split tensile test results for (a) tensile strength and (b) percentage change in strength.

The tensile strength relations for the 7th day test is $f_{ct} = -0.0204\nu + 0.139\nu^2 - 0.042\nu + 1.833$ with a coefficient of correlation (R^2 = 0.931). The 28th day tensile strength relation with respect to fibre content is $f_{ct} = -0.0407\nu^3 + 0.277\nu^2 - 0.127\nu + 2.022$ (R^2 = 0.931). The tensile strength increased with increase in the fibre content. The tensile strength and increase in tensile strength share similar trend with respect to fibre tensile strength as shown in Fig. 7.

For a 7th day test, the concrete specimens attained a maximum tensile strength increase of 50% at 4% fibre content and later dropped to 38.9% tensile strength increase at 5% fibre content. Likewise for the 28th day tensile strength test results, the tensile strength increase non-linearly cubic with increase in fibre content until it reached a maximum tensile strength increase of 70% at 4% fibre content, but later dropped to 60% strength increase at 5% fibre dosage in concrete. It can be concluded that the optimum fibre content for split tensile strength of concrete is 4%.

C. Compressive strength of SFRC

Compressive strength is the measured maximum resistance of a concrete specimen to axial loading. The 7th day and 14th day compressive strengths were about 61.8% and 83.9% of the 28th day compressive strength results. As shown in Fig. 8 as expected, the compressive strength increased with curing age of concrete cubes. The relation between the compressive strength and fibre content is cubic polynomial of coefficient of correlation of at least 0.85.

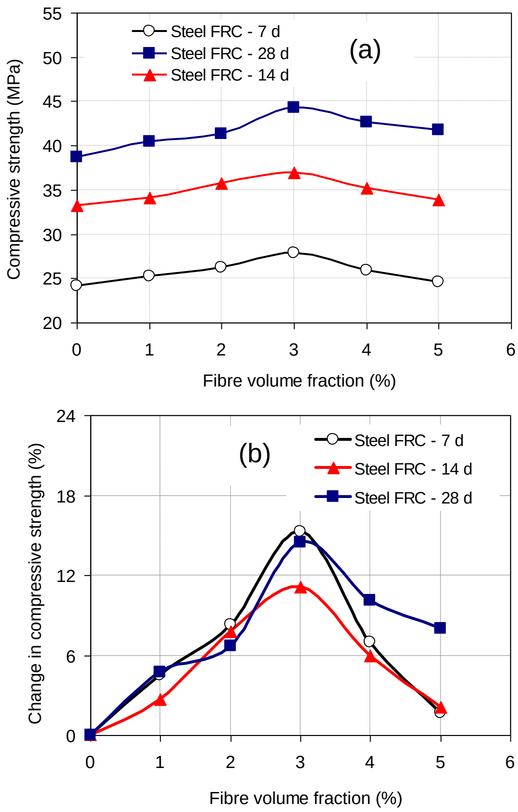

Fig. 8: Plots of test results for (a) compressive strength and (b) change in compressive strength

The maximum compressive strength for the three curing ages 7 days, 14 days and 28 days were 15.3%, 11.1% and 14.5% higher than the control compressive strength values at the optimum fibre dosage of 3%. It can be concluded that steel fibres do not only improve the tensile strength of concrete, they also enhance the compressive strength of concrete with the maximum strength at 3% fibre content. However, the tensile strength enhancement is more significant than the compressive strength.

D. Flexural strength of SFRC

The flexural test results of SFRC for 1% to 5% steel fibre content at the 28th and 56th test days are presented in Fig. 9. Similar to the tensile and compressive strength, the flexural strength is also non-linearly cubic with respect to the fibre content. Both 28th and 56th flexural strength are comparable and the correlation coefficient for the varying fibre content is 0.967 for both the strength and increase in flexural strength. As shown in Fig. 9a, flexural strength of SFRC beams increased nonlinearly until the maximum flexural strengths were attained at 3% optimum fibre content. The rate of increase in flexural strength was about twice the rate beyond the optimum fibre content. On the other hand, SFRC beams had about 30% improvement in flexural strength for both test days at 3% fibre content. Contrary to common claims in several literature that recommend steel fibre volumes in concrete in the range of 0.25% to 2% [23-24], this study has shown that concrete can accommodate up to 3% fibre content without any compromise in tensile, flexural and compressive strength.

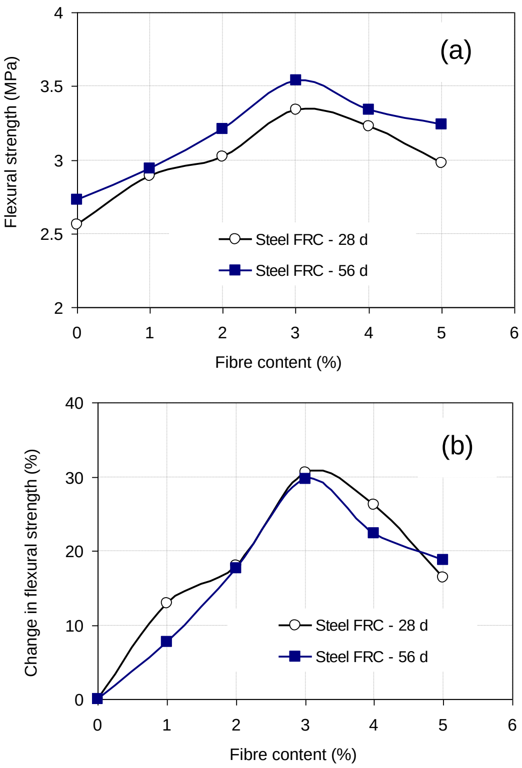

Fig. 9: Plots of test results for (a) flexural strength and (b) change in flexural strength

IV. Conclusion

This work has confirmed the potentials of steel fibre for FRC concrete for tension and flexural strength enhancement and crack control in concrete. Steel fibre contents from 1% to 5% were added into concrete mixes at an interval of 1% to evaluate the influence on fresh and hardened concrete properties. The following conclusions can be drawn from the experimental study conducted on the suitability of steel-FRC in compression, tension and flexure.

1. Contrary to the common claim, it has been established that steel fibres (30 mm length, 0.5 mm diameter and an aspect ratio of 60) can conveniently enhance the compressive, tensile and flexural capacity of unreinforced concrete.
2. The workability of fresh SFRC decreased with increase in steel fibre content. Fibre volume fractions more than 3% compromise workability requirement and would therefore reuire special mix design, introduction of plasticizer, air entrainer or special placement techniques.
3. The workability of SFRC with 0% to 3% fibre volumes was found to be within the specification plain and reinforced concrete.
4. The optimum steel fibre content was 4% split tensile strength, and 3% for both compressive and flexural strength.
5. At the optimum dosage, the study has shown that steel fibres increase compressive strength by 15%, tensile strength by 70% and the flexural strength by 30%.

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