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Flexural behaviour of steel fibre-reinforced concrete under cyclic loading

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HIGHLIGHTS

- The flexural behaviour of fibre reinforced concrete under cyclic loading was studied.
- The fibres orientation depends mainly upon the workability properties of the concrete mixture.
- The use of steel fibres in concrete improved the flexural tensile strength and the ductility.
- The fibre content and the aspect ratio have an important influence on the reversibility of FRC.
- The cumulative energy of FRC increases with the fibres content.

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ABSTRACT

This paper presents the results of cyclic loading tests on fibre-reinforced concrete (FRC). The main objective of this research is to evaluate simultaneously the influence of the workability, the steel fibres and the compressive strength on the flexural behaviour of FRC under cyclic loading. Prismatic concrete specimens having dimensions of 150 × 150 × 700 mm were fabricated with concrete of various workability and different compressive strengths (30, 60 and 80 MPa) and reinforced with hooked end steel fibres of aspects ratios of 65 and 80 at contents of 0.5 and 1%. A four-point bending test with notched specimens was conducted using Digital Image Correlation technique. The orientation of the fibres, failure modes, hysteresis loops, flexural strength, local analysis, cumulative energy and ductility of FRC beams are presented and analyzed. The experimental results show that the cyclic flexural behaviour of FRC flexural strength and ductility of fibre-reinforced concrete are significantly improved by the fibre content, the aspect ratio, the fibres orientation and the concrete strength. The increase in flexural strength reaches 242%. The workability of concrete plays an important role on the orientation and distribution of the fibres in the matrix.

1. Introduction

With the continuous advances in materials' technology, the performance of concrete is being continuously improved and its compressive strength exceeding well 60 MPa, making it widely used in industry throughout the world. However, with the increase of its compressive strength, the concrete becomes more brittle, less ductile and hence liable to sudden failures. To improve its ability to absorb energy and deformation before failure, and behave as a ductile material, steel fibres are added to the concrete forming fibre-reinforced concrete. The steel fibres also improve the tensile strength, considered as the main weakness in the structural properties of concrete, and enhance its flexural behaviour [1,2]. By bridging across a crack, fibres take up partially the tension force and hence cracked concrete does loose completely its tensile strength after cracking [3,4].

The extent of the improvement in ductility and tensile strength is, however, influenced by several parameters such as the type, shape, aspect ratio, volume and distribution of fibres [5–11]. Furthermore, the geometry and the quantity of the fibres used influence directly the workability of the fresh concrete [12,13].

A residual tensile strength still remains in fibre concrete after cracking, contrary to unreinforced concrete. The importance of this residual tensile strength depends on the efficiency of the fibres in terms of bonding, anchorage and on their content in the concrete-fibres mixture. The stability of any concrete structure during an earthquake is heavily governed by its ductility. The survival of the structure against a seismic loading depends on the capacity for disposal of the cumulative energy. Park and Paulay [14] have showed that crack occurrence is necessary for the energy dissipation.

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Table 1
Properties of steel fibres used.

	Type 1	Type 2
Length l_f (mm)	35	60
Diameter d_f (mm)	0.55	0.75
Aspect ratio (l_f/d_f)	65	80
Tensile strength (MPa)	1100	1100
Shape		

On the other hand, the orientation of fibres is the key parameter that affects most the flexural behaviour of FRC and is significantly improved when the fibres are oriented in the direction of the tensile stresses; a larger number of fibres parallel to the direction of the tensile stresses is required to achieve optimum benefits from the fibres [2,5–9]. The efficiency of fibres in the concrete depends on the number of effective fibres oriented in the direction of the principal stress [15]. The effectiveness of FRC is found to decrease by 70% for randomly oriented fibres with regard to totally aligned fibres, since with a larger number of fibres crossing the failure plane, more fibre pull-out resistance would be activated, leading to an improved flexural strength [2,16].

However, the orientation of the fibres depends on a number of parameters, essentially the amount and geometry of fibres, the workability of concrete, the casting method, the means of pouring and compacting, the formwork geometry and the fine to coarse aggregate ratio [1,2,7–10].

A higher content of fibres during mixing increases the interaction of fibres with aggregates, which in turn causes the effect of balling and affects negatively the workability of the concrete mixture. The workability and the compaction method affect the movement of fibres during the casting of specimens; a too high workability allows for a better orientation of the fibres. Specimen size indirectly affects the orientation of fibres since the latters are forced to align along moulded surfaces [2,12,13,17].

Most research has been conducted on the flexural response of FRC under monotonic loading, but few of them have investigated the cyclic behaviour. The objective of the present work is to investigate experimentally the flexural behaviour of FRC under cyclic loading and the effect of some other parameters of the material with different levels of workability, matrix strength, fibre volume fractions and aspect ratios.

2. Experimental work

2.1. Materials and fabrication of the test specimens

The cement used was a CEM I 52.5 N with a specific surface of 3520 cm^2/g. Standard silica fume and limestone filler was used as mineral additives; their specific surface was 230,000 cm^2/g and 3970 cm^2/g respectively. The silica fume was used in proportion of 10% by weight of cement for high strength concrete. The Super-plasticizer was a polycarboxylate-based admixture.

Two types of hooked-end steel fibres with two aspect ratios (65 and 80) have been used. Two fibres dosages 0.5% and 1% by volume of concrete were made along with a concrete without fibres for reference. Table 1 shows the characteristics of the steel fibres used.

Three mixtures of concretes were performed: an ordinary concrete (OC), a self-compacting concrete (SCC) and a high strength concrete (HSC). The mix proportions are given in Table 2. For each mix, three prismatic specimens 150 × 150 × 700 mm on a span of 600 mm were performed for the flexural test and three concrete cylinders (110 × 220 mm) were tested to measure the compressive strength. The bottom side of each specimen was notched with 10 mm depth and 2 mm width.

Compaction was achieved by means of a vibrating table for ordinary and high strength concretes. After 24 h, the specimens were removed from the moulds and stored in a moist room at a temperature of 22 °C and 95 % relative humidity until the day of testing. All the tests were carried out at 28 days of age.

The magnitude of the residual strength beyond cracking is provided by fibres bridging the crack and hence it is important that the fresh concrete allows for a uniform distribution and a better orientation of the fibres. A too much stiff concrete results in a poor distribution of fibres which are not properly enveloped by concrete and blocked in clusters in the presence of higher coarse aggregate. This justifies the use of higher paste content by using higher quantity of limestone filler and limiting the coarse aggregates [3,12,13].

2.2. Flexural test setup

The four-point bending tests were conducted on a 250-kN servo-hydraulic universal testing machine. The testing machine has the capability to control test using load and displacement control. All the beams are subjected to repeated loading up to failure. The deflection of the beam specimens is measured at mid-span using LVDT. The beams were supported by two roller bearings, one of which was fixed and the other was free to move horizontally. A uniform/random speckle pattern is applied on one face of the specimen Fig. 1.

The loading procedure involved two load steps, namely, a displacement-controlled step and a load-controlled step. For loading and reloading, the tests were carried out under displacement-controlled conditions at a constant rate of 0.2 mm/min. For unloading, the tests were carried under load-controlled conditions at a constant rate 6 kN/min until a near zero load level. The cyclic flexural testing involved unloading to deflection levels of 0.2, 0.5, 1, 2, 3, 4 and 5 mm. Fig. 2 shows the loading procedure.

A Digital Image Correlation technique obtained by a digital recording camera was used to detect the first crack and to follow the cracking process until failure.

Table 2
Mix proportions of concretes (kg/m^3).

Mixture	OC	FROC	SCC	FRSCC	HSC	FRHSC
Cement (C)	275	275	425	425	425	425
Silica fume (SF)	–	–	–	–	42.5	42.5
Limestone filler (LF)	90	90	200	200	90	90
Gravel 4/10	910	900	825	814	825	814
Sand 0/4	830	820	750	740	750	740
Water (W)	178	178	192	192	161	161
Super-plasticizer (%C)	–	0.70	1.20	1.70	1.00	1.60
Steel fibres	–	39; 78	–	39; 78	–	39; 78
W/P*	0.49	0.49	0.32	0.32	0.30	0.30

Notations used: FROC: Fibre Reinforced Ordinary Concrete; FRSCC: Fibre Reinforced Self-Compacting Concrete; FRHSC: Fibre Reinforced High Strength Concrete.

* P (Powder) = C + SF + LF.