Mechanical properties of self-compacting concrete reinforced with polypropylene fibres

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The properties of hardened concrete can be significantly improved by fibres. However, the addition of fibres to fresh concrete results in a loss of workability. Self-compacting concrete (SCC) is an innovative concrete that is able to flow under its own weight, completely filling formwork and achieving full compaction without vibration. In the present study, the workability and mechanical properties of SCC with fly ash reinforced with monofilament polypropylene fibres were investigated. Two cement contents at 350 and 450 kg m^{-3} were studied as well with four fibre contents at 3, 6, 9 and 12 kg m^{-3}. The water/cement ratio, fly ash and superplasticiser contents were kept constant at 0·40, 120 kg m^{-3} and 1% of cement content respectively. Slump flow, J ring, V funnel and air content tests were conducted for evaluating the fluidity, filling ability and segregation risk of the fresh concretes. Unit weight, compressive strength, splitting tensile strength, flexural strength, pulse velocity and elasticity modulus of concrete were determined. The materials used in this study exhibit no problems with mixing or workability when the fibre distribution is uniform. The polypropylene fibres enhance the strength of SCC significantly, without causing well known problems associated with steel fibres.

Keywords: Reinforced cement/plaster, Concrete rheology, Concrete mechanics, Polypropylene fibre reinforcement

Introduction

Concrete, one of the principal materials for structures and widely used all over the world, is a heterogeneous material consisting of cement, water, sands and aggregates. Very extensive literature on concretes includes a number of reviews.[1–5] While the heterogeneous structure of concrete can produce some undesirable effects,[6] concrete remains an indispensable construction material and allows engineers to incorporate many materials into it. A variety of types of concrete exist.[7]

Self-compacting concrete (SCC) was first developed in Japan in 1986.[8] The SCC can flow through and fill the gaps of reinforcement and corners of moulds without any need for vibration and compaction during the placing process.[9,10] The use of SCC is increasing.[11] So called superplasticisers (SPs) are typically used in SCC to reduce the water/binder ratio. Moreover, supplementary cementitious or inert materials, such as limestone powder, natural pozzolans and fly ash (FA), can be used to increase the viscosity and fresh concrete workability and reduce the cost of SCC. The use of pozzolanic admixtures extends the hydration reaction and produces good micropore structures, resulting in improved durability.[12]

The use of FA reduces the demands for cement, fine fillers and sand that are required in SCC.[13,14] The FA, a byproduct of coal power plants, has been reported to improve the mechanical properties, such as freeze–thaw resistance, sulphate resistance, alkali–silica reaction, durability and abrasion resistance, when it is used as a cement replacement material in mortar and concrete. In addition, shrinkage and permeability of hardened concrete are decreased due to the filling of micropores by FA.[15] Utilisation of FA in concrete technology is becoming more common, causing a reduction in chloride penetration, steel corrosion[16] and wear loss of the concrete.[17,18] On the other hand, unsalvaged FA causes environmental pollution, while its storage costs are quite high.[15] The advantage of usage of industrial waste materials in concrete, both to lower environmental pollution and to provide less expensive materials, is beyond dispute.

The term 'fibre reinforced concrete' is defined by the American Concrete Institute (ACI) in their ACI 116R Cement and Concrete Terminology document as a concrete containing dispersed randomly oriented fibres. Inherently, concrete is brittle under tensile loading; it can be recalled that the definition of brittleness includes inverse proportionality to elongation at break in tensile

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Table 1 Aggregate gradations

	16 mm	12·5 mm	9·5 mm	4·75 mm	2·36 mm	1·18 mm	600 μm	300 μm	150 μm	75 μm
NRS	100·0	100·0	100·0	96·0	81·0	53·0	32·0	18·0	5·0	1·0
Cst-I	100·0	83·0	50·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Cst-II	100·0	35·0	12·0	1·0	1·0	0·0	0·0	0·0	0·0	0·0
Mixture	100·0	82·8	69·9	53·3	44·6	29·2	17·6	9·9	2·8	0·6

testing.[19,20] The mechanical properties of concrete may be improved by randomly oriented short discrete fibres, which prevent or control the formation, propagation or coalescence of cracks.[21] Apparently, fibres in concrete can improve flexural strength, compressive strength, tensile strength, creep behaviour, impact resistance and toughness.[22]

In general, reinforced concrete performance depends on formulations as well as fibre characteristics, including type, geometry, distribution, orientation and concentration.[23] Many different kinds of fibres, such as metallic, polymeric, coated, uncoated or modified by irradiation, have been used in concrete engineering for their specific advantages.[24–30]

Steel fibres have high elastic modulus and stiffness, so they can improve the compressive strength and toughness of concrete. Polypropylene (PP) fibres have good ductility; hence, they can restrain plastic cracks.[27] However, steel fibres at concrete surfaces undergo rusting and also might cause electric conductivity and magnetic field problems. If steel fibre reinforced concrete is used in the runway of an airport, high speed railway systems and/or nuclear power plants, safety problems can ensue.[31]

Steel fibres reduce the workability of concrete, a handicap for onsite applications. One of the ways to compensate for the workability loss associated with the usage of steel fibres can be a combination of SCC+reinforcing fibres+FA. In the belief that PP fibres are a potential replacement for steel fibres, it was to use coarse synthetic monofilament PP fibres in SCC with FA and to evaluate the physical and mechanical properties of such concretes.

Materials and methods

Materials

Aggregates

Aggregates typically constitute 70–80 wt-% of concrete; hence, aggregate types and sizes play an essential role in modifying the concrete properties. Limestone based aggregates with three different grain sizes were used: up to 3 mm diameter crushed stone (CSt-I), up to 7 mm natural river stone (NRS) and 7–15 mm crushed stone II (CSt-II). The aggregates were graded, washed and cleaned of clay and silts. The maximum 15 mm size was selected to reduce difficulties of producing, mixing and placing concretes and to prevent segregation of aggregates in fresh concretes. Results of sieve analysis of fine and coarse aggregates used and the grading of the mixed aggregate are presented in Table 1. The physical and mechanical properties and the mixing ratios of all the aggregates are presented in Table 2.

Cement

The cement used in all the concrete mixtures was Portland cement CEM II/A-M (P-LL) 42·5 N. The physical and mechanical properties and the chemical analysis of cement are presented in Tables 3 and 4 respectively.

Fly ash

Class F of FA was used in this study; its chemical composition is listed in Table 5. The Blaine fineness, which is defined as a measure of the particle size or fineness of cement and supplementary cementitious materials, was 5230 $cm^2 g^{-1}$. The specific gravity was 2·1 g cm^{-3}. The cement paste in SCC is quite important since it is an agent to carry the aggregates. As a consequence, the FA has been used to increase the amount of cement paste.[32]

Superplasticiser

A novel SP based on a modified polycarboxylic ether type was employed to obtain a satisfactory workability of fresh concrete for all the mixtures. Pertinent properties of the mixture are presented in Table 6. In developing an SCC, usually, such plasticisers are used together with either some chemical or mineral admixtures that provide the necessary viscosity.

Table 2 Physical properties of aggregates

Aggregate codes	Specific gravity/g cm^{-3}	Loose unit weight/g cm^{-3}	Dry rodded unit weight/g cm^{-3}	Water absorption/%	Mixing ratio/%
CSt-I	2·69	1·913	2·151	2·91	30
NRS	2·67	1·830	1·974	3·02	25
CSt-II	2·70	1·676	1·594	0·93	45

Table 3 Physical and mechanical properties of Portland cement

Compressive strength/MPa			Flexural strength/MPa			Initial setting time/h	Final setting time/h	Le Chatelier/mm	Specific gravity/g cm^{-3}	Blaine/$cm^2 g^{-1}$
2 days	7 days	28 days	2 days	7 days	28 days	2·25	3·15	1	3·15	4150
22·5	36·6	47·8	3·7	5·6	6·9					

Table 4 Chemical analysis of Portland cement

Compound	Total SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl	LOI*	Free CaO	Total admixture
wt-%	22·9	5·32	3·63	55·83	1·99	2·62	0	4·2	0·82	19·45

*Loss on ignition.

Fibres

The monofilament PP fibres (Propex Inc., Southampton, UK) used in this work are shown in Fig. 1. Bunsell and Renard discuss in detail the role of fibres in composites.[33] Wavy shape fibres are 45 mm long with 1 mm of diameter and density of 0·91 g cm^{-3}. The respective elastic modulus is 5·88 GPa, and the tensile strength is 320 MPa.

Unlike steel, PP monofilament fibres are not affected by atmospheric conditions, the alkali environment found in concrete or the presence of moisture. Since there is no corrosion and rusting, the concretes used here should have long term durability and strength.

Mix proportions

Ten mixture compositions for each cubic metre of concrete are defined in Table 7. The mixture design is made according to the absolute volume method. The water/cement ratio, SP and FA content were kept constant as 0·40, 1% of cement content and 120 kg m^{-3} respectively. Two cement contents of 350 and 450 kg m^{-3} were used, identified as series I and II. The fibre contents were 0 (control), 3, 6, 9 and 12 kg m^{-3} for each cement content. As already mentioned, the maximum aggregate size was 15 mm in order to avoid subsequent blocking effects.

Mixing, casting, curing and testing specimens

The concrete mixtures were prepared in a laboratory mixer with capacity of 60 dm^3. In a typical mixing procedure, the materials were placed in the mixer in the following sequence: first course aggregates and fine aggregates and fibres together followed by cement, initially dry material mixed for 1 min and finally addition of 85% of water. After 1·5 min of mixing, the rest of the mixing of water together with the SP was added. All the batches were mixed for a total time of 5 min; in order to prevent fresh concrete from segregation, the mixing duration was kept as low as possible. The specimens for testing the hardened concrete properties were prepared by direct pouring of concrete into moulds without compaction.

From each concrete mixture, three specimens were cast in cylindrical moulds of 150 mm diameter and 300 mm height. Three 150 mm cubes were cast. The cubes were used for compressive strength and ultrasonic pulse velocity tests, while the cylinders were used for elasticity modulus and splitting tensile strength tests. After casting, the concrete specimens were covered with wet burlap and polyethylene sheets and kept in the laboratory at room temperature for 24 h. After demoulding, they were placed in a saturated limewater bath until the time of testing. Curing was performed in accordance with the ASTM C511 standard. It is well recognised that adequate curing of concrete is very important not only to achieve the desired compressive strength but also to make durable concrete. The compressive strength tests were carried out in accordance with ASTM C39-86 at 28 days. The splitting tensile strength tests were performed according to ASTM C496-87 at 28 days. Ultrasonic pulse velocity, flexural strength and elasticity modulus were determined according to ASTM C597, 293-94 and C469-87 respectively.

Fresh concrete is a mixture of coarse and fine aggregates, which are suspended in a binder paste matrix. The mortar viscosity, the volumetric fraction of aggregate and the fibres control the flow behaviour.

Numerous test methods are available for measuring the rheological behaviour and the workability of concrete with or without fibre reinforcement, such as those used by some of the authors.[28–30] The self-compactability of the mixtures was examined according to standards of the Self-Compacting Concrete Committee of EFNARC.[34]

In this study, to evaluate workability of fresh concrete, three types of workability tests were performed on fresh concrete mixtures, namely slump flow tests, J ring tests and V funnel tests. These tests have been described by Sahmaran and Yaman[35] and are also presented below.

The slump flow test is used to evaluate the horizontal free flow (deformability) of SCC in the absence of obstructions. The test method is very similar to the test method for determining the slump of concrete. The difference is that, instead of the loss in height, the diameter of the spread concrete is measured in two perpendicular directions and recorded as slump flow. The higher the slump flow, the greater the concrete's ability to fill formworks. During the slump flow test, the time required for the concrete to reach a diameter of 500 mm is also measured and recorded as t_{500}. This parameter is an indication of the viscosity of concrete and indicates how stable the concrete is. A lower time points to a greater fluidity or smaller workability loss.

The J ring test is used to determine the passability of the concrete. It is an extension of the slump flow test in

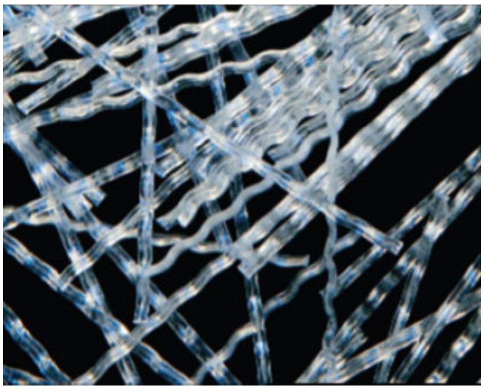
Table 6 Properties of chemical admixture

Specific gravity/ g cm^{-3}	pH	Solid content/ %	Recommended/ % cement content	Main component
1·08	5·7	40	0·5–2·5	Polycarboxylic ether

Table 5 Chemical analysis of FA

Compound	Total SiO_2	Al_2O_3	Fe_2O_3	S+A+F	CaO	MgO	TiO_2	SO_3	K_2O	Na_2O	Cl	LOI*	Free CaO
wt-%	57·2	25·53	6·01	89·04	1·14	2·42	1·16	0·16	4·6	0·42	0·014	1·12	0·12
ASTM C 618 limit (class F)			>70·00				<5·00				<10·00		

*Loss on ignition.



1 Monofilament polypropylene fibres

which a ring apparatus (Fig. 2) is used with the inside diameter h_1 and the outside diameter h_2. The flow of mix is obstructed by the bars, thereby creating a difference of level in the concrete. This gives an indication of the passing ability and restricted deformability of the concrete.

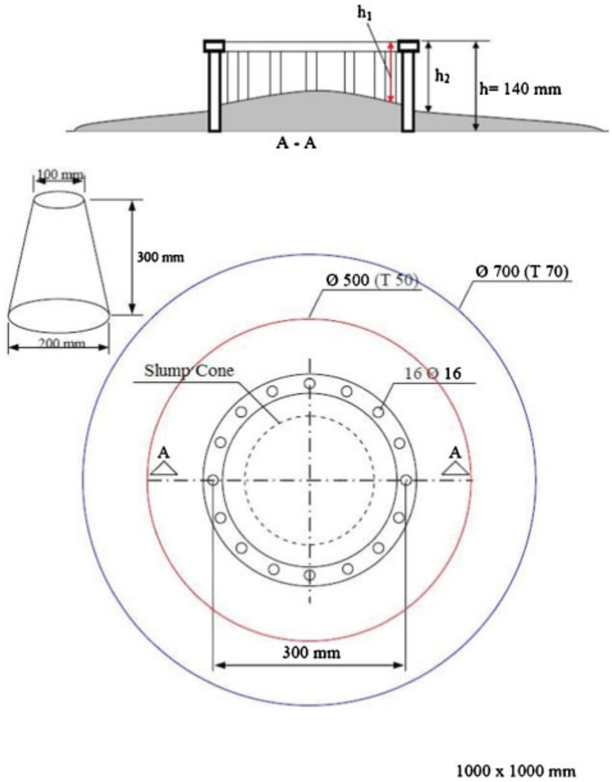
The V funnel test is used to determine the fluidity or viscosity of concrete. The V funnel (Fig. 3) is filled with concrete; the time it takes for the concrete to flow through the apparatus is measured. Clearly, good flowable and stable concrete would take a short time to flow out. The V funnel test results are related to material viscosity.

Fresh concrete properties

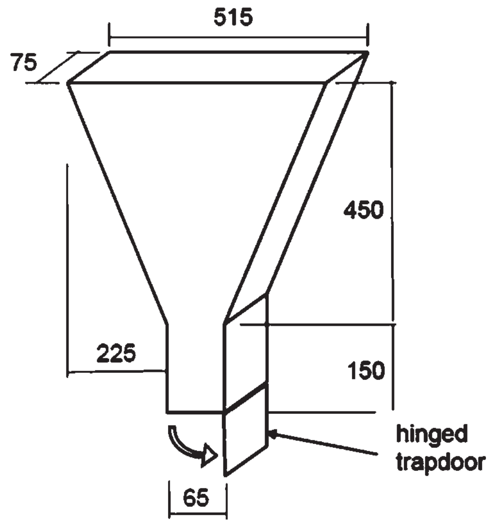
The basic workability requirements for the successful casting of SCC are summarised by Khayat[36] as 'excellent deformability, good stability and low risk of blockage'. The results of fresh properties of all SCCs are presented below. The following figures show properties such as slump flow, J ring height differences, V funnel and slump flow times.

The air contents of mixtures are presented in Fig. 4. As seen from the figure, the air content of concrete increases with increasing fibre content for all concretes.

Since concrete consists of a graded mix of aggregate particles in a cement paste matrix while the cement paste consists of unhydrated cement, hydration products and the residue of the water filled space result in capillary porosity. Capillary pores are up to 1 μm in diameter, whereas gel pores are ~2 nm. Concrete may also contain entrained air, entrapped air and other voids. Intentionally, the entrained air voids are bubbles typically 0·1 mm in diameter and are distributed evenly throughout the cement paste. Accidentally entrapped air usually forms much larger voids, often up to several millimetres in diameter.[37] It is well known that these



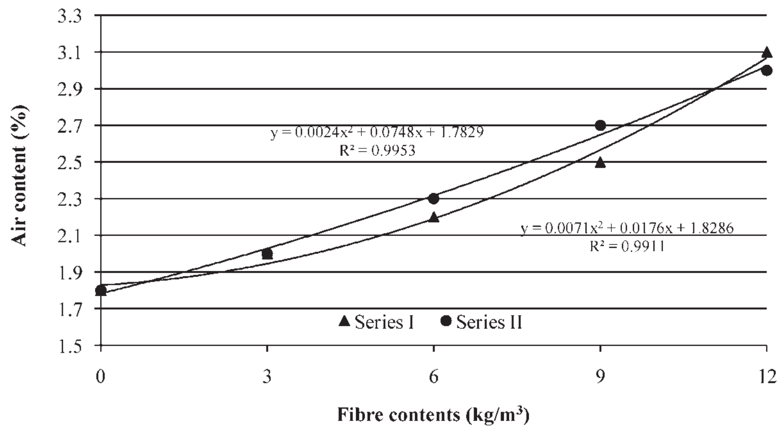
2 Workability tests and apparatus for slump flow and J ring testing



3 V funnel test apparatus

Table 7 Mix proportions in mass/kg m^{-3}

	Mix codes	Cement	Water	SP	FA	Fibre	Sand	CSt-I	CSt-II
Series I	A	350	140	3·5	120	0	960·1	443·1	361·1
	B	350	140	3·5	120	3	956·8	441·5	359·9
	C	350	140	3·5	120	6	953·5	440·0	358·6
	D	350	140	3·5	120	9	950·2	438·5	357·4
	E	350	140	3·5	120	12	946·9	436·9	356·1
Series II	F	450	180	4·5	120	0	855·9	395·0	321·9
	G	450	180	4·5	120	3	852·6	393·4	320·7
	H	450	180	4·5	120	6	849·3	391·9	319·4
	K	450	180	4·5	120	9	846·0	390·4	318·2
	L	450	180	4·5	120	12	842·7	388·9	316·9

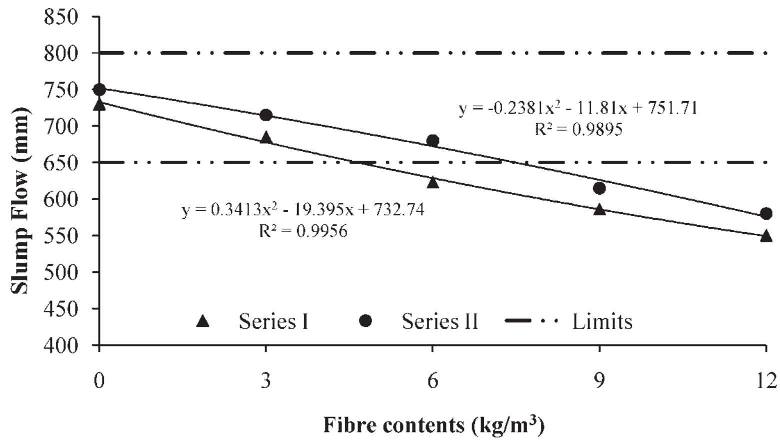


4 **Air content changes for concretes in their fresh states**

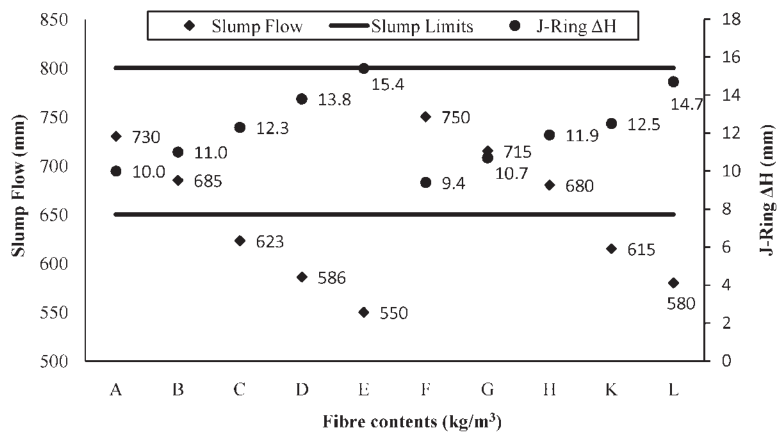
voids can be seen as defects where microcracking starts. In this respect, the voids must be kept in a range, which will typically account for 2 vol.-% of the concrete.

Figure 5 shows the slump flow values as a function of fibre content. As seen in the figure, the slump flows for C, D and F in series I and for K and L in series II were less than the allowable limits suggested by EFNARC. The other concretes in both series exhibited satisfactory slump flow in the range of 550–800 mm, an indication of good deformability. The concretes had enough deformability under their own weight and had moderate viscosity, properties necessary to avoid segregation. Increasing the fibre content reduces the slump flow significantly. Comparison of the two cement series indicates that high volume binder (cement + FA) content increases the slump flow ability of the fresh concrete. The increased viscosity of the mixture is directly linked to the amount of binder or powder (FA) and SP. Thus, the increased content of binder or powder and SP and increased viscosity result in enhancement of the slump flow. However, it should be kept in mind that utilisation of >2·5% SP in the mixtures would result in too many air bubbles in the mixture.

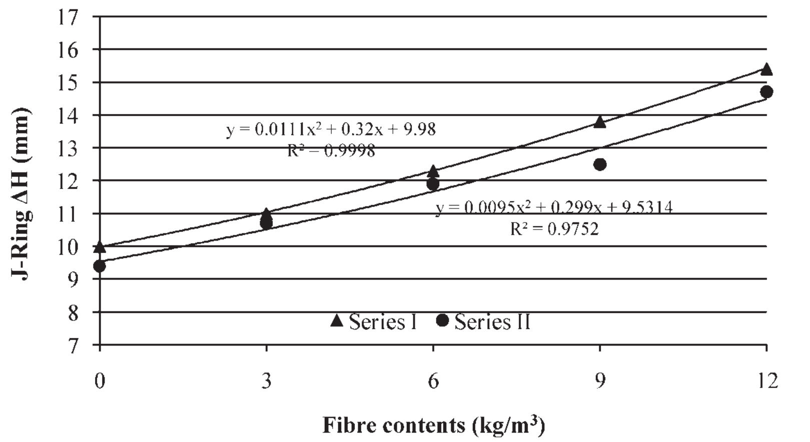
The J ring test results are presented in Figs. 6 and 7. The passing ability seems to be affected by the fibre inclusion. The SCCs exhibit a difference in heights ΔH



5 **Slump flow values as function of fibres content**



6 **Passing ability and slump flow comparison of concretes**



7 Average height changes of concretes inside and outside of ring in fresh state

of the concrete inside and outside of the ring in the range from 9·4 to 15·4 mm. The fibres cause blocking of particles during flow by and are dependent on fibre content in the mixture. Mix F has the value under 10 mm suggested by EFNARC. Although some mixtures were slightly higher than the allowable range, it should be kept in mind that the limits suggested by EFNARC are designed for plain SCCs.

In the V funnel tests, all the SCCs show flow time values in the range of 9·4–20·6 s. The fibres cause a partially blocking effect, thus increasing the V funnel time. Thus, the t_{500} measurements and the V funnel tests are affected by the fibre inclusion. As seen in Fig. 8, the increased binder content reduces the flow time; hence, it increases the flowability. The behaviour is the same for the t_{500} time. Apparently, the t_{500} and V funnel times increase when the binder amount and viscosity increase.

In order to quantify the effects of fibre and cement content on the viscosity of the concrete, multiple regression analysis was applied to obtain the following equations

$$V_{\mathrm{f}} = 13{\cdot}02 - 0{\cdot}00198\ S + 0{\cdot}8017P\ (R^2 = 0{\cdot}9966) \quad (1)$$

$$S_{\mathrm{f}} = 608{\cdot}5 + 0{\cdot}332\ S - 14{\cdot}9833P\ (R^2 = 0{\cdot}9882) \quad (2)$$

where V_{f} is the V funnel flow time (s), S is the cement content (kg m^{-3}), P is the fibre content (kg m^{-3}) and S_{f} is the slump flow (mm).

As can be seen from the high R^2 correlation coefficients, the agreement between experimental and calculated values is outstanding.

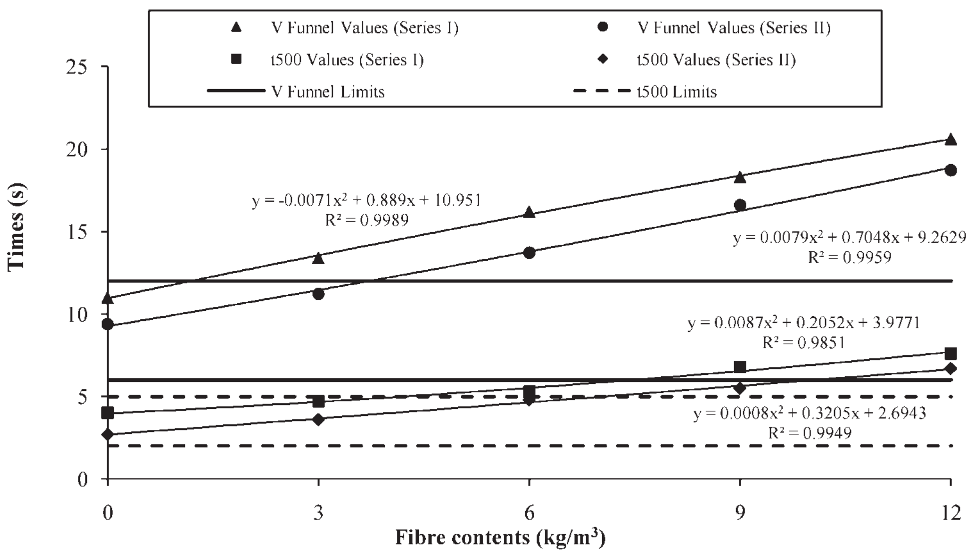
Hardened concrete properties

Unit weight

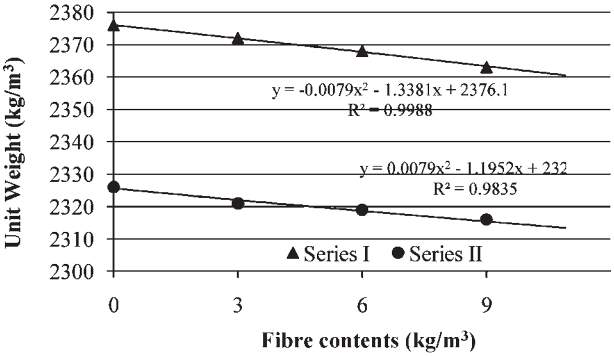
The unit weights of the concretes are presented in Fig. 9. The weights in series II are lower than those in series I. If the water/cement ratio (w/c) is kept constant and the cement content is increased, then the water content in the mixture increases. Thus, the unit weight decreases due to the low specific gravity of water. Since the specific gravity of PP fibres is low, a higher fibre content also reduces the unit weight of concrete. This is the opposite effect to the use of steel fibres since such fibres increase the unit weight. When Figs. 4 and 9 are considered together for both series, the air content increases with the fibre content and consequently the unit weight goes down.

Compressive strength

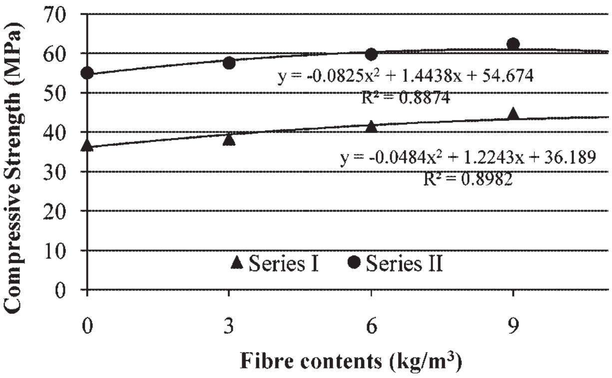
Figure 10 presents the compressive strength results of the concretes. The strength varies as a function of both cement and fibre content. Both curves have maxima at 9 kg m^{-3}. Possibly above that value, the increased air content may cause microcracking. The compressive strength values range between 36·8 and 44·8 MPa in



8 Times required to flow through V funnel and to reach 500 mm slump flow



9 Unit weights of concretes



10 Compressive strength results as function of fibre content

series I and between 55·1 and 62·4 MPa in series II. Clearly, a higher binder ratio gives better compressive strength when series I and II are compared.

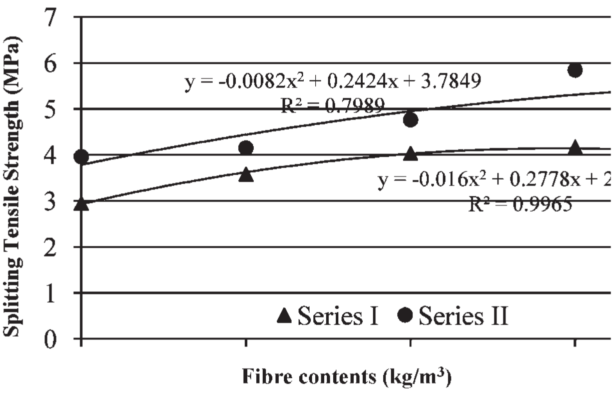
It was found that PP monofilament fibres in the range of 3–12 kg m^{-3} provide similar effects to those of steel fibres in the range of 15–60 kg m^{-3} [6,35,38–40] – without the risk of corrosion. Multiple regression analysis was applied to obtain the following equation

$$CS = 0{\cdot}1796S + 0{\cdot}5483P - 25{\cdot}23\ (R^2 = 0{\cdot}9774) \quad (3)$$

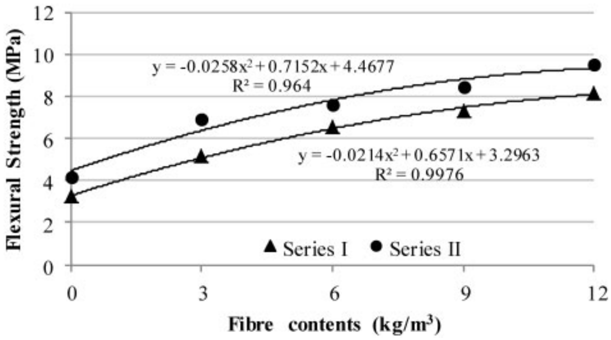
where CS is the compressive strength of concrete (MPa).

Splitting tensile strength

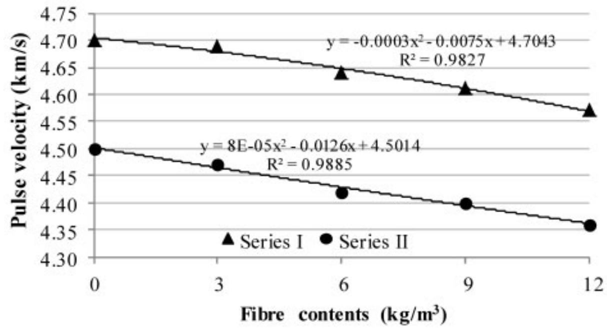
Splitting tensile strength results are presented in Fig. 11. As now expected, the values first increase with increasing fibre content in the concrete, again with a maximum at 9 kg m^{-3} of fibres . The values range between 2·95 and 5·84 MPa. Series II gives better results than series I due to the higher cement content.



11 Splitting tensile strength changes of concretes



12 Flexural strength of concretes



13 Pulse velocities in concretes

Fibres generally bridge the microcracks and hamper the crack propagation. When the tensile stress is transferred to fibres, the transfer can arrest the propagating macrocracks and substantially improve the splitting tensile strength of the concrete.

Flexural strength

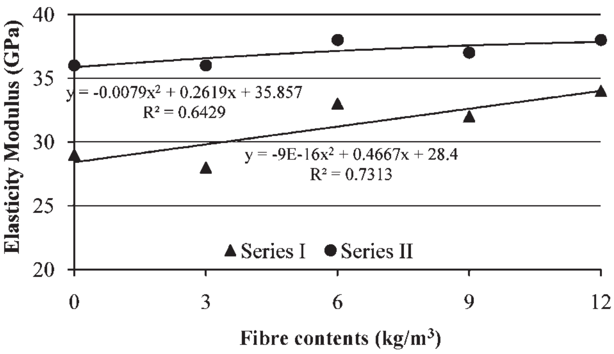
The results of flexural strength tests are presented in Fig. 12. The flexural strength is affected by the fibre and cement contents. When compared with plain concrete, the flexural strength of fibre reinforced concretes is significantly higher. The highest value seen for mix L is 9·53 MPa.

Pulse velocity

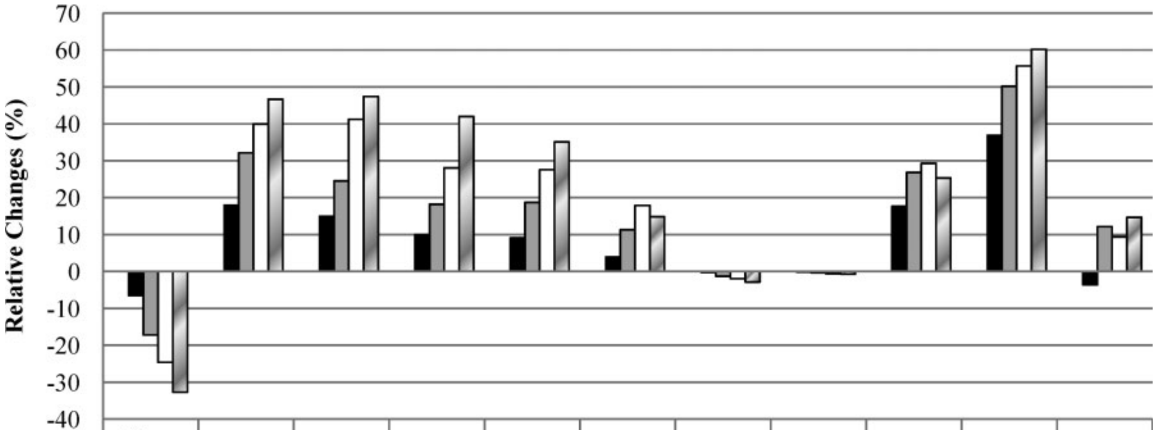
The ultrasonic pulse velocities of concretes are presented in Fig. 13. The values are expected to increase with decreasing unit weight, thus with increasing pore volume in concrete. This is also the case with the authors' materials.

Elasticity modulus

The fibres embedded in the matrix affect the stress and strain, enhancing stress redistribution and reducing strain



14 Elasticity modulus changes of concretes



	Slump Flow	V-funnel	t500 (s)	AIR	J-Ring ΔH	CS	UPV	UW	STS	FS	EM
A											
■B	-6.6	17.9	14.9	10.0	9.1	3.9	-0.2	-0.2	17.6	36.9	-3.6
▨C	-17.2	32.1	24.5	18.2	18.7	11.3	-1.3	-0.3	26.8	50.2	12.1
□D	-24.6	39.9	41.2	28.0	27.5	17.9	-2.0	-0.6	29.3	55.7	9.4
▨E	-32.7	46.6	47.4	41.9	35.1	14.8	-2.8	-0.7	25.3	60.2	14.7

15 Relative effects of fibre content for series I

localisation; thus, ductility of concrete under load is increased by fibre content. The results are presented in Fig. 14.

Figures 15 and 16 present the relative effects of fibre inclusion on fresh and hardened concrete properties.

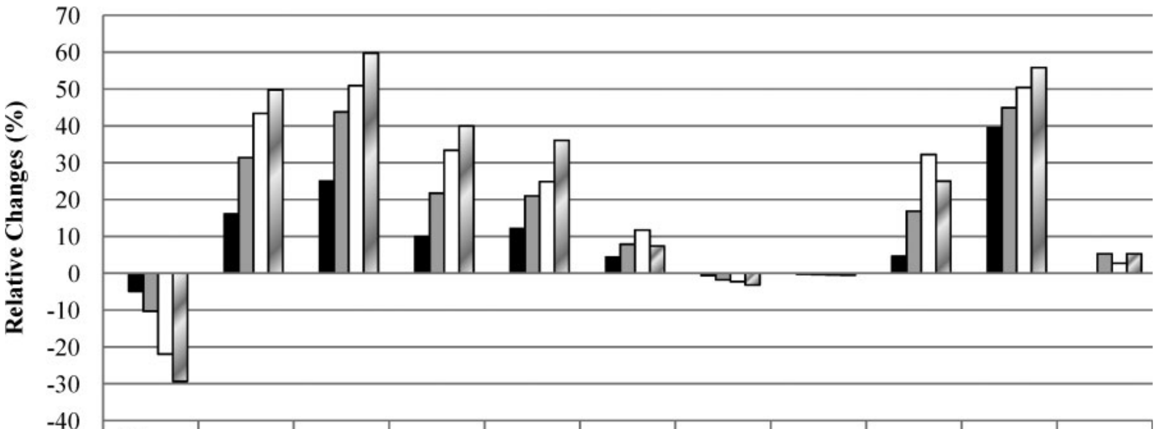
Figure 17 shows the relative effect of cement content as a comparison of concrete pairs.

Survey of results

There are a variety of methods of reinforcing concretes and of modification of their properties.[2–4,6,41–43] In the case of SCCs, the workability requirements for successful placement necessitate that the concrete exhibits good deformability and proper stability to flow under its own weight without segregation and blockage. The current study investigated the effects of monofilament PP fibres instead of steel fibre inclusion on the flow characteristics of SCC and certain mechanical properties. Two cement contents and four fibre contents were used in combination, and tests were performed in both fresh and hardened states.

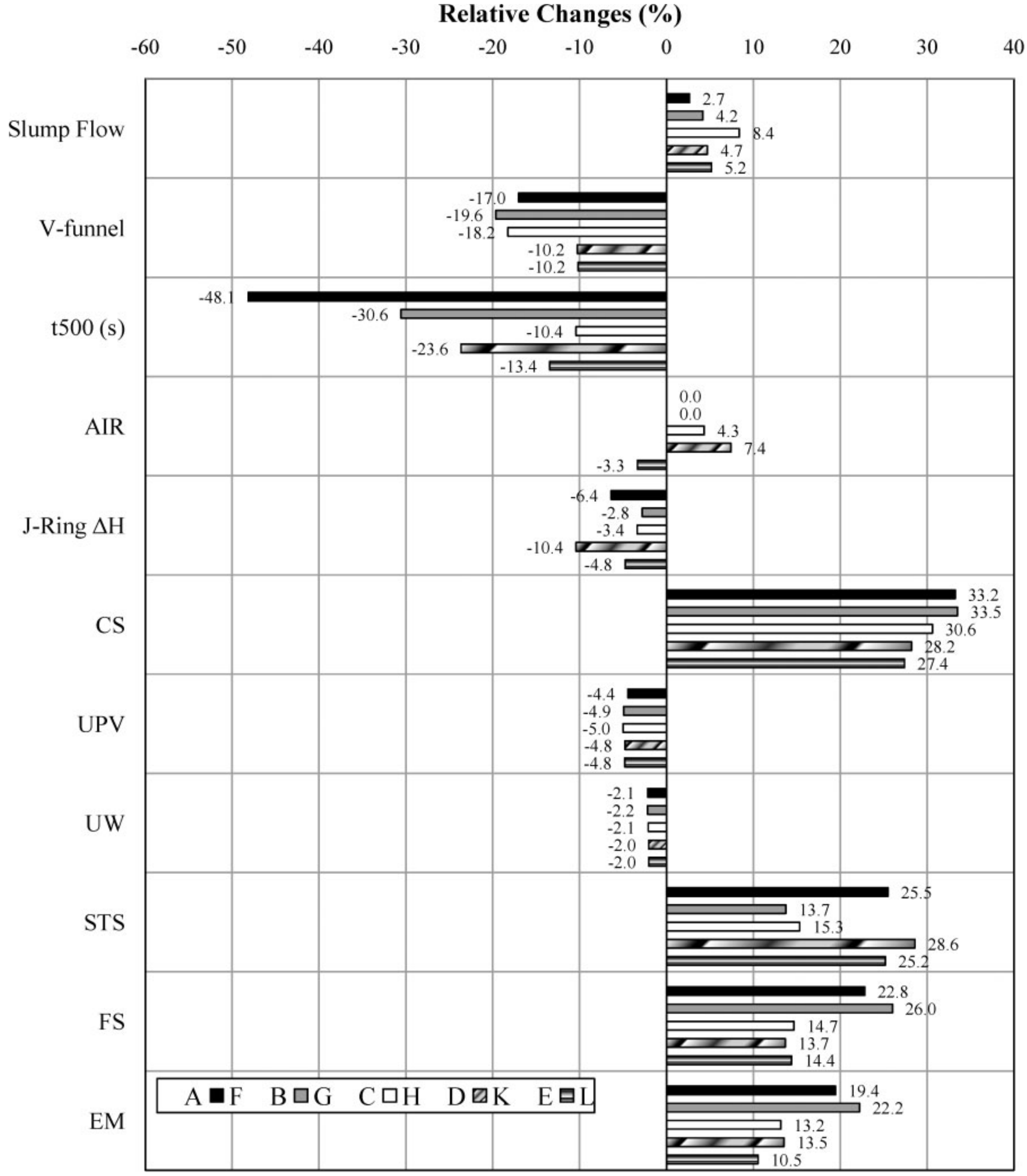
It was found that for all the mixture proportions there were no problems in mixing while the fibre distribution was uniform. The air content of concrete has increased depending on the increase in fibre content. Fibre inclusion up to 9 kg m^{-3} has provided satisfactory results. While fibres in general cause loss of flow and workability, in all the mixtures, the fibres in this study have good flow and workability, even if some mixtures are somewhat below the limits of EFNARC. The authors recall that these limits have been suggested for conventional concretes.

Adding PP fibres to concrete has decreased the unit weight of concrete and increased the compressive strength



	Slump Flow	V-funnel	t500 (s)	AIR	J-Ring ΔH	CS	UPV	UW	STS	FS	EM
F											
■G	-4.9	16.1	25.0	10.0	12.1	4.3	-0.7	-0.2	4.6	39.5	0.0
▨H	-10.3	31.4	43.8	21.7	21.0	7.9	-1.8	-0.3	16.8	44.9	5.3
□K	-22.0	43.4	50.9	33.3	24.8	11.7	-2.3	-0.4	32.2	50.4	2.7
▨L	-29.3	49.7	59.7	40.0	36.1	7.4	-3.2	-0.6	25.0	55.8	5.3

16 Relative effects of fibre content for series II



17 Relative comparison of A–F, B–G, C–H, D–K and E–L concrete pairs

of concrete. Monofilament PP fibres can be used at much lower content than steel fibres; the lowest steel fibre content used is 60 kg m^{-3}. Compressive strength, splitting tensile strength and especially flexural strength and elasticity modulus have been increased by PP fibre inclusion – while pulse velocity has decreased.

Future work is planned using monofilament PP fibres with admixtures (mineral and chemical) and possibly use of two different fibre kinds incorporated in the SCC mixes.

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