
Use of polypropylene fibre reinforced concrete as a construction material for rigid pavements

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Quantitatively concrete occupies the largest volume in any modern construction activity and it is expected that there will be no substitute for concrete in the near future. Since such high volumes of concrete are being used for new construction, it is imperative to produce good quality concrete that will be durable with enhanced mechanical properties to maximize the service life of a structure. Though good concrete can be produced using automation and controlled environment, it is not possible to alter its inherent brittle nature and the lack of any tensile strength. In this context, fibre reinforced concrete (FRC) seems to be a viable alternative. The present study focuses on feasibility of using polypropylene fibres as secondary reinforcement to concrete to change its brittle nature. Accordingly, various percentages of polypropylene fibres were added to concrete and a series of laboratory experiments were conducted to investigate the use of polypropylene FRC in rigid pavements. Mechanical properties of concrete such as compressive strength, modulus of elasticity, flexural strength and toughness, abrasion and impact were determined. Except for abrasion, polypropylene fibres improved the mechanical properties of control concrete and 0.6% by volume was found to be the ideal fibre dosage.

Keywords: *fibre reinforced concrete, polypropylene, rigid pavements, impact*

Concrete is a widely used construction material in the construction industry and is known for its high compressive strength and durability. However, typically concrete's tensile strength is very low and is only 10% of its compressive strength. This lack of tensile strength of concrete limits its use in isolation and hence concrete has to be combined with other construction materials such as steel to carry the tensile loads in a structure. This tensile strength of concrete is even lower when concrete is young without a fully developed, strong microstructure.¹ When this low tensile strength of concrete is exceeded by the tensile stresses, cracking occurs, which in turn allows ingress of aggressive chemicals and reduces the durability of concrete. Thus, there is a need to improve the inherent tensile strength of concrete. In this context, fibre reinforced concrete (FRC) seems to be a viable alternative. Fibre reinforcement (depending on fibre type) is expected to improve the mechanical performance, deformability, toughness, impact resistance and fatigue endurance of the overlay.^{2,3}

Though the use of straws in bricks and hair in mortar predates the use of conventional Portland Cement Concrete, the use of synthetic fibres in concrete is the innovation of 20th century. FRC has now become a well known and commercially available construction material. Over the years, the mechanical properties of FRC especially steel fibre reinforced concrete (SFRC)

have been thoroughly researched.⁴⁻¹⁰ However, synthetic fibres have been mainly used for reducing the early-age shrinkage of concrete and there is a need to study the use of synthetic fibres for other applications.^{1,11} In this paper, first the fibre matrix interactions are discussed pertaining to synthetic fibres, followed by a description about the effect of polypropylene fibres on the mechanical properties of concrete and its use for rigid pavements.

Concrete-fibre interaction

Fibre interaction with homogeneous uncracked matrix

This type of interaction occurs in almost all composites during the initial stages of loading. When under no load, the stress in both the matrix and the fibre are assumed to be zero. However, when the composite is subjected to tensile and compressive loads or to temperature changes, it results in the development of stresses and deformation. When the load is applied to the composite, a part of the load is transferred to the fibre along its surface. Because of the difference in stiffness of matrix and fibre, shear stresses develop along the surface which help to transfer the applied load to the fibre. If the modulus of rupture of fibre is less than that of the matrix, then deformation around the fibre is higher. This occurs in polymeric and naturally occurring fibres.

Fibre interaction in cracked matrix¹²

When the composite containing the fibres is loaded in tension, the matrix cracks at a certain load. The fibres come into action only after the formation of the first crack. The fibres bridge across the cracks and prevent the brittle failure of the matrix. If the fibres can transmit sufficient load across the crack, more cracks form along the length of the specimen. This stage of loading is called the multiple cracking stage. For synthetic fibres, owing to their lower modulus of elasticity, generally a higher volume fraction is required to achieve multiple cracking.

Research significance

It is well known that steel fibres improve concrete's mechanical properties. Therefore, steel fibres are widely used in many applications such as shotcrete, slabs on grade, side walks, etc. However, the use of synthetic fibres has been mainly limited to controlling cracking due to shrinkage. There is a need to investigate the use of synthetic fibres in applications such as rigid pavements and study the effect of such fibres on the mechanical properties of rigid pavements. There is very limited published data on the effect of synthetic

Table 1. Properties of the materials

Material	Property/Grade	Value
Ordinary Portland Cement	G-43	-
Fine Aggregates	Specific gravity	2.65
	Moisture content	2.2%
	Fineness modulus	3.97
Coarse Aggregates	Specific gravity	2.60
	Water absorption	2.3%
	Aggregate impact value	16.5%
Polypropylene Fibers	Specific gravity	0.9
	Length	< 50mm
	Aspect ratio	50-150
	Tensile strength	276 MPa
	Modulus of elasticity	3.24 GPa
	Critical fiber length	35 mm
	Breaking load	36 N

fibres produced in India on the abrasion and impact of FRC. The present study focuses on determining these mechanical properties of polypropylene fibre reinforced concrete (PFRC). The performance of PFRC is compared with ordinary concrete through extensive tests comprising modulus of elasticity, static flexure, abrasion, and impact.

Experimental Investigation

Materials

The materials used for concrete were cement, fine aggregates (natural sand), coarse aggregates (maximum size 20 mm), tap water and polypropylene fibres. All these constituent materials were first tested in the laboratory according to the methods described in the relevant I.S. codes of practice. To maintain brevity, only some tests are described in this paper. Properties of the materials used in this study are reported in Table 1.

To ensure quality of cement, fineness test (by dry sieving method), standard consistency test, initial and final setting time test, and compressive strength tests were performed but are not reported here to maintain brevity. The test results confirmed that the cement met the IS requirements for 43 grade cement. The fine aggregates met the Zone III requirements specified by the IS codes for gradation. The silt content was determined according to IS and the aggregates met the specified requirements. Based on the crushing strength of the coarse aggregates, they were found to satisfy the IS requirement for use in wearing surface on concrete pavements.

The mechanical properties of fibres (Figure 1) were confirmed by testing. A Mikrotech Tensometer (Figure 2) was used to determine the average tensile strength of six specimens and was found to be 276 MPa and the average modulus of elasticity was 3.24 GPa.

The pull out load for the fibres was measured using a specially designed trapezoidal shaped specimen (Figure 3). The special mould used for constructing the specimen is shown in Figure 4. This was needed to have different lengths of fibres (ranging from 25 to 85 mm) in the same specimen, which then facilitated determining the minimum fibre length required to prevent pull-out and estimate bond strength of the fibres. Cement and

sand proportion of 1:3 made the matrix mortar. None of the fibres pulled-out from the mortar, indicating that the critical fibre length was less than 35 mm. The average breaking load for the fibres was 36 N.

Concrete mix design

The target strength of the concrete was 40 MPa and the mix proportion shown in Table 2 was used for preparing the concrete. To study the effect of fibre volume on the mechanical properties of concrete, behaviour of the control mix (0% fibres) was compared with those of the mixes containing 0.4%, 0.6%, and 0.8% fibres by volume.

Mixing

During initial mixing, balling of the polypropylene fibres was noticed due to the low density of the fibres. An innovative method was used to address this problem. The fibres were made wet by soaking them in the cement mortar. The cement mortar used was a part of the concrete mix and since the polypropylene fibres are

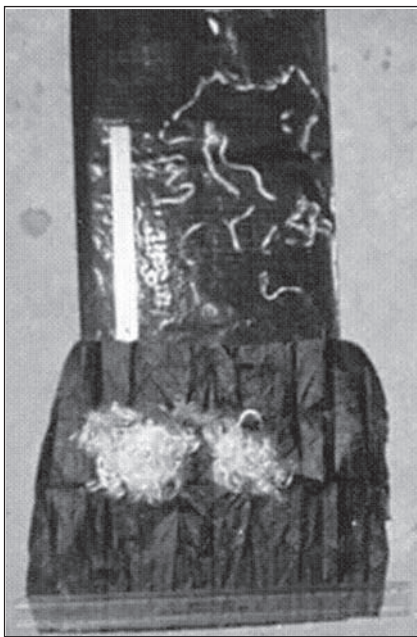


Figure 1. Polypropylene fibres used in the investigation

Table 2. Mix proportion

Cement, kg/m ³	Sand, kg/m ³	Coarse aggregates, kg/m ³	Water/Cement
459	523	1221	0.40



Figure 3. Specimen and mould for pull out test



Figure 2. Mechanical testing of fibres

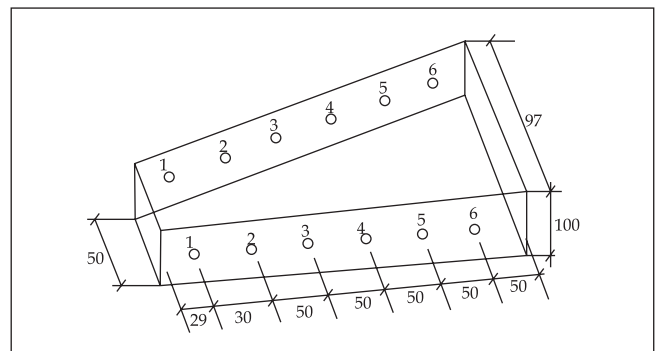


Figure 4. Sketch for pull out mould

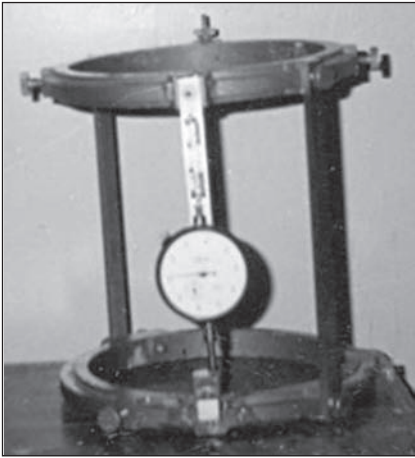


Figure 5. Compressometer used to measure deflection of cylinder specimen

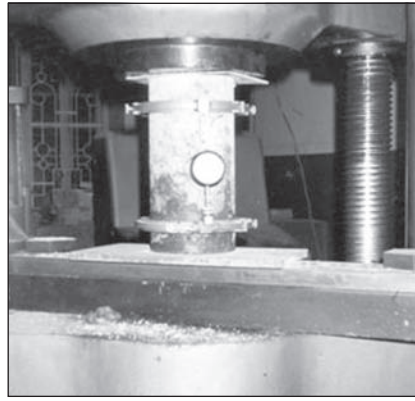


Figure 6. Cylinder loaded in a UTM

length over a gauge length of 185 mm (Figure 5). Deflection measuring gauge was attached to the cylinders (Figure 5), which consisted of two rings mounted on the cylinder with the help of two vertical flat bars. This gave a gauge length of 185 mm. Then the specimen was positioned under a Universal Testing Machine as shown in Figure 6.

The load was applied at the rate of 10 kN/min. and the readings on the deflection gauge were taken every 10 kN. Since the cylinders bulged during loading (Figure 7), the loading was continued until it

was possible to safely remove the rings of the deflection measuring apparatus. After unscrewing the rings, the loading was continued until the cylinder failed.

The load versus deflection data was converted to obtain stress versus strain data and the initial portion of the curves required for calculating the modulus of elasticity is presented in Figures 8 to 11. Table 3 summarises the average peak-failure-load of the specimens.

hydrophobic, they do not absorb any mixing water, so no additional cement, water or sand was required. The cement mortar made the fibres relatively heavier and prevented them from balling. The heavy and wet fibres dispersed easily and randomly in the concrete mix.

Test results

Compressive strength and modulus of elasticity

The compressive strength of the control concrete determined according to IS 516:1969 was compared with the compressive strength of the FRC containing various percentage of fibres. Tests were conducted using a 100-ton capacity machine on cubes 150 mm in size after 28 days of curing. The average 7 day and 28 day strength of the control concrete was 29.8 MPa and 39.3 MPa respectively. To measure the modulus of elasticity, cylinders 150 mm in diameter and 300 mm in height, were used and tested according to IS: 516-1969. A compressometer was used to measure the change in

Toughness

Toughness of FRC was calculated using a Toughness Index (I_t), which is given by Equation (1). Fibre type, fibre geometry, fibre volume fraction, matrix composition, specimen size, loading configuration, loading rate are the major factors that affect the load deflection behavior and hence the toughness of FRC.



Figure 7. Bulging of cylinders during compression testing

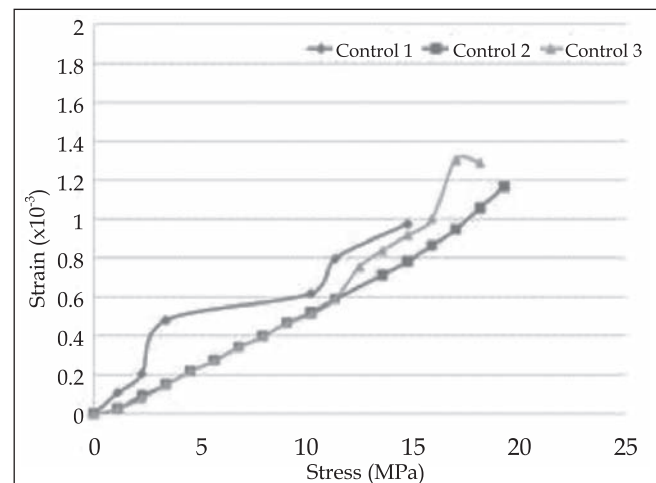


Figure 8. Stress versus strain data for control

$$I_t = \frac{\text{(Area under load – deflection curve till load reaches zero for the fiber)}}{\text{(Area under load – deflection curve till load reaches zero for the plain matrix)}} \dots(1)$$

From the stress vs. strain plots, the initial tangent modulus was calculated as reported in Table 4. Knowing the modulus of elasticity and the volume of both the fibre and the matrix, theoretical value of E was also calculated using the simple rule of mixtures using Equation (2), see Table 4.

$$E_c = V_f \times E_f + V_m \times E_m \dots(2)$$

where, E_c is the combined Modulus of Elasticity of FRC, V_f is the volume fraction of the Fibres, E_f is the Modulus of Elasticity of the Fibres, V_m is the volume of the matrix, it is considered to be equal to 1 when the fibre orientation is random and E_m is the Modulus of Elasticity of the Matrix.

It is clear that since both the volume and E of the fibres are low, the increase in E when compared to control is marginal (theoretically). However, the test results indicate a minimum of 11.4% (for FRC 0.8%) increase in E in compression compared to the control specimen.

Table 3. Average peak failure load

Mix	Control	FRC (0.4%)	FRC (0.6%)	FRC (0.8%)
Load (kN)	353.3	385.2	448.1	325.0

Table 4. Measured modulus of elasticity

Mix Type	Specimen #	Recorded E ($\times 10^3$ N/mm ²)	Average E ($\times 10^3$ N/mm ²)	Theoretical E ($\times 10^3$ N/mm ²)
Control	1	30.79	30.79	30.79
	2	31.58		
	3	30		
FRC (0.4%)	1	35.29	36.4	30.8
	2	37.5		
	3	*		
FRC (0.6%)	1	42.857	41.68	30.81
	2	30		
	3	52.17		
FRC (0.8%)	1	33.33	34.31	30.82
	2	35.29		
	3	*		

*Test Results not available.

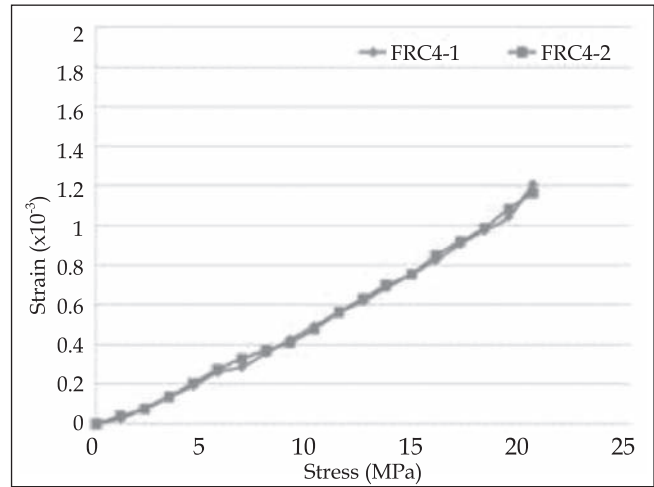


Figure 9. Stress versus strain data for FRC (0.4%)

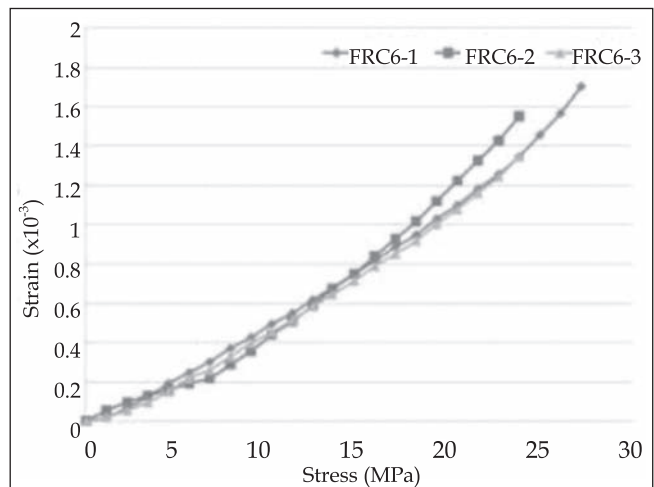


Figure 10. Stress versus strain data for FRC (0.6%)

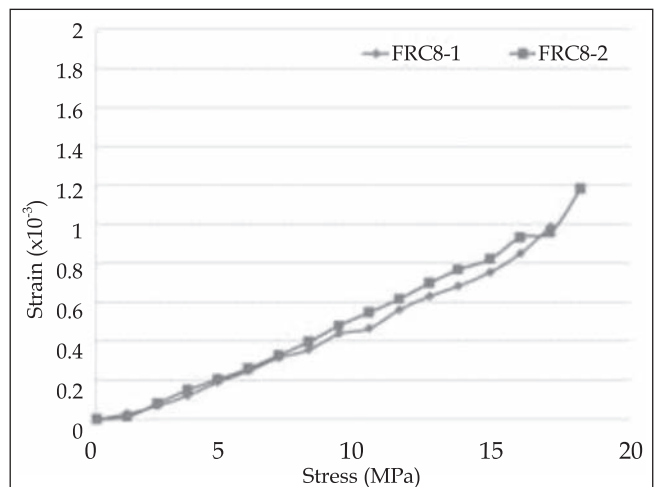


Figure 11. Stress versus strain data for FRC (0.8%)



Figure 12. Beams on vibrating table

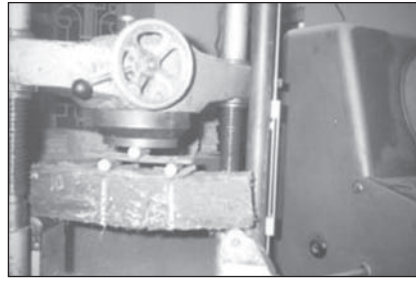


Figure 13. Testing of beam for static flexure



Figure 14. Beam after static flexure test

Static flexure test

Static flexure test was conducted to determine the modulus of rupture of concrete and to determine the effect of fibres on this mechanical property as per IS 576. Concrete was filled in moulds and then placed on a vibrating platform (Figure 12) for one minute. Specimens were covered and demoulded after 24 hours and placed in a water tank for curing. For testing, the specimen was placed in the machine (Figure 13) such that the load would be applied to the uppermost surface; as cast in the mould. The load was applied through two point loads at a rate such that the extreme fibre stresses increased approximately at 0.7 N/mm^2 i.e. 400 kg/min . The load was increased to cause failure of the specimens. The cracks were observed in the middle third portion of the specimens (Figure 14). The average failure load and the calculated MOR are presented in Table 5.

Clearly, the results in Table 5 show that the FRC had a significantly higher MOR compared to the control. FRC containing 0.6% fibres had a 35% higher modulus of rupture compared to the control. By increasing the fibres volume 0.8%, the MOR dropped but was still higher than that of the control test.

Abrasion test

The abrasion resistance of concrete was evaluated for various dosages of fibres because a pavement constantly comes in contact with a wide variety of specified and

unspecified loads, which result in wear of the pavement. In the case of rigid pavements no wearing course is provided. The wear results in reducing the pavement thickness. In this test, the test specimens were abraded on a revolving grinding table. The reduction in thickness of the specimen and the reduction in the weight of specimen were measured after a certain number of revolutions.

The test specimens were $65 \text{ mm} \times 65 \text{ mm}$ with a thickness of 25 mm. The specimens were cut from 100 mm cubes (Figure 15). The cubes were cast with various percentages of polypropylene fibres. Three cubes, (Figure 16) of both plain concrete and FRC having 0.4%, 0.6%, and 0.8% fibres by volume of concrete, were cast and cured for 28 days in a water tank. After curing, the test specimens were cut from the cubes and were dried for 24 hours and then weighed to the nearest 0.1 gm. For conducting this test, an abrasion testing machine as shown in Figure 17 was used.

After initial drying, the specimens were placed in the thickness-measuring gauge with the wearing surface facing upwards for initial readings. The grinding path of abrasion testing machine was evenly spread with an abrasive powder (20 gm). The specimen was then placed in the holding device over the surface of the grinding disc and loaded with a load of 300 N. The grinding disc was rotated with a speed of 300 rpm and the abrasive powder was continuously fed to the grinding path, so that it remained uniformly distributed in the tracks. After 22 revolutions the disc was stopped and the abraded specimen and the abrasive powder were removed from the disc. Then the specimen was turned about its vertical axis through 90° in clockwise direction and the quantity of abrasive powder was applied again. The above procedure was repeated 5 times, exposing each specimen to 110 revolutions. At the end of the test, the specimen was weighed to the nearest 0.1 gm. It

Table 5. Average peak loads and MOR

Mix type	Average Failure load, P (N)	Average modulus of rupture, f_R (N/mm^2)
Control	1117	5
FRC (0.4%)	13067	5.9
FRC (0.6%)	15167	6.8
FRC (0.8%)	12000	5.4



Figure 15. Cubes used for cutting abrasion specimen

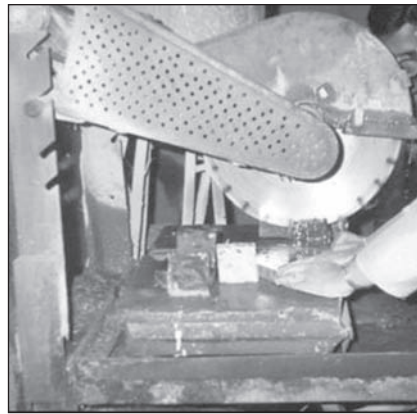


Figure 16. Cutting of specimen for abrasion test



Figure 17. Abrasion testing equipment

was then placed in thickness measuring gauge for the readings using the same positions, as used initially.

Determination of wear

The wear was determined from the difference in reading before and after the abrasion test. The value was checked against the average loss of material using Equation 3.

$$t = \frac{(W_1 - W_2) \times V_1}{(W_1 \times A)} \quad \dots(3)$$

where, t = average loss in thickness (mm), W_1 = initial mass of specimen (gm), W_2 = final mass of specimen (gm), V_1 = initial volume mass of specimen (mm^3), and A = surface area of specimen (mm^2)

The percentage reduction in thickness was calculated using the recorded thicknesses of the specimens whereas the theoretical thickness was calculated based on the loss in weight. The reduction in thickness was larger in the FRC specimens as compared to the control specimens, however, all specimens met the IS requirements for

heavy-duty tiles. The requirement for the heavy-duty tiles is that the average wear should not be greater than 2.0 mm and wear of individual specimen should not be greater than 2.5 mm.

Impact test by drop weight method

This test was conducted to compare the impact strength of plain cement concrete with that of the polypropylene fibre reinforced concrete. Concrete was filled in oiled moulds and compacted to achieve a thickness of 65 mm. The depth of concrete was checked at five different positions before vibrating it for one minute. After 24 hours, the specimens were demoulded and cured in a water tank for 28 days. The cured specimens were coated at bottom with a thin layer of grease to reduce the friction between the specimen and the base plate. Impact testing machine as shown in Figure 18 was used to conduct the tests.

The specimens were placed in the impact testing machine between four guide angles located 4.8 mm from the sample (Figure 18). A hardened steel ball was placed at the centre of concrete disc, a hammer weighing 4.54 kg was allowed to fall from a height of 460 mm along

Table 6. Actual and theoretical reduction in thickness

Mix Type	Initial thickness, (mm)*	Final thickness (mm)*	Initial weight (gm)	Final weight (gm)	Actual reduction (%)	Theoretical reduction (mm)	Theoretical reduction (%)
Control	21.74	20.60	248.67	232.33	5.25	1.32	6.08
FRC (0.4%)	21.78	20.60	247.00	233.33	5.45	1.19	5.49
FRC (0.6%)	22.23	20.90	243.67	228.33	5.99	1.35	6.06
FRC (0.8%)	21.86	20.46	228.33	213.00	6.41	1.40	6.41

* Values are average of five readings

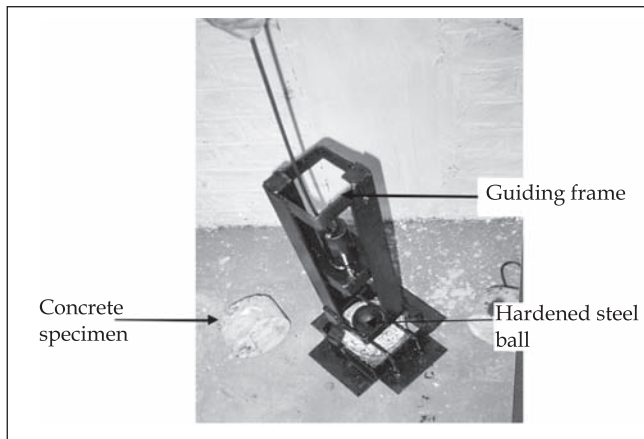


Figure 18. Impact specimens and test arrangement

the frame to target the steel ball. The hammer ball was held with the help of a rope and pulley arrangement, and repeated blows were manually induced on the specimen. The number of blows that caused the first visible crack was recorded as the first crack strength. The loading was continued until the disc shaped specimen failed and opened up such that it touched three of four positioning angles. The number of blows that caused this condition was recorded as the failure strength.

The test results from the impact testing are presented in Table 7 and Figure 19. Clearly, the number of cracks for both the first crack and failure increased with the fibre content increasing from 0 to 0.6% and then decreased. However, the impact resistance decreased when the fibre volume increased to 0.8%, but was still higher than the control. It can also be seen that the standard deviation of these measurements was very low; a maximum of 14% for control and only 11% for FRC.

It is evident that barring abrasion, other mechanical properties of concrete improved with the use of synthetic fibres and the energy absorption capacity also improved. Based on the results, it is also clear that there is an

Table 7. Average number of blows indicating impact resistance of concrete

Mix Type	Number of blows for first crack	Number of blows for failure
Control	73 (14.2%)	97 (13.7%)
FRC (0.4%)	336 (7.6%)	494 (3.3%)
FRC (0.6%)	754 (10.8%)	933 (9.2%)
FRC (0.8%)	530 (8.5%)	723 (7.6%)

Note: Percentage standard deviation shown in parentheses.

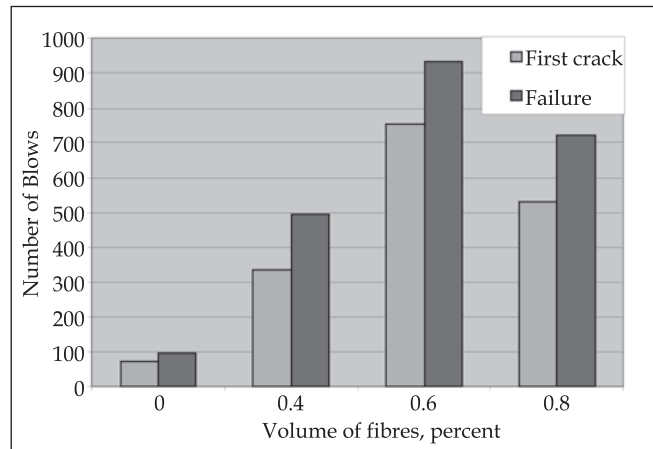


Figure 19. Plot showing number of blows for first crack and failure

optimum dosage of synthetic fibres. Increasing fibre dosage beyond this optimum causes problems with mixing and fibre balling. Concluding remarks in the next section summarise these improvements. Specific tests were conducted in the project to enable design of rigid pavements using PFRC. The future scope of research and further steps required to design pavements according to IRC guidelines are discussed in the section "Future Research."

Concluding remarks

The mechanical properties of polypropylene fibres including elasticity and tensile strength were determined. Critical fibre length was found to be lower than 25 mm, which indicates that the fibres used in this project (greater than 25 mm) would not be expected to pull-out from the matrix.

Increasing the fibres volume up to 0.6% increased the modulus of elasticity in compression and modulus of rupture compared to control. Both MOE and MOR reduced, when the fibre volume increased to 0.8%, however these properties were still higher than the control.

Addition of fibres did not increase the abrasion resistance of concrete, however, the energy absorption capacity and impact resistance of FRC was much higher than those of the control. The impact resistance of FRC before and after the first crack until complete failure was exceptionally high. This can be attributed the fibre induce ductility in plain concrete and increase in energy absorption capacity of the concrete.

Based on the tests conducted, it is clear that the optimum dosage of fibres is 0.6% by volume. Beyond 0.6%, balling of fibres during mixing was observed that led to improper compaction and finishing. Honeycombing was also observed in such mixes.

Further research

It has been found from previous studies that there is a definite increase in fatigue resistance of FRC under alternating stresses. Under cyclic loading, microscopic cracks are formed, and later, concentration of stresses at these points causes fracture and failure. As compared to plain concrete, FRC experiences much lower deflections and fails at much lower stresses under dynamic loading. Therefore, the addition of fibres in plain concrete results in increased durability of concrete, especially under dynamic loading. This aspect is very important for rigid pavements and needs to be further investigated. Other fibre types and hybrid combinations should also be considered to improve the abrasion resistance of concrete. Development of high performance composites with superior matrices having better interfacial characteristics needs to be studied. Ductility characteristics for potential application in seismic design and construction need further consideration.

Now that the mechanical properties of both control concrete and PFRC are known, the authors are investigating the effect of using fibres on the design of rigid pavement as per Indian Road Congress guidelines.¹³

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