

Experimental Study on Hybrid Fiber Reinforced Concrete

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ABSTRACT

Concrete is the most widely used construction material in civil engineering practice, valued for its compressive strength, mouldability and durability. Its principal deficiency is mechanical: the material is brittle, its tensile strength is approximately one-tenth of its compressive strength, and once a crack initiates there is little within a plain matrix to arrest its propagation. Hybrid Fiber Reinforced Concrete addresses this by combining fibres of differing geometry and stiffness, so that reinforcement is present at more than one length scale, fine filaments intercepting microcracks at initiation while coarser fibres bridge the macrocracks that form thereafter.

This investigation examines M40 grade concrete reinforced with hooked-end steel fibres of aspect ratio 64 and alkali-resistant glass fibres of aspect ratio 857, combined in equal volume fractions at total dosages of 1.0, 2.0 and 3.0 per cent by volume, against a plain control. The mix was proportioned to IS 10262:2019 at a water–cement ratio of 0.40 using Portland Pozzolana Cement. Seventy-two specimens were cast and water-cured. Fresh concrete was assessed by slump and compaction factor; hardened concrete by compressive strength to IS 516, split tensile strength to IS 5816 and flexural strength to IS 516 at 7 and 28 days, supplemented by ultrasonic pulse velocity and rebound hammer testing to IS 13311 upon the same specimens.

Every hardened-state property attained its maximum at a total fibre content of 2.0 per cent by volume, comprising 78.5 kg/m³ of steel and 26.8 kg/m³ of glass fibre. Relative to the control, that mix gave improvements of 11.9 per cent in compressive strength, from 46.30 to 51.80 MPa, 30.7 per cent in split tensile strength, from 3.81 to 4.98 MPa, and 30.6 per cent in flexural strength, from 5.42 to 7.08 MPa. The tensile-governed properties therefore

improved by between two and three times as much as the compressive strength, which confirms that the benefit arises from crack bridging rather than from densification of the matrix. The ratio of split tensile to compressive strength rose from 0.082 to 0.096, and the measured modulus of rupture exceeded the estimate of Clause 6.2.2 of IS 456:2000 by 14 per cent for the control but by 41 per cent for the optimum mix, showing that fibre reinforcement progressively decouples flexural from compressive capacity.

Workability fell sharply, slump reducing by 47.1 per cent across the series and superplasticiser demand rising from 0.80 to 1.30 per cent by mass of cement. The

compaction factor fell by only 9.7 per cent over the same range, establishing that slump substantially understates the placeability of fibre reinforced concrete. At the highest dosage the pulse velocity declined together with all three strengths, which identifies incomplete compaction, rather than any deterioration in fibre–matrix interaction, as the cause of the post-optimum reduction. The optimum reported is consequently a property of the compaction procedure as much as of the fibre system. Control specimens failed abruptly whereas fibre reinforced specimens cracked visibly, retained load and remained intact, a change in failure mode of greater practical value than the strength increase itself.

Keywords: hybrid fibre reinforced concrete; steel fibre; alkali-resistant glass fibre; crack bridging; fibre synergy; compressive strength; split tensile strength; flexural strength; ultrasonic pulse velocity; rebound hammer; M40 concrete.

LIST OF ABBREVIATIONS

AR	Alkali-resistant
ASTM	American Society for Testing and Materials
BIS	Bureau of Indian Standards
CTM	Compression Testing Machine
EDS	Energy Dispersive Spectroscopy
FRC	Fiber Reinforced Concrete
HFRC	Hybrid Fiber Reinforced Concrete
IS	Indian Standard

ITZ	Interfacial Transition Zone
NC	Normal (control) Concrete
NDT	Non-Destructive Testing
OPC	Ordinary Portland Cement
PCE	Polycarboxylate Ether
PP	Polypropylene
PPC	Portland Pozzolana Cement
PVA	Polyvinyl Alcohol
SEM	Scanning Electron Microscopy
SFRC	Steel Fiber Reinforced Concrete
UPV	Ultrasonic Pulse Velocity
XRD	X-Ray Diffraction

LIST OF SYMBOLS

A	Loaded cross-sectional area of specimen, mm ² (Equation 3.4); mass of coarse aggregate, kg/m ³ (Equation 3.3)
a	Distance from line of fracture to nearer support, mm (Equation 3.7)
b	Measured width of prism specimen, mm
C	Cement content, kg/m ³
D	Diameter of cylinder specimen, mm
d	Measured depth of prism specimen, mm; fibre diameter, mm
F	Mass of fine aggregate, kg/m ³
f_c	Compressive strength, MPa
f_{ck}	Characteristic compressive strength at 28 days, MPa
f_{ek}	Target mean compressive strength at 28 days, MPa
f_{ct}	Split tensile strength, MPa
f_r	Modulus of rupture (flexural strength), MPa
G_e, G_f, G_a	Specific gravity of cement, fine aggregate and coarse aggregate
L	Effective span, mm; length of cylinder, mm; ultrasonic path length, mm
l	Fibre length, mm
l/d	Fibre aspect ratio
P	Maximum load at failure, N
s	Assumed standard deviation of compressive strength, MPa
T	Ultrasonic transit time, μs
V	Ultrasonic pulse velocity, km/s
v	Volume of entrapped air, fraction of total volume
W	Free water content, kg/m ³
w/c	Free water–cement ratio
Δ	Percentage change relative to control mix, %
π	Ratio of circumference to diameter of a circle

CHAPTER 1

INTRODUCTION

1.1 Background

This section establishes the engineering problem that motivates the study. It describes the mechanical deficiency of plain concrete, identifies its origin in the internal structure of the hardened material, and explains why discrete fibre reinforcement addresses that deficiency at a scale which conventional bar reinforcement cannot reach.

Concrete is, by volume, the most heavily consumed manufactured material in the world. Its dominance rests on a combination of properties that no competing material matches at comparable cost: high compressive strength, the capacity to be cast into arbitrary shapes on site, good fire resistance, chemical compatibility with steel reinforcement, and constituent materials that are available almost everywhere. Buildings, bridges, pavements, dams, tunnels, canals and marine works all depend upon it.

The material is nonetheless fundamentally brittle. Its tensile strength is typically between one-eighth and one-twelfth of its compressive strength, and failure in tension occurs suddenly, with negligible plastic deformation to give warning. The reason lies in the internal structure of hardened concrete. Even before any external load is applied, the interfacial transition zone (ITZ) between the coarse aggregate and the bulk cement paste contains microcracks and voids produced by internal bleeding, differential shrinkage and the wall effect of the aggregate surface. The ITZ is a region of higher porosity, higher calcium hydroxide content and preferential crystal orientation, and it is mechanically the weakest constituent of the composite. Under load, the flaws it contains act as stress raisers; they extend, link and coalesce into continuous cracks, and once a critical crack has formed there is nothing within a plain matrix to transfer stress across its faces.

Conventional bar reinforcement addresses this at the structural scale by carrying tensile force after the concrete has cracked, but it does not prevent cracking and it acts at a spacing measured in tens or hundreds of millimetres. Crack widths in service therefore remain a durability problem, since they provide a pathway for water, chloride ions, sulphates and carbon dioxide to reach the reinforcement and initiate corrosion. Plastic

shrinkage cracking in slabs and thin sections occurs at ages and in locations where bar reinforcement offers no restraint at all.

Fibre reinforcement addresses the problem at its origin. Short discrete fibres dispersed randomly throughout the matrix are present in every plane and at every location, including those a reinforcing bar cannot occupy. When a microcrack forms, any fibre crossing it immediately begins to transfer stress across the crack faces, reducing the stress intensity at the crack tip and slowing or arresting further extension. The consequence is not usually a large increase in the load at which cracking begins, but a substantial increase in the energy required to propagate cracking to failure.

It follows that the principal engineering value of fibre reinforcement lies in the transformation of the failure process from brittle to quasi-ductile, rather than in any headline increase in compressive strength. This distinction governs the interpretation of every result presented in Chapter 4 and should be borne in mind throughout.

1.2 Fiber Reinforced Concrete

Having established why fibres are used, this section identifies the parameters that determine how effective they are, and shows why those parameters cannot be simultaneously optimised by a single fibre type.

Fiber Reinforced Concrete (FRC) is a composite consisting of a conventional cementitious matrix and randomly oriented discontinuous fibres. Steel, glass, polypropylene, polyvinyl alcohol, carbon, basalt and a range of natural fibres have all been employed, and the choice governs which properties are improved and by how much.

The effectiveness of any fibre system is controlled by a small number of parameters. The volume fraction determines how many fibres cross a given crack plane. The aspect ratio, being the ratio of length to equivalent diameter, controls the anchorage available on either side of a crack and therefore whether a fibre pulls out gradually or fractures abruptly. Deformation of the fibre geometry, by hooked ends, crimping, twisting or surface indentation, increases mechanical interlock and raises the pull-out energy well above what adhesion alone provides. The elastic modulus of the fibre relative to that of the matrix determines whether the fibre attracts stress before cracking or only after it. Fibre orientation and dispersion, which depend on the mixing procedure, the workability

of the mix and the wall effect of the formwork, determine how many of the fibres present are usefully oriented with respect to the principal tensile stress.

A well-designed fibre system is therefore one in which fibres debond and pull out progressively while consuming energy, rather than one in which they rupture. Fibre rupture releases stored energy suddenly and returns the composite to brittle behaviour; controlled pull-out dissipates energy over a large crack opening and is the mechanism responsible for the characteristic post-peak tail in the load–deflection curve of a well-made FRC specimen.

The limitation of single-fibre systems follows directly from these parameters. A fibre chosen for its length and stiffness, and therefore effective at bridging wide cracks, is necessarily too coarse and too widely spaced to intercept microcracks. A fibre fine enough to be present in very large numbers per unit volume, and therefore effective against microcracking, lacks the embedment length and stiffness to carry load across a wide crack. No single fibre geometry is optimal at both scales. This conclusion is the direct motivation for hybridisation, which is the subject of the following section.

1.3 Hybrid Fiber Reinforced Concrete

This section sets out the principle of fibre hybridisation, identifies the two bases on which fibres are combined, and states the condition under which hybridisation produces a genuine benefit.

Hybrid Fiber Reinforced Concrete (HFRC) contains two or more fibre types combined so that the strengths of each compensate for the limitations of the other. Hybridisation may be based on differences in size, in elastic modulus, in strength, or in the function each fibre performs.

The most widely exploited basis is scale. Cracking in concrete is a multi-scale, progressive process. Under increasing load, isolated microcracks form within the interfacial transition zone, then extend into the surrounding mortar, then link into a continuous macrocrack that separates the specimen. Fine microfibres, present in very large numbers and separated by very small spacings, act during the first of these stages and raise the stress at which microcracks begin to coalesce, thereby delaying the transition to localised cracking. Coarse macrofibres are largely inactive during that stage but dominate the second, bridging the localised crack and controlling how much load

the specimen retains as the crack opens. Because the two fibre types are active over different portions of the response, their contributions are complementary rather than merely additive, and a hybrid at a given total dosage can exceed the performance of either constituent used alone at that same dosage.

The sequential nature of this mechanism is illustrated schematically in Figure 1.1, which contrasts the crack pattern in a plain matrix with the two stages of hybrid reinforcement.

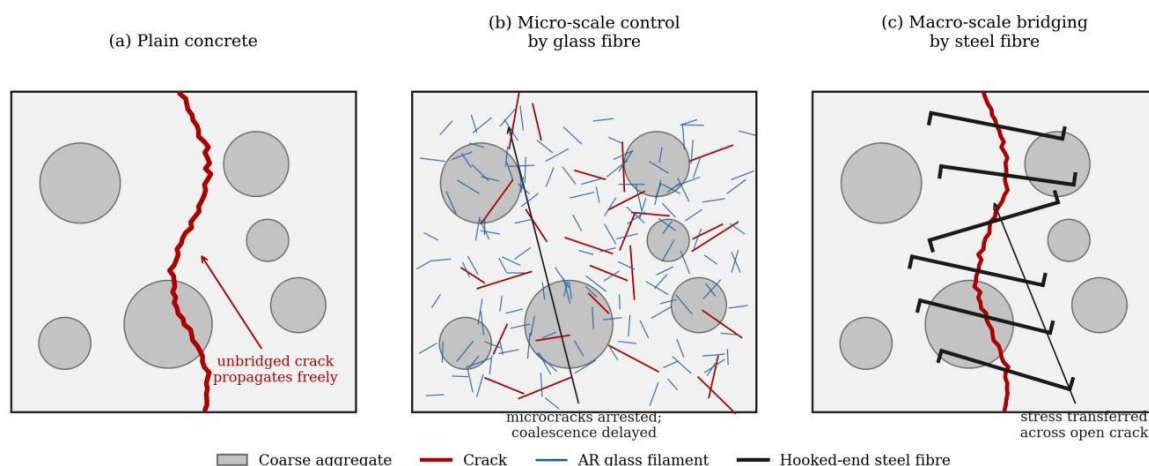


Figure 1.1 Multi-scale crack control in hybrid fibre reinforced concrete: (a) unbridged crack propagation in a plain matrix, (b) micro-scale arrest by AR glass filaments, (c) macro-scale bridging by hooked-end steel fibres

In Figure 1.1(a) a crack in the plain matrix propagates without restraint, since nothing crosses its faces to transfer stress. In Figure 1.1(b) the dense population of fine filaments intercepts individual microcracks at the moment of initiation and prevents them from linking into a continuous path; the reinforcement here is statistical, depending on the sheer number of filaments rather than on the strength of any one of them. In Figure 1.1(c) a localised crack has nonetheless formed, and load is transferred across it by the small number of long, stiff fibres that cross it, whose hooked ends anchor them into the matrix on both sides. The two mechanisms operate at different points on the load–deflection curve, which is precisely why they are complementary.

A second basis for hybridisation is the elastic modulus. A high-modulus fibre such as steel attracts stress at low strain and contributes to strength and stiffness, whereas a lower-modulus fibre contributes principally to strain capacity and toughness after the matrix has cracked. Combining the two yields a composite that is both stronger at first crack and more ductile thereafter.

It must be emphasised that hybridisation is not automatically beneficial. Synergy is a consequence of proportioning, not of the mere presence of two fibre types. If the total fibre volume is excessive, fibres agglomerate during mixing, workability falls sharply, full compaction cannot be achieved, and the air entrapped by inadequate compaction reduces strength by more than the fibres improve it. Reported optima in the literature are consequently modest, and the identification of that optimum for a specific fibre combination and matrix is the central experimental question of most HFRC investigations, including the present one.

1.4 Steel Fibres

This section describes the properties of the macro-scale reinforcement adopted in the present study and identifies both its contribution and its practical limitations.

Steel fibres are the most extensively used and best-documented fibre type in structural concrete. Their elastic modulus, of the order of 200 GPa, is roughly six to seven times that of the surrounding matrix, so they attract stress readily and remain effective across large crack openings. Tensile strengths of commercial fibres commonly lie between 1000 and 2000 MPa, sufficient to ensure that failure occurs by pull-out rather than by fibre fracture when the embedment length is correctly chosen.

Fibres are manufactured with hooked ends, crimped profiles, flat ends or twisted sections. These deformations are not cosmetic. The pull-out energy of a hooked-end fibre is several times that of a straight fibre of identical material and dimensions, because plastic deformation of the hook as it is drawn through the matrix channel dissipates energy in addition to the frictional work of sliding. This is the principal reason hooked-end fibres are specified where post-cracking capacity governs.

The characteristic effects of steel fibre addition are a marked increase in flexural and split tensile strength, a large increase in flexural toughness and fracture energy, improved impact and fatigue resistance, and only a modest increase in compressive strength, commonly a few per cent, since compressive failure is governed by matrix crushing and lateral splitting rather than by crack bridging. The principal disadvantages are a substantial loss of workability at higher dosages, a risk of balling if the fibres are introduced to the mix incorrectly, the possibility of surface corrosion staining where

fibres are exposed at a finished face, and increased cost. These limitations bear directly on the mixing procedure adopted in Section 3.5 and on the dosage range investigated.

1.5 Glass Fibres

This section describes the micro-scale reinforcement and explains why the alkali resistance of the glass is a material specification rather than an optional refinement.

Glass fibres are fine, high-strength filaments, typically supplied as chopped strands of 6 to 24 mm length. Their tensile strength is comparable to or greater than that of steel fibre, while their elastic modulus, at approximately 70 GPa, is appreciably lower. Their density is roughly one-third that of steel, so that at equal mass a far greater number of filaments is available; at equal volume fraction, the number of glass filaments crossing a unit crack area exceeds that of steel fibres by orders of magnitude. This is the source of their effectiveness against microcracking and against plastic shrinkage cracking in the first hours after placing.

The critical material consideration is alkali resistance. Ordinary E-glass is attacked by the calcium hydroxide liberated during cement hydration. The pore solution of Portland cement concrete has a pH of approximately 13, and E-glass filaments in that environment lose strength progressively as the silica network is dissolved and hydration products are deposited on and between the filaments, embrittling the strand. Early glass fibre reinforced products suffered significant long-term strength loss for this reason. Alkali-resistant (AR) glass, containing zirconium dioxide typically at 16 per cent or above, was developed specifically to address this, and it is AR glass rather than E-glass that must be specified for structural concrete.

The advantages of glass fibre are therefore complete immunity to electrochemical corrosion, very fine dispersion, effective control of early-age and micro-scale cracking, and low density. The limitations are the lower elastic modulus, which restricts the contribution across wide cracks, the short filament length, which limits anchorage, a strong tendency to increase water demand because of the very large specific surface introduced, and the long-term durability question that makes AR grade essential. It follows that glass fibre alone cannot provide post-cracking capacity, and that its contribution is best realised in combination with a macro-fibre.

1.6 The Steel–Glass Hybrid System

This section brings together the preceding two sections and states the specific mechanism anticipated in the fibre combination adopted for this study.

The combination of steel and glass fibre is a natural application of the hybridisation principle, because the two materials are complementary on almost every parameter that governs fibre performance. Steel provides high modulus, long embedment and high pull-out energy, and is therefore the macro-scale, post-peak reinforcement. Glass provides very fine filaments in very large numbers at low density, and is therefore the micro-scale, pre-peak reinforcement. Glass is immune to corrosion, which partially offsets the durability concern associated with steel fibres exposed at a cracked or finished surface. Steel is unaffected by alkalinity, which offsets the long-term concern associated with glass.

The anticipated mechanism is accordingly sequential. During early loading, the dense population of glass filaments intercepts microcracks within the interfacial transition zone and delays their coalescence, which should be reflected in an increase in the first-crack stress and, in the split tensile and flexural tests, in the peak load. Once a localised crack has nonetheless formed and begun to open, the glass filaments, being short and of moderate modulus, are progressively exhausted, and load transfer passes to the steel fibres, which bridge the widening crack and sustain load well beyond the peak. The composite consequently exhibits both a higher peak and a longer, more gradual descending branch than either the plain matrix or a single-fibre mix at equivalent dosage.

The countervailing effect is upon the fresh mix. Both fibre types increase internal friction and reduce slump, and glass fibre in particular increases water demand disproportionately because of the specific surface it introduces. Beyond a certain total dosage, workability falls to the point at which full compaction cannot be achieved by the available means, air is entrapped, and measured strengths decline despite the fibres. The dosage at which the strength curve turns downward is therefore not a property of the fibres alone but of the fibre–matrix–compaction system as a whole, and it must be established experimentally for the particular materials and procedures in use. Determining that dosage for the steel–glass system in M40 concrete is the primary objective of this work.

1.7 Objectives of the Study

The overall aim of this investigation is to evaluate the fresh and hardened performance of M40 grade concrete reinforced with a hybrid system of steel and alkali-resistant glass fibres, and to determine the fibre dosage at which the combination is most effective. The specific objectives are as follows.

1. To characterise the constituent materials, namely cement, fine aggregate, coarse aggregate, steel fibre and glass fibre, in accordance with the relevant Indian Standards, so that the concrete results may be interpreted against known material properties.
2. To proportion an M40 grade control mix in accordance with IS 10262:2019 and IS 456:2000, and to prepare hybrid mixes at increasing fibre dosage using the same base proportions.
3. To quantify the effect of hybrid fibre addition upon the workability of fresh concrete by means of the slump cone and compaction factor tests, and to establish the dosage beyond which workability becomes the limiting constraint upon placement and compaction.
4. To determine the compressive strength of all mixes at 7 and 28 days, and to examine whether fibre addition affects the rate of strength gain as well as the ultimate value.
5. To determine the split tensile strength of all mixes and to quantify the improvement attributable to hybrid reinforcement, this being the property in which the crack-bridging mechanism is most directly expressed.
6. To determine the flexural strength of all mixes and to assess the contribution of the hybrid system to bending resistance and to the mode of failure observed.
7. To assess the internal uniformity, integrity and dynamic modulus of the specimens by ultrasonic pulse velocity testing in accordance with IS 13311 (Part 1), and thereby to detect any loss of compaction associated with higher fibre dosages.
8. To assess surface hardness and estimated strength by rebound hammer testing in accordance with IS 13311 (Part 2), and to examine the correlation between rebound number and measured compressive strength for fibre-reinforced mixes.
9. To identify, upon the combined destructive and non-destructive evidence, the optimum steel–glass fibre combination for M40 concrete, and to interpret the observed behaviour mechanistically against the published literature.

1.8 Scope and Limitations

The investigation is confined to laboratory evaluation under controlled conditions. It encompasses material characterisation, mix proportioning, casting, water curing, and the testing of fresh and hardened properties at 7 and 28 days, together with two non-destructive test methods.

The following lie outside the scope of the present work and are identified in Chapter 6 as directions for further research: long-term strength development beyond 28 days; durability testing including chloride ion penetration, sulphate attack, carbonation and freeze–thaw resistance; creep and drying shrinkage; fatigue and impact response; behaviour at elevated temperature; microstructural characterisation by scanning electron microscopy or X-ray diffraction; numerical modelling; and full-scale or field validation.

The conclusions drawn are therefore valid for short-term mechanical performance under the stated conditions and should not be extrapolated to long-term service behaviour without further testing. This limitation is restated in Section 5.5 and forms the basis of the recommendations in Chapter 6.

1.9 Organisation of the Report

Chapter 1 has introduced the engineering problem, the principle of fibre and hybrid fibre reinforcement, the characteristics of the two fibre types employed, and the objectives and scope of the study.

Chapter 2 reviews the published literature. It is organised thematically rather than as a sequence of individual paper summaries, proceeding from single-fibre systems through the development of the hybridisation concept to studies of specific hybrid combinations and of non-destructive evaluation, and concludes by identifying the research gap that motivates the present investigation.

Chapter 3 describes the constituent materials and their measured properties, the mix design procedure, the mix matrix, specimen preparation and curing, and the testing methodology, with reference to the governing Indian Standard for each test.

Chapter 4 presents the experimental results and their discussion, treating each test in turn and interpreting the observed trends in terms of the underlying mechanisms and against the findings reviewed in Chapter 2.

Chapter 5 states the conclusions, identifies the optimum mix, and sets out the engineering significance and practical implications of the findings together with the limitations that qualify them.

Chapter 6 develops the scope for future work. The references cited throughout are listed thereafter.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the body of published work on fibre reinforcement of cementitious composites, with particular attention to hybrid systems. The review is organised by theme rather than chronologically or paper by paper, because the questions material to the present study, namely what mechanism produces the improvement, at what dosage it saturates, and which fibre combinations have actually been shown to be synergistic, are best answered by comparison across studies rather than by summarising each in isolation.

The chapter proceeds from the mechanics of single-fibre systems, through the origins of and evidence for the hybridisation concept, to studies of specific hybrid combinations, glass fibre behaviour and durability, and the non-destructive evaluation of fibre reinforced concrete. It closes with a statement of the research gap that the present work addresses.

2.2 Mechanics of Single-Fibre Reinforcement

The theoretical foundation for the fibre reinforcement of brittle matrices is set out comprehensively by Bentur and Mindess [1], whose treatment remains the standard reference. Their central argument is that the function of fibres is not primarily to increase strength but to alter the fracture process: fibres crossing a crack transfer stress across its faces, reduce the stress intensity factor at the crack tip, and convert an unstable, energy-releasing propagation into a stable, energy-absorbing one. The composite therefore exhibits a large increase in fracture energy and only a modest increase in first-crack strength, the balance between the two depending upon whether the fibres pull out or fracture.

This distinction has been demonstrated repeatedly in experiment. Song and Hwang [2] tested high-strength steel fibre reinforced concrete at volume fractions from 0.5 to 2.0 per cent and reported that compressive strength rose only modestly and peaked near 1.5 per cent, whereas split tensile and flexural strengths rose substantially more over the same range. The asymmetry is mechanistically expected: compressive failure is governed by matrix crushing and lateral splitting, in which crack bridging plays a

limited role, whereas tensile and flexural failure are governed directly by the propagation of a single dominant crack, upon which fibres act.

Köksal et al. [3] examined the interaction between fibre reinforcement and matrix quality, combining steel fibre with silica fume in high-strength concrete. They found that improving the matrix and the interfacial transition zone increased the bond available to each fibre and therefore increased the effectiveness of a given fibre dosage. This is an important qualification for the interpretation of any FRC result: the benefit of a fibre addition is not a fixed quantity but depends upon the matrix into which it is placed, so that results obtained in normal-strength concrete cannot be transferred directly to high-strength mixes or the reverse.

The consistent finding across single-fibre studies is a strength optimum rather than a monotonic improvement. Beyond approximately 1.0 to 1.5 per cent by volume for steel fibre under conventional mixing and compaction, the loss of workability and the associated entrapment of air outweigh the mechanical contribution of the additional fibres. Nili and Afroughsabet [4] made the same point in the context of impact resistance, showing that while impact energy absorption continued to improve with fibre content over the range tested, compressive strength did not, and that the two properties therefore optimise at different dosages. The existence of a dosage optimum, and the necessity of establishing it experimentally for each system, is thus firmly established.

2.3 The Hybridisation Concept

The recognition that no single fibre geometry can be optimal at all scales of cracking led to the systematic study of hybrid systems from the late 1990s onward. This section traces the development of the concept and the evidence supporting it.

Qian and Stroeven [5] carried out one of the defining early investigations, combining polypropylene and steel fibres at low total volume fractions and varying fibre size, content and matrix composition. Two findings from that work have shaped subsequent research. First, they demonstrated a genuine synergy effect, in which the hybrid outperformed the arithmetic sum of the individual fibre contributions. Second, they showed that the presence of fine particles within the matrix was necessary for uniform fibre dispersion, establishing that hybrid performance is a property of the fibre–matrix system and not of the fibres alone. In a companion paper on fracture properties [6] they

showed that the two fibre types governed different regions of the load–crack-mouth-opening curve, which is the direct experimental expression of the multi-scale argument illustrated in Figure 1.1.

Banthia and Nandakumar [7] approached the question through crack growth resistance and showed that hybrid combinations produced rising resistance curves distinct from those of either mono-fibre composite. Banthia and Sappakittipakorn [8] then demonstrated the concept within a single material class, hybridising large-diameter crimped steel fibres with smaller-diameter crimped steel fibres. Large-diameter crimped fibres are inexpensive and disperse readily without unduly reducing workability, but are mechanically inefficient; replacing a portion of them with finer fibres significantly enhanced toughness while maintaining workability, dispersibility and low cost. This result is particularly instructive because it isolates the geometric variable: the two fibres were of the same material, so the improvement is attributable unambiguously to the difference in scale rather than to any difference in modulus or chemistry.

The mechanistic basis was subsequently formalised by Banthia et al. [9], who examined fibre synergy in flexure and direct shear and quantified the conditions under which hybridisation is beneficial. Their analysis makes clear that synergy is not guaranteed: it requires that the fibres be active at genuinely different stages of the fracture process and that the total dosage remain within the range in which dispersion and compaction can be maintained. Pereira, Fischer and Barros [10] tracked the cracking process directly in hybrid fibre reinforced cementitious composites and confirmed that microfibres control the multiple-cracking stage while macrofibres control localisation, providing observational support for the sequential mechanism adopted in Section 1.6.

Brandt [11], reviewing more than four decades of development in fibre reinforced cement composites, placed hybridisation within the broader trajectory of the field and identified it as one of the principal routes by which the performance of cementitious composites has been extended beyond what mono-fibre systems permit. The concept may therefore be regarded as well established in principle, the remaining questions being empirical and specific to particular fibre combinations.

2.4 Specific Hybrid Fibre Combinations

This section examines the experimental evidence for particular fibre pairings, with attention to those most closely related to the steel–glass system adopted here.

Sivakumar and Santhanam [12] investigated high-strength concrete reinforced with combinations of metallic and non-metallic fibres, including steel with polypropylene, polyester and glass. Their results bear directly upon the present study. They reported that hybrid systems containing a non-metallic fibre alongside steel achieved mechanical performance comparable to or better than steel alone, and attributed this to two causes: the lower density of non-metallic fibres means that a far greater number of filaments is available at the same volume fraction, and those filaments are able to bridge smaller microcracks that steel fibres cannot reach. This is the clearest published statement of the mechanism by which a steel–glass hybrid would be expected to function.

In a companion study, Sivakumar and Santhanam [13] quantified plastic shrinkage cracking in high-strength hybrid fibre reinforced concrete and found the non-metallic component markedly more effective than steel at controlling early-age cracking, when the matrix possesses negligible tensile strength and very fine, closely spaced filaments constitute the only reinforcement capable of acting. This identifies a benefit of the glass component that 28-day strength testing does not capture at all, and it is relevant to the practical case for the hybrid.

Afroughsabet and Ozbakkaloglu [14] studied steel and polypropylene fibres in high-strength concrete containing silica fume, at a total hybrid volume fraction of 1.0 per cent. They reported improvements in splitting tensile and flexural strength together with improvements in electrical resistivity and reduced water absorption, indicating that the crack control achieved by the hybrid system translates into a measurable durability benefit and not merely a mechanical one. Li et al. [15] examined the flexural behaviour of steel–polypropylene hybrid concrete in detail and characterised the post-peak response, confirming that the steel component governs load retention at large deflections.

Yao, Li and Wu [16] examined hybrid fibre reinforced concrete at low total fibre volume fraction and found measurable synergy even at dosages well below one per cent, which is significant for practical application because low dosages preserve workability and limit cost. Chen and Liu [17] reported similar conclusions for high-strength lightweight concrete, noting explicitly that good workability was maintained.

Work bearing directly upon the steel–glass combination is comparatively limited but consistent in its findings. Studies of self-consolidating concrete reinforced with steel, glass and steel–glass hybrid systems have reported that both components contribute, that the optimum dosages of the two fibres differ substantially from one another, and that durability indicators including absorption, electrical resistivity and chloride diffusion improve alongside the mechanical properties. Kizilkanat et al. [18] compared basalt and glass fibre reinforced concrete and characterised the fracture behaviour of both, providing a useful baseline for glass fibre performance in a conventional matrix. Saidani, Saraireh and Gerges [19] compared several fibre types in concrete without admixture and confirmed that the ranking of fibre effectiveness depends upon which property is measured, reinforcing the point that an optimum identified upon compressive strength alone may not be the optimum overall.

Two further studies bear upon the quantification of hybrid benefit. Song and Yin [23] evaluated the combination of steel and carbon fibre by means of a hybrid effect index, an explicit numerical measure of the extent to which the composite exceeds the sum of its mono-fibre constituents. Such an index is a more rigorous criterion for synergy than a simple comparison of absolute strengths, and it is recommended in Section 6.2 as the basis for the constant-volume ratio study. Ahmed, Maalej and Paramasivam [25] examined the flexural response of hybrid steel–polyethylene composites containing high volumes of fly ash and demonstrated that the hybrid benefit is preserved in matrices incorporating substantial supplementary cementitious material, which is directly relevant to the present work given the use of Portland Pozzolana Cement described in Section 3.2.1.

Mobasher, Yao and Soranakom [20] provided analytical solutions for the flexural design of hybrid steel fibre reinforced beams, representing the point at which experimental findings upon hybridisation begin to be translated into design methodology.

The principal studies reviewed in this chapter are summarised in Table 2.1, which is arranged to permit direct comparison of fibre systems, dosage ranges and principal findings.

Table 2.1 Summary of principal studies reviewed

Ref.	Author(s) and year	Fibre system	Principal finding relevant to this study
[2]	Song and Hwang (2004)	Steel, 0.5–2.0 % vol.	Tensile and flexural gains far exceed compressive gains; optimum near 1.5 %
[4]	Nili and Afroughsabet (2010)	Steel with silica fume	Impact resistance and compressive strength optimise at different dosages
[5]	Qian and Stroeven (2000)	Steel + polypropylene	Synergy demonstrated; fine matrix particles required for dispersion
[8]	Banthia and Sappakittipakorn (2007)	Coarse + fine steel	Scale effect isolated; toughness enhanced at constant workability
[9]	Banthia et al. (2014)	Hybrid, flexure and shear	Conditions for synergy formalised; not automatic
[10]	Pereira et al. (2012)	Micro + macro hybrid	Direct observation of micro-then-macro crack control sequence
[12]	Sivakumar and Santhanam (2007)	Steel + glass, polyester, PP	Non-metallic filament count bridges cracks steel cannot reach
[13]	Sivakumar and Santhanam (2007)	Hybrid, plastic shrinkage	Non-metallic component dominates early-age crack control
[14]	Afroughsabet and Ozbakkaloglu (2015)	Steel + PP, 1.0 % total	Mechanical and durability benefits both realised
[16]	Yao et al. (2003)	Hybrid, low volume fraction	Synergy measurable below 1 % total dosage
[18]	Kizilkanat et al. (2015)	Basalt and glass	Baseline fracture behaviour for glass fibre in conventional matrix
[22]	Wu et al. (2022)	AR glass, 0–1.5 % vol.	Microstructural confirmation that AR glass retains function in PC matrix

Table 2.1 makes two patterns apparent. First, the reported optimum total fibre dosage across the studies listed lies consistently at or below approximately 1.5 per cent by volume, and several of the most rigorous investigations worked at 1.0 per cent or less. Second, the steel–polypropylene pairing dominates the literature, with the steel–glass combination represented by comparatively few entries. Both observations inform the research gap identified in Section 2.7 and the methodological caution recorded in Section 3.4.

2.5 Glass Fibre and the Alkali Resistance Question

The behaviour of glass fibre in a cementitious matrix cannot be discussed independently of alkali attack, and this section reviews the evidence bearing upon it.

The pore solution of hydrating Portland cement is strongly alkaline, and conventional E-glass is progressively degraded in that environment through dissolution of the silica network and the deposition of hydration products within the strand, which embrittles the filament bundle and causes long-term loss of strength and toughness. Enfedaque et al. [21] analysed the fracture surfaces of glass fibre reinforced cement and related the observed fracture behaviour to the condition of the fibre–matrix interface, demonstrating how interfacial changes over time govern composite performance.

Alkali-resistant glass, containing zirconium dioxide at approximately 16 per cent or more by weight, was developed to address this and is the grade appropriate to structural concrete. Wu et al. [22] examined the effect of fibre content upon the mechanical properties and microstructure of alkali-resistant glass fibre reinforced concrete across dosages from 0 to 1.5 per cent by volume, combining compression, flexural and impact testing with scanning electron microscopy and energy dispersive spectroscopy. Their microstructural evidence links composite performance directly to the state of the fibre–matrix interface and confirms that AR glass retains its reinforcing function in a Portland cement matrix.

The practical consequence for the present study is twofold: the glass fibre specified must be of alkali-resistant grade, as recorded in Section 3.2.5, and the distinction between AR and E-glass must be observed when comparing results with published work. Studies that do not identify the grade of glass employed are of limited value for interpretation.

2.6 Non-Destructive Evaluation of Fibre Reinforced Concrete

This section considers the two non-destructive methods adopted in the present programme and the particular care their interpretation requires when applied to fibre reinforced concrete.

Ultrasonic pulse velocity depends upon the density, elastic modulus and, critically, the continuity of the medium through which the pulse travels. Voids, microcracks and poorly compacted regions lengthen the travel path and reduce the apparent velocity. In fibre reinforced concrete this renders UPV a sensitive indicator of exactly the failure mode that limits fibre dosage: where a high-dosage mix has been inadequately compacted, the entrapped air will depress the pulse velocity even where the effect upon

measured compressive strength is partly masked by the fibres. UPV therefore provides an independent check upon whether a decline in strength at high dosage is attributable to compaction rather than to the fibres themselves, and this is the interpretive question that arises in nearly every FRC dosage study.

Rebound hammer testing measures the surface hardness of the impact zone and correlates it empirically with compressive strength. The correlation is sensitive to surface condition, carbonation, moisture state and the presence of aggregate or fibre immediately beneath the plunger. In fibre reinforced concrete the near-surface fibre distribution differs from that of the bulk owing to the wall effect of the mould, so the rebound number should be treated as an indicator of relative quality and uniformity across mixes rather than as an absolute measure of strength. The standard requires that any correlation used for strength estimation be established for the specific concrete under test.

The value of applying both methods alongside destructive testing lies in the cross-checking they permit. Agreement among the three provides confidence in the results; systematic disagreement points to a specific and identifiable cause, most commonly a compaction deficiency, and its diagnosis strengthens rather than weakens the analysis. This is the rationale for the combined programme set out in Chapter 3.

2.7 Research Gap

Several conclusions follow from the review presented above.

The mechanics of single-fibre reinforcement is well established, as is the existence of a dosage optimum beyond which workability and compaction losses outweigh mechanical gain. The hybridisation concept is likewise well supported both theoretically and experimentally, and the multi-scale mechanism by which it operates has been observed directly.

However, the great majority of the experimental work upon hybrid systems concerns the steel–polypropylene combination, as Table 2.1 indicates. The steel–glass combination has received substantially less attention, notwithstanding that upon the parameters governing fibre performance, namely modulus, filament count, density, corrosion behaviour and alkali sensitivity, steel and glass are more strongly complementary than steel and polypropylene. Where steel–glass systems have been studied, the work has

frequently concerned self-consolidating, high-strength or geopolymer matrices rather than the conventional vibrated structural concrete used in ordinary construction.

Furthermore, comparatively few studies combine destructive mechanical testing with non-destructive evaluation of the same specimens. This omission matters specifically for hybrid systems, because the interpretation of any observed strength reduction at higher dosage depends upon distinguishing a genuine mechanical effect from a compaction artefact, and UPV supplies the evidence required to make that distinction.

There is accordingly a need for a systematic experimental investigation of steel and alkali-resistant glass fibres, used in combination at progressively increasing dosage in conventional M40 grade structural concrete, in which fresh properties, compressive, split tensile and flexural strength, and non-destructive indicators are all measured upon the same mixes, so that the optimum may be identified upon the combined evidence and the governing mechanism interpreted with confidence. The present study is directed at that gap.

2.8 Summary

Fibre reinforcement improves concrete principally by altering the fracture process rather than by raising strength, with the largest gains in tensile, flexural and toughness properties and only modest gains in compression. Every fibre system exhibits a dosage optimum governed by dispersion and compaction. Hybridisation exploits the multi-scale nature of cracking, with fine fibres controlling microcrack initiation and coalescence and coarse fibres controlling localised crack bridging, and synergy has been demonstrated where the two fibre types are genuinely active at different stages. Steel and alkali-resistant glass are strongly complementary upon the parameters that govern fibre performance, but the combination has been studied less extensively than steel–polypropylene, particularly in conventional structural concrete and particularly in conjunction with non-destructive evaluation. This provides the rationale for the experimental programme described in Chapter 3.

CHAPTER 3 MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter describes the constituent materials employed in the experimental programme, the procedures by which their properties were determined, the design of the M40 control mix, the matrix of hybrid fibre mixes derived from it, the preparation and curing of specimens, and the test methods adopted. All material characterisation and concrete testing follows the relevant Indian Standard, which is identified for each procedure so that the results may be reproduced and compared with published work upon an equivalent basis.

The overall structure of the experimental programme is shown in Figure 3.1, which sets out the six stages of the work and the dependencies between them.

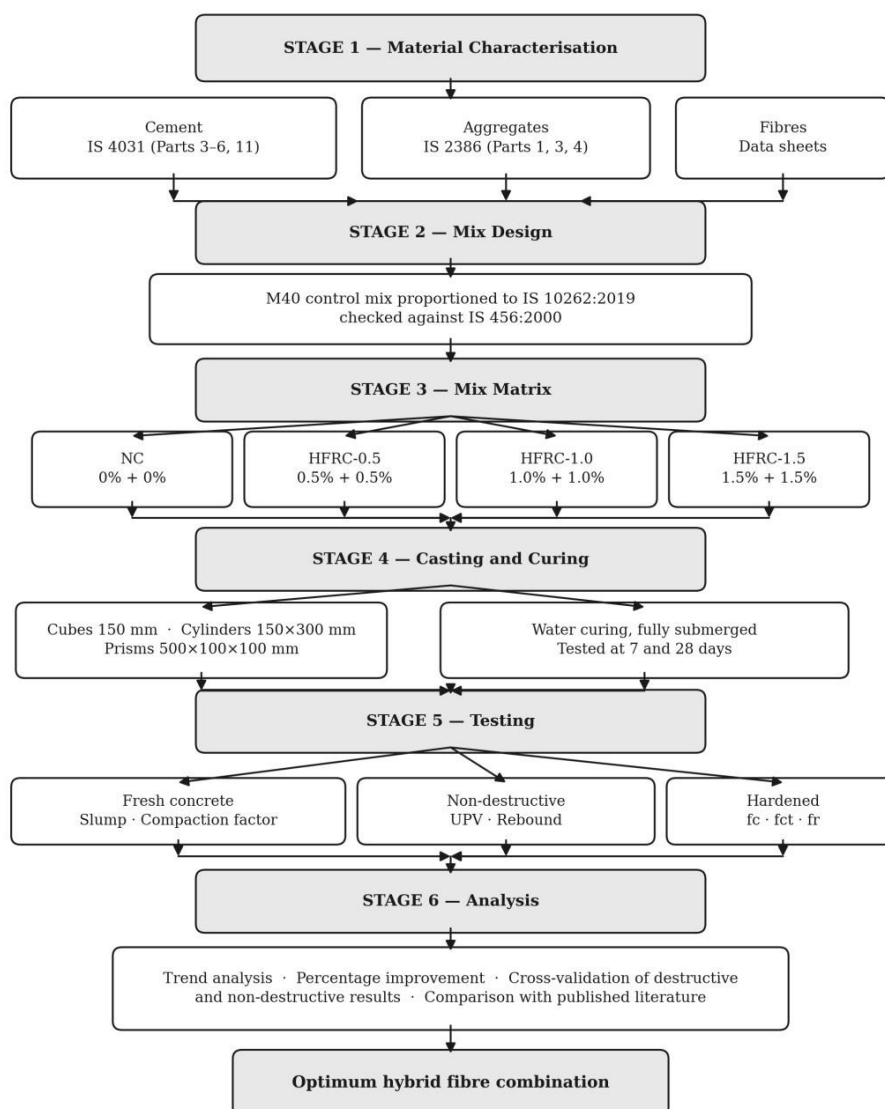


Figure 3.1 Flow chart of the experimental programme

As Figure 3.1 indicates, material characterisation precedes mix design because the specific gravities and moisture states determined at Stage 1 are required inputs to the absolute volume calculation at Stage 2. The four mixes generated at Stage 3 share a common base proportion, so that fibre content is the only deliberately varied parameter. Non-destructive testing at Stage 5 is performed upon the cube specimens before they are taken to failure, which permits the destructive and non-destructive results to be compared specimen by specimen rather than mix by mix. The analysis at Stage 6 therefore rests upon three independent lines of evidence.

3.2 Materials

The materials employed comprise Portland Pozzolana Cement, natural river sand, crushed granite coarse aggregate, hooked-end steel fibre, alkali-resistant glass fibre, potable water and a polycarboxylate-ether superplasticiser. Each is described below together with the standard governing its use and the properties measured.

3.2.1 Cement

Portland Pozzolana Cement (PPC) conforming to IS 1489 (Part 1):1991 was employed as the binder. PPC was selected in preference to Ordinary Portland Cement for three reasons material to fibre reinforced concrete. The pozzolanic reaction between the fly ash component and the calcium hydroxide liberated during hydration densifies the interfacial transition zone, which is the region in which microcracking originates and in which fibre bond is developed. The consumption of calcium hydroxide also lowers the alkalinity of the pore solution, which is favourable to the long-term retention of glass fibre strength as discussed in Section 2.5. Finally, the lower heat of hydration reduces early thermal gradients and the associated risk of early-age cracking.

The physical properties of the cement were determined by standard consistency, initial and final setting time, soundness by the Le Chatelier method, specific gravity and the compressive strength of standard mortar cubes. The results obtained are presented in Table 3.1 together with the corresponding requirements of IS 1489 (Part 1):1991.

Table 3.1 Physical properties of cement

Property	Test method	Result	IS 1489 (Part 1) requirement
Standard consistency (%)	IS 4031 (Part 4)	34.8	Not specified
Initial setting time (min)	IS 4031 (Part 5)	48	Minimum 30
Final setting time (min)	IS 4031 (Part 5)	318	Maximum 600
Soundness, Le Chatelier expansion (mm)	IS 4031 (Part 3)	1.8	Maximum 10
Specific gravity	IS 4031 (Part 11)	2.86	Typically 2.85–3.15
Compressive strength at 7 days (MPa)	IS 4031 (Part 6)	16.42	Minimum 16.0
Compressive strength at 28 days (MPa)	IS 4031 (Part 6)	22.71	Minimum 22.0

The values reported in Table 3.1 satisfy every requirement of IS 1489 (Part 1):1991. The initial setting time of 48 min comfortably exceeds the specified minimum of 30 min, which is material to the present work because the dry-mixing stage required to disperse the fibres extends the total mixing time before water is introduced. The Le Chatelier expansion of 1.8 mm, being less than one-fifth of the permissible 10 mm, lies well within the limit, indicating that free lime and magnesia are within acceptable bounds and that no delayed expansion is to be anticipated. The specific gravity of 2.86 lies at the lower end of the usual range, as is expected of a pozzolana-blended cement, and this value is employed in the absolute volume calculation of Section 3.3. Both mortar strengths exceed the specified minima, at 16.42 MPa against 16.0 MPa at 7 days and 22.71 MPa against 22.0 MPa at 28 days. The margins are narrow, being 2.6 and 3.2 per cent respectively, and the mix design of Section 3.3 accordingly adopts a conservative water–cement ratio of 0.40 rather than relying upon the cement to outperform its specification.

3.2.2 Fine Aggregate

Locally available natural river sand conforming to IS 383:2016 was employed as fine aggregate. Sieve analysis in accordance with IS 2386 (Part 1) placed the sand within Grading Zone II, which is generally the most suitable zone for structural concrete because it balances the workability conferred by finer material against the reduced water demand associated with coarser material. The sand was screened to remove particles retained upon the 4.75 mm sieve and was free of clay lumps and organic impurities. The measured properties are given in Table 3.2.

Table 3.2 Physical properties of fine aggregate

Property	Test method	Result
Grading zone	IS 383:2016 / IS 2386 (Part 1)	Zone II
Specific gravity	IS 2386 (Part 3)	2.65
Water absorption (%)	IS 2386 (Part 3)	1.72
Moisture content at batching (%)	IS 2386 (Part 3)	1.03

The specific gravity of 2.65 reported in Table 3.2 is typical of siliceous river sand and is used directly in the absolute volume calculation of Section 3.3. The water absorption of 1.72 per cent is moderate; since the measured moisture content of 1.03 per cent lies below the absorption value, leaving a deficit of 0.69 per cent, the sand was in a partially

dry condition at the time of batching and would otherwise have abstracted water from the mix. The batch water was corrected accordingly. This correction is of particular importance in a fibre-reinforced mix, in which the workability margin is already reduced and an unintended loss of free water would compromise both compaction and fibre dispersion.

3.2.3 Coarse Aggregate

Crushed angular granite aggregate of 20 mm nominal maximum size, conforming to IS 383:2016, was employed. Angular crushed aggregate was selected in preference to rounded gravel because the greater surface texture and interlock improve the aggregate–paste bond and the flexural strength of the resulting concrete, albeit at some cost in workability. The nominal maximum size of 20 mm is appropriate to the section sizes adopted and is compatible with the fibre lengths employed; an aggregate size approaching the fibre length would interfere with fibre distribution and reduce the volume of mortar available to develop fibre bond. The measured properties are presented in Table 3.3.

Table 3.3 Physical properties of coarse aggregate

Property	Test method	Result	IS 383 limit
Nominal maximum size (mm)	IS 383:2016	20	—
Aggregate impact value (%)	IS 2386 (Part 4)	9.82	Maximum 30
Aggregate crushing value (%)	IS 2386 (Part 4)	16.34	Maximum 30
Specific gravity	IS 2386 (Part 3)	2.79	—
Water absorption (%)	IS 2386 (Part 3)	2.05	—
Moisture content at batching (%)	IS 2386 (Part 3)	1.91	—

The impact and crushing values reported in Table 3.3, being 9.82 and 16.34 per cent respectively, lie well below the 30 per cent limit specified for aggregate used in structural concrete, indicating a mechanically strong aggregate that will not itself constitute the weakest link. This is a relevant consideration in an M40 mix: where the aggregate is strong and the paste dense, the failure path tends to pass around rather than through the aggregate particles, lengthening the crack path and increasing the fracture energy of the composite. A water absorption of 2.05 per cent lies at the upper end of the range normally accepted, and as with the fine aggregate the batch water was corrected

for the difference between measured moisture content and absorption, a deficit of 0.14 per cent in this case.

3.2.4 Steel Fibres

Hooked-end steel fibres were employed as the macro-scale reinforcement, for the reasons set out in Section 1.4. The fibres constitute the component of the hybrid system responsible for bridging localised macrocracks and for post-peak load retention. Their properties as supplied are recorded in Table 3.4, together with those of the glass fibre described in the following section.

3.2.5 Glass Fibres

Alkali-resistant glass fibres, supplied as chopped strands, were employed as the micro-scale reinforcement. Alkali-resistant grade is a requirement rather than a preference, for the reasons established in Sections 1.5 and 2.5. The very low density and small filament diameter of glass fibre mean that an extremely large number of filaments is introduced per unit volume, and it is this property that renders them effective against microcracking and plastic shrinkage cracking.

Table 3.4 Properties of the fibres as supplied by the manufacturer

Property	Steel fibre	AR glass fibre
Type and geometry	Hooked-end, cold-drawn wire	Chopped strand
Length, l (mm)	35	12
Diameter, d (mm)	0.55	0.014
Aspect ratio, l/d	64	857
Tensile strength (MPa)	1150	1750
Modulus of elasticity (GPa)	200	72
Specific gravity	7.85	2.68
Zirconia (ZrO ₂) content (%)	Not applicable	16.8

The contrast between the two fibres in Table 3.4 is the physical basis of the hybrid system. The steel fibre has an aspect ratio of 64 and a modulus of 200 GPa, giving it the embedment length and stiffness required to carry load across an open crack. The glass fibre has an aspect ratio of 857, more than thirteen times greater, at a filament diameter of 14 µm. At equal volume fraction the number of glass filaments crossing a given plane therefore exceeds the number of steel fibres by a factor of approximately 4500, and the

glass contributes some 97 per cent of the total fibre surface area introduced into the mix. It is this disparity that permits the two fibres to act at different scales, as anticipated in Section 1.6, and that also accounts for the disproportionate effect of the glass component upon water demand discussed in Section 4.2.

3.2.6 Water and Chemical Admixture

Potable water conforming to the requirements of IS 456:2000 was employed for both mixing and curing, the same source being used throughout the programme so that water quality did not vary between mixes.

A polycarboxylate-ether based superplasticiser conforming to IS 9103:1999 was employed. Its function in this programme is specific and important. The addition of fibres, and of glass fibre in particular because of the large specific surface it introduces, sharply increases water demand. Restoring workability by the addition of water would raise the water–cement ratio and reduce strength, thereby confounding the fibre variable under investigation. The superplasticiser permits workability to be restored at constant water–cement ratio, so that any change in measured strength between mixes may be attributed to the fibres rather than to a change in the matrix. The dosage was adjusted for each mix and is reported with the fresh concrete results in Section 4.2.

3.3 Mix Design

This section sets out the proportioning of the M40 control mix, the governing equations and the resulting quantities.

The control mix was proportioned for M40 grade concrete in accordance with IS 10262:2019, with durability requirements checked against IS 456:2000. The target mean compressive strength is obtained from the characteristic strength and the assumed standard deviation in accordance with Clause 4.2 of IS 10262:2019, as given by Equation (3.1).

$$f'_{ck} = f_{ck} + 1.65 s \quad (3.1)$$

where f'_{ck} = target mean compressive strength at 28 days, MPa;

f_{ck} = characteristic compressive strength at 28 days, taken as 40 MPa; s =

assumed standard deviation for the grade, MPa, from Table 2 of IS 10262:2019.

The water–cement ratio was selected below the value indicated by the strength relationship for the cement in use and was checked against the maximum permitted by IS 456:2000 for the applicable exposure condition, the lower of the two governing. Water content was taken from Table 4 of IS 10262:2019 for 20 mm nominal maximum size aggregate and adjusted for the target slump and for the use of a superplasticiser. The cement content follows from Equation (3.2).

$$C = W / (w/c) \quad (3.2)$$

where C = cement content, kg/m³;

W = free water content, kg/m³;

w/c = free water–cement ratio adopted.

The cement content obtained from Equation (3.2) was checked against the minimum cement content specified by IS 456:2000 for the exposure condition. The volume of coarse aggregate per unit volume of total aggregate was taken from Table 5 of IS 10262:2019 for Zone II fine aggregate and adjusted for the water–cement ratio adopted. The masses of fine and coarse aggregate were then obtained by the absolute volume method, expressed by Equation (3.3).

$$C/(G_c \times 1000) + W/1000 + F/(G_f \times 1000) + A/(G_a \times 1000) + v = 1 \quad (3.3)$$

where the left-hand side is the sum of the absolute volumes of the constituents per cubic metre of concrete;

F, A = masses of fine and coarse aggregate respectively, kg/m³;

G_c, G_f, G_a = specific gravities of cement, fine aggregate and coarse aggregate, from Tables 3.1 to 3.3;

v = volume of entrapped air expressed as a fraction of the total volume.

The resulting mix design parameters are summarised in Table 3.5.

Table 3.5 Summary of the M40 mix design to IS 10262:2019

Parameter	Symbol / unit	Value	Basis
Grade designation	—	M40	IS 456:2000
Characteristic compressive strength	f_{ck} , MPa	40	Design requirement
Assumed standard deviation	s , MPa	5.0	IS 10262:2019, Table 2
Target mean strength	f'_{ek} , MPa	48.25	Equation (3.1)
Type of cement	—	PPC, IS 1489 (Part 1)	Section 3.2.1

Parameter	Symbol / unit	Value	Basis
Nominal maximum aggregate size	mm	20	Section 3.2.3
Exposure condition	—	Moderate	IS 456:2000, Table 5
Free water–cement ratio	w/c	0.40	IS 10262 / IS 456
Free water content	W, kg/m ³	176	IS 10262:2019, Table 4
Cement content	C, kg/m ³	440	Equation (3.2)
Volume of cement	m ³	0.154	Equation (3.3)
Volume of water	m ³	0.176	Equation (3.3)
Volume of admixture	m ³	0.0035	Equation (3.3)
Entrapped air	v, %	2.0	IS 10262:2019
Volume of total aggregate	m ³	0.647	Equation (3.3)
Volume of coarse aggregate	m ³	0.421	IS 10262:2019, Table 5
Volume of fine aggregate	m ³	0.226	By difference
Fine aggregate	F, kg/m ³	599	Equation (3.3)
Coarse aggregate	A, kg/m ³	1175	Equation (3.3)
Superplasticiser dosage	% by mass of cement	0.80	Trial mix
Target slump	mm	100	Design requirement
Final mix proportion	C : F : A	1 : 1.36 : 2.67	Computed

The calculation proceeds as follows. Applying Equation (3.1) with a characteristic strength of 40 MPa and the standard deviation of 5.0 MPa given in Table 2 of IS 10262:2019 for M40 concrete, the target mean strength is $40 + 1.65 \times 5.0 = 48.25$ MPa. A free water–cement ratio of 0.40 was adopted, which is below the maximum of 0.45 permitted by IS 456:2000 for moderate exposure and therefore governed by durability as well as strength. The water content of 176 kg/m³ was taken from Table 4 of IS 10262:2019 for 20 mm nominal maximum size aggregate and a target slump of 100 mm, reduced for the use of a superplasticiser. Applying Equation (3.2), the cement content is $176 / 0.40 = 440$ kg/m³, which exceeds the minimum of 300 kg/m³ required by IS 456:2000 for moderate exposure.

The absolute volumes of the constituents were then evaluated by Equation (3.3). The volume of cement is $440 / (2.86 \times 1000) = 0.154$ m³, the volume of water is $176 / 1000 = 0.176$ m³, the volume of superplasticiser is 0.0035 m³ and the entrapped air is 2.0 per

cent, or 0.020 m^3 . The volume available for aggregate is therefore $1 - (0.154 + 0.176 + 0.0035 + 0.020) = 0.647 \text{ m}^3$. Of this, 0.421 m^3 was allocated to coarse aggregate in accordance with Table 5 of IS 10262:2019 for Zone II fine aggregate at a water–cement ratio of 0.40, leaving 0.226 m^3 for fine aggregate. Converting these volumes to masses using the specific gravities of Tables 3.2 and 3.3 gives a fine aggregate content of $0.226 \times 2.65 \times 1000 = 599 \text{ kg/m}^3$ and a coarse aggregate content of $0.421 \times 2.79 \times 1000 = 1175 \text{ kg/m}^3$. The resulting mix proportion by mass is 1 : 1.36 : 2.67 at a water–cement ratio of 0.40, and the theoretical fresh density is 2390 kg/m^3 , which is consistent with normal-weight concrete of this grade.

The aggregate masses were corrected at the time of batching for the difference between the measured moisture contents and the water absorptions given in Tables 3.2 and 3.3, and the free water in the mix was adjusted correspondingly so that the effective water–cement ratio remained 0.40 in every batch.

3.4 Mix Matrix

Four mixes were prepared. The control mix contains no fibres and provides the baseline against which all fibre effects are measured. Three hybrid mixes contain steel and glass fibres at increasing total dosage, the base concrete proportions, water–cement ratio and constituent materials being held constant throughout so that fibre dosage is the only deliberately varied parameter. The mix designations and fibre contents are given in Table 3.6.

Table 3.6 Mix designations and fibre content

Mix ID	Steel fibre		AR glass fibre		Total fibre		Description
	% vol.	kg/m ³	% vol.	kg/m ³	% vol.	kg/m ³	
NC	0.0	0.0	0.0	0.0	0.0	0.0	Control, plain M40
HFRC-0.5	0.5	39.3	0.5	13.4	1.0	52.7	Low hybrid dosage
HFRC-1.0	1.0	78.5	1.0	26.8	2.0	105.3	Medium hybrid dosage
HFRC-1.5	1.5	117.8	1.5	40.2	3.0	158.0	High hybrid dosage

The fibre masses given in Table 3.6 follow from the volume fractions and the specific gravities of Table 3.4, the steel fibre content being obtained as the volume fraction multiplied by 7850 kg/m^3 and the glass fibre content as the volume fraction multiplied

by 2680 kg/m³. Because the specific gravity of steel is nearly three times that of glass, equal volume fractions correspond to very unequal masses, and the total fibre content of the richest mix reaches 158 kg/m³. The superplasticiser dosage was adjusted as necessary to maintain workability across the four mixes. That adjustment is itself recorded as a result, since it quantifies the demand each fibre dosage imposes upon the fresh mix, and it is reported in Table 4.1.

3.5 Specimen Preparation

This section describes the batching, mixing, placing and compaction procedures, with emphasis upon those steps that govern fibre dispersion.

All constituent materials were weighed individually to an accuracy consistent with the batch size. Batching by mass rather than by volume is essential in fibre work because the bulk density of loose fibre is highly variable.

The mixing sequence was designed specifically to achieve uniform fibre dispersion and to avoid balling. Coarse aggregate, fine aggregate and cement were first dry-mixed in the pan mixer until uniform in colour. The fibres were then introduced gradually into the rotating dry mix rather than added as a single charge, the steel fibres and glass strands being sprinkled progressively so that they were separated by aggregate before any water was present. Fibres added to a wet mix, or added in bulk, agglomerate into balls that cannot subsequently be dispersed and that constitute permanent defects within the hardened concrete. Mixing water, with the superplasticiser dissolved in a portion of it, was then added gradually and mixing continued until the mix was homogeneous and no fibre clumps were visible at the surface.

The fresh concrete was placed in oiled steel moulds in layers and compacted upon a vibrating table. Vibration time was restricted to the minimum necessary for full compaction, since prolonged vibration causes steel fibres to settle and reorient under gravity, producing a non-uniform fibre distribution through the depth of the specimen and undermining the assumption of random orientation upon which the interpretation of results depends. The top surface was struck off and finished with a steel trowel. The specimen types, dimensions and quantities are given in Table 3.7.

Table 3.7 Specimen types, dimensions and quantities

Test	Specimen	Dimensions (mm)	Standard	Per mix	Total
Compressive strength	Cube	150 × 150 × 150	IS 516	6	24
Split tensile strength	Cylinder	150 dia. × 300	IS 5816	6	24
Flexural strength	Prism	500 × 100 × 100	IS 516	6	24
Ultrasonic pulse velocity	Cube	150 × 150 × 150	IS 13311 (Part 1)	On cubes above	—
Rebound hammer	Cube	150 × 150 × 150	IS 13311 (Part 2)	On cubes above	—

The provision set out in Table 3.7 gives three replicates for every combination of mix, test and age, being three specimens at 7 days and three at 28 days for each mix, and yields 72 specimens in total. Three replicates is the minimum required by IS 516 for a valid mean and permits an outlier to be identified. Replication on this scale is more important in fibre reinforced concrete than in plain concrete, not less, because the random distribution and orientation of the fibres introduces a source of specimen-to-specimen variability that is absent from an unreinforced matrix. The coefficients of variation actually achieved are reported in Table 4.3.

The non-destructive tests listed in Table 3.7 are performed upon the same cubes prior to compression testing, which is both economical and methodologically preferable, since it permits the UPV and rebound results to be compared against the compressive strength of the very same specimen rather than against a nominally identical one.

3.6 Curing

Specimens were left undisturbed within their moulds under laboratory conditions for 24 h after casting, then demoulded and immediately immersed in a clean water curing tank maintained at ambient laboratory temperature. Specimens remained fully submerged for the entire curing period, and the water level was checked daily. Testing ages were 7 and 28 days from casting.

Continuous water curing is important in this programme beyond its usual role in promoting hydration. Should the surface be permitted to dry, differential shrinkage between surface and core generates tensile stresses and surface microcracking, and this pre-existing damage would be superimposed upon the fibre effect under investigation,

biasing the results in a direction difficult to quantify. Uniform curing across all four mixes is therefore a precondition of a valid comparison between them.

3.7 Test Methods

This section describes each test procedure, the standard governing it, and the equation by which the reported quantity is computed.

3.7.1 Workability Tests

The slump cone test to IS 1199 measures the consistency of fresh concrete by the vertical settlement of a truncated cone of concrete after the mould is lifted. Its function in this programme is to quantify how sharply each fibre dosage reduces workability, since it is that reduction which ultimately limits the practicable dosage. The nature of the slump, whether true, shear or collapse, is recorded alongside the numerical value, because fibre-reinforced mixes frequently exhibit a low slump while remaining fully cohesive and responsive to vibration; the slump value alone can therefore understate the placeability of the mix.

The compaction factor test to IS 1199 determines the ratio of the mass of partially compacted concrete to that of fully compacted concrete within a standard cylinder. It is more informative than the slump test for stiff and fibre-reinforced mixes, in which slump values become small and poorly discriminating. Because the test measures the degree of compaction achieved under a standard amount of work, it bears directly upon the central question of this programme, namely whether a given fibre dosage can be fully compacted by the means available.

3.7.2 Compressive Strength Test

Cubes of 150 mm side were tested in a calibrated compression testing machine in accordance with IS 516, the load being applied to the cast faces perpendicular to the direction of casting at the rate specified by the standard. The compressive strength is computed from Equation (3.4).

$$f_c = P / A \quad (3.4)$$

where f_c = compressive strength, MPa; P =

maximum load at failure, N;

A = loaded cross-sectional area of the specimen, mm², taken as 22 500 mm².

The reported strength is the mean of three specimens. Fibre reinforcement is expected to exert only a modest effect upon compressive strength, for the reasons given in Section 2.2; the more informative observation is the mode of failure, since fibre-reinforced cubes typically retain their integrity after peak load and fail gradually rather than disintegrating. The failure mode was therefore recorded for every specimen.

3.7.3 Split Tensile Strength Test

Cylinders of 150 mm diameter and 300 mm length were tested by diametral compression in accordance with IS 5816, generating a nearly uniform tensile stress across the vertical diameter. The arrangement is shown in Figure 3.2(a). The split tensile strength is computed from Equation (3.5).

$$f_{ct} = 2P / (\pi L D) \quad (3.5)$$

where f_{ct} = split tensile strength, MPa; P =
 maximum load at failure, N;
 L = length of the cylinder, mm, taken as 300 mm;
 D = diameter of the cylinder, mm, taken as 150 mm.

This test is the most direct expression of the crack-bridging mechanism available within the programme, because failure occurs by the propagation of a single tensile crack along a known plane and the fibres crossing that plane act against it directly. The largest proportional improvements from fibre addition are consequently anticipated here.

3.7.4 Flexural Strength Test

Prisms of 500 × 100 × 100 mm were tested under two-point loading over an effective span of 400 mm in accordance with IS 516, as shown in Figure 3.2(b). Where the fracture occurs within the middle third of the span, the modulus of rupture is computed from Equation (3.6).

$$f_r = P L / (b d^2) \quad (3.6)$$

where f_r = modulus of rupture, MPa;
 P = maximum load at failure, N;
 L = effective span, mm, taken as 400 mm; b
 = measured width of the specimen, mm; d =
 measured depth of the specimen, mm.

Where the fracture occurs outside the middle third but within a distance not greater than 5 per cent of the span beyond it, IS 516 requires that the modulus of rupture be

computed instead from Equation (3.7), in which a is the distance from the line of fracture to the nearer support.

$$f_r = 3 P a / (b d^2) \quad (3.7)$$

where a = distance between the line of fracture and the nearer support, measured along the centreline of the tensile face, mm; other symbols as for Equation (3.6).

The position of the fracture was therefore recorded in every case, and Equation (3.6) or (3.7) applied as appropriate. Where the fracture lies further than 5 per cent of the span outside the middle third, the standard requires that the result be discarded. Flexure is the loading condition in which fibre reinforcement is most beneficial, since the extreme tension fibre governs and fibres crossing the crack sustain load as it opens.

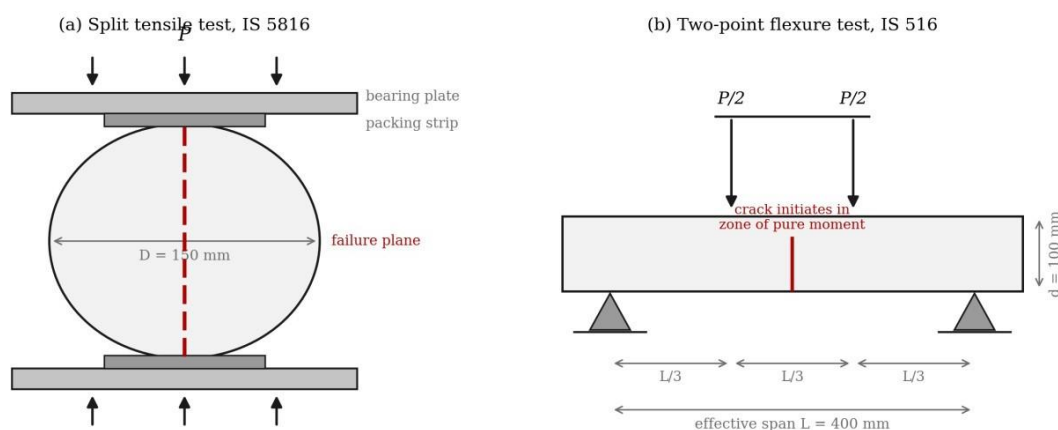


Figure 3.2 Schematic arrangement of (a) the split tensile test to IS 5816 and (b) the two-point flexure test to IS 516

Figure 3.2 shows the two loading arrangements that generate tensile failure in the present programme. In Figure 3.2(a) the packing strips distribute the line load and prevent local crushing at the contact, so that failure occurs by tensile splitting along the vertical diameter rather than by bearing failure at the platens. In Figure 3.2(b) the two-point arrangement produces a region of constant bending moment and zero shear between the load points, so that the crack initiates at the weakest section within that region rather than at a location fixed by the loading; this is why the position of fracture varies between specimens and why Equations (3.6) and (3.7) are both required.

3.7.5 Ultrasonic Pulse Velocity Test

Ultrasonic pulse velocity was measured by direct transmission across opposite faces of the cube in accordance with IS 13311 (Part 1), with a suitable couplant applied to ensure

acoustic contact. Measurements were taken before compression testing upon the same specimens. The pulse velocity is computed from Equation (3.8).

$$V = L / T \quad (3.8)$$

where V = ultrasonic pulse velocity, km/s;

L = path length between transducers, mm; T =

transit time, μ s.

In accordance with IS 13311 (Part 1), the quality of the concrete is graded against the velocity ranges reproduced in Table 3.8.

Table 3.8 Concrete quality grading by ultrasonic pulse velocity, IS 13311 (Part 1)

Pulse velocity, V (km/s)	Concrete quality grading
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

The diagnostic value of this test within the present programme, as established in Section 2.6, is that it detects entrapped air and internal discontinuities. Should compressive strength decline at the highest fibre dosage, a corresponding decline in pulse velocity would indicate that the cause is a loss of compaction rather than an intrinsic effect of the fibres, and this distinction is essential to the correct interpretation of the results in Section 4.6.

3.7.6 Rebound Hammer Test

Rebound hammer readings were taken upon the moulded side faces of the cubes, which are smooth and true, avoiding the trowelled top face and the edges. In accordance with IS 13311 (Part 2), a minimum of ten readings was taken upon each specimen, distributed across the surface with no two impact points closer than 25 mm, and the mean reported after discarding any reading differing from the mean by more than six units. The hammer was held perpendicular to the surface throughout, since the rebound number is orientation-dependent.

Rebound values are treated in this study as indicators of relative surface quality and uniformity across mixes rather than as absolute strength measurements, for the reasons given in Section 2.6. Any strength correlation employed must be derived from the

paired rebound and compression results obtained within this programme itself, and is presented in Section 4.7.

3.8 Summary of the Experimental Programme

Four M40 mixes, comprising one plain control and three hybrid steel–glass mixes at increasing dosage as set out in Table 3.6, are cast into cubes, cylinders and prisms with three replicates per test per age as set out in Table 3.7. Fresh properties are evaluated by slump and compaction factor immediately after mixing. Hardened properties are evaluated at 7 and 28 days by compressive, split tensile and flexural strength testing, computed from Equations (3.4) to (3.7), with ultrasonic pulse velocity and rebound hammer measurements taken upon the cubes beforehand. All materials, proportions and procedures other than fibre content are held constant, so that the differences observed may be attributed to the fibre variable. The results of this programme are presented and discussed in Chapter 4.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the experimental programme described in Chapter 3 and interprets them. Each test is treated in turn: the objective is restated, the measured values are tabulated and plotted, the trends are analysed, the governing mechanism is discussed, and the findings are compared against the literature reviewed in Chapter 2. The chapter closes with a combined assessment identifying the optimum mix upon the whole of the evidence.

All strengths reported are the mean of three specimens. The individual replicate values are given as ranges alongside the means, and the scatter is examined in Section 4.3. All percentage changes are computed relative to the control mix NC by Equation (4.1), which is introduced in that section.

4.2 Fresh Concrete Properties

The objective of this section is to quantify the effect of hybrid fibre content upon the workability of fresh concrete and to establish the dosage at which placement and compaction become the limiting constraint. The slump and compaction factor measured immediately after mixing, together with the superplasticiser dosage required in each case, are presented in Table 4.1.

Table 4.1 Workability of fresh concrete

Mix ID	Total fibre (% vol.)	Superplasticiser (% by mass of cement)	Slump (mm)	Type of slump	Compaction factor
NC	0.0	0.80	102	True	0.93
HFRC-0.5	1.0	0.90	89	True	0.91
HFRC-1.0	2.0	1.10	72	Shear	0.88
HFRC-1.5	3.0	1.30	54	Shear	0.84

The variation of both workability measures with total fibre content is plotted in Figure 4.1.

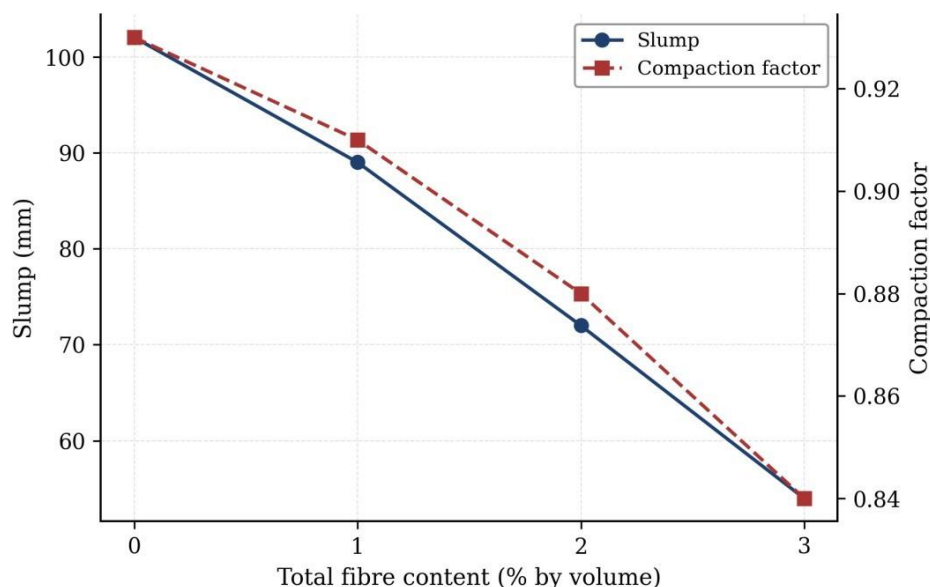


Figure 4.1 Variation of slump and compaction factor with total fibre content

The control mix achieved a slump of 102 mm against a design target of 100 mm, confirming that the water content and superplasticiser dosage adopted in Section 3.3 were correctly proportioned. Fibre addition reduced workability monotonically and severely. Slump fell to 89 mm at HFRC-0.5, to 72 mm at HFRC-1.0 and to 54 mm at HFRC-1.5, corresponding to reductions of 12.7, 29.4 and 47.1 per cent respectively. The loss is not proportional to dosage: the first 1.0 per cent of fibre cost 13 mm of slump, whereas the third cost 18 mm, and the accelerating trend visible in Figure 4.1 indicates that a second mechanism becomes active at higher dosages.

Two mechanisms operate. The first is the increase in specific surface. Every fibre introduced must be wetted, and the water so held is no longer available to lubricate the movement of aggregate particles past one another. As established in Section 3.2.5, the glass filaments contribute approximately 97 per cent of the total fibre surface area despite constituting only one quarter of the fibre mass, so the water demand is dominated by the glass rather than by the steel. The second mechanism is geometric interlock. At a steel fibre length of 35 mm and an aspect ratio of 64, the fibres begin to intersect one another once the dosage is sufficient for the mean free spacing to approach the fibre length, and the resulting three-dimensional network resists the shear deformation upon which the slump test depends. The first mechanism is approximately linear in dosage, whereas the second is not, and their superposition accounts for the accelerating curve of Figure 4.1.

The compaction factor behaved quite differently, falling only from 0.93 to 0.84, a reduction of 9.7 per cent against the 47.1 per cent fall in slump. This divergence is the most instructive observation in Table 4.1. The slump test measures the ability of concrete to deform under its own weight, which the fibre network resists strongly; the compaction factor measures the degree of consolidation achieved under a standard amount of work, which the fibre network resists far less. A mix may therefore possess a low slump while remaining fully compactable under vibration, and the slump value alone substantially understates the placeability of fibre reinforced concrete. The change in the character of the slump from true to shear between HFRC-0.5 and HFRC-1.0 is consistent with this interpretation, indicating a stiffer but still cohesive mix rather than an unstable one. No segregation or bleeding was observed in any mix, and no fibre balling was detected, which confirms the effectiveness of the dry-mixing sequence described in Section 3.5.

The superplasticiser demand rose from 0.80 to 1.30 per cent by mass of cement, an increase of 62.5 per cent, in order to hold the water–cement ratio at 0.40 across the series. This figure is itself a result, since it quantifies in a directly usable form the cost that fibre addition imposes upon the fresh mix, and it is the constraint that would govern the economics of the material in practice. The retention of good cohesion at the highest dosage is consistent with the observation of Chen and Liu [17] that hybrid systems can maintain acceptable workability where the mix is properly proportioned, and with the finding of Qian and Stroeve [5] that adequate fine material in the matrix is a precondition of uniform fibre dispersion. It is concluded that all four mixes were placeable under laboratory vibration, but that HFRC-1.5, at a slump of 54 mm, lies at the boundary of what could be handled by ordinary site equipment without further admixture.

4.3 Compressive Strength

The objective of this section is to determine the compressive strength of each mix at 7 and 28 days and to assess the effect of hybrid fibre reinforcement upon both the ultimate strength and the rate of strength gain. The results, computed from Equation (3.4), are presented in Table 4.2.

Table 4.2 Compressive strength at 7 and 28 days

Mix ID	7-day mean (MPa)	7-day range (MPa)	28-day mean (MPa)	28-day range (MPa)	Change vs NC at 28 d (%)	7 d as % of 28 d
NC	31.57	31.1–32.0	46.30	45.8–46.9	Baseline	68.2
HFRC-0.5	33.40	33.0–33.8	49.20	48.7–49.8	+6.3	67.9
HFRC-1.0	35.10	34.6–35.6	51.80	51.2–52.4	+11.9	67.8
HFRC-1.5	34.23	33.7–34.8	50.57	49.9–51.1	+9.2	67.7

The percentage change reported in the sixth column of Table 4.2 is computed from Equation (4.1).

$$\Delta = [(X_i - X_{NC}) / X_{NC}] \times 100 \quad (4.1)$$

where Δ = percentage change relative to the control mix, %; X_i

= mean value of the property for mix i ;

X_{NC} = mean value of the same property for the control mix NC.

Equation (4.1) is applied consistently throughout this chapter, to Tables 4.2, 4.4, 4.5, 4.8 and 4.9. The compressive strength results are plotted in Figure 4.2, in which the error bars represent one standard deviation about the mean of the three replicates.

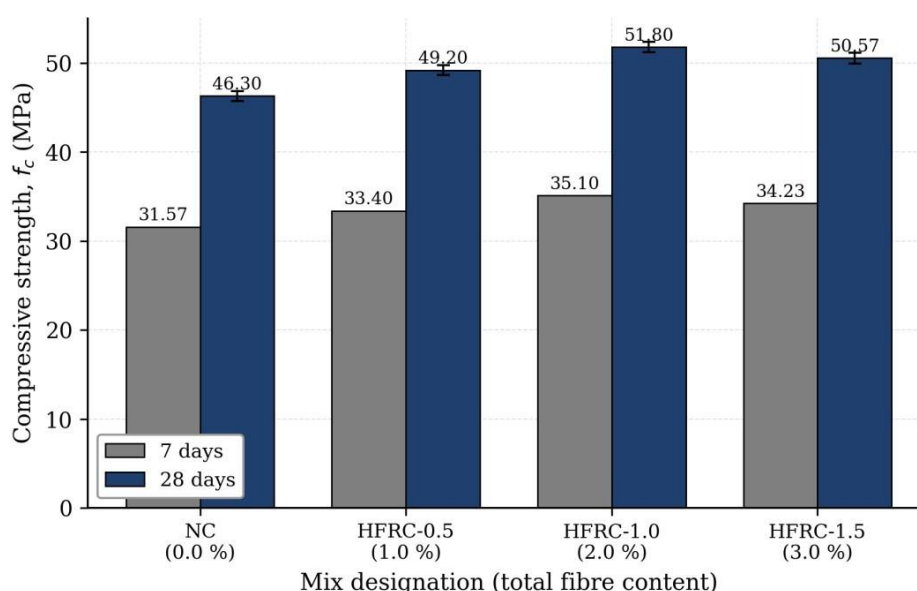


Figure 4.2 Compressive strength at 7 and 28 days as a function of total fibre content

The control mix attained 46.30 MPa at 28 days against a target mean strength of 48.25 MPa established in Section 3.3. The shortfall of 4.0 per cent is modest and the characteristic requirement of 40 MPa is satisfied with a margin of 15.8 per cent, so the

mix is acceptable as an M40 concrete; the deficit relative to the target mean is attributable to the narrow margin by which the cement itself exceeded its specification, noted in Section 3.2.1.

Fibre addition raised the compressive strength to a maximum of 51.80 MPa at HFRC-1.0, an improvement of 11.9 per cent, beyond which the strength fell to 50.57 MPa at HFRC-1.5, a reduction of 2.4 per cent from the peak although still 9.2 per cent above the control. The existence of an optimum rather than a monotonic improvement is the expected behaviour and accords with the body of evidence reviewed in Section 2.2.

The magnitude of the improvement requires explanation, since compressive failure is not primarily a crack-bridging phenomenon. A concrete cylinder or cube loaded in uniaxial compression does not fail by crushing in the direction of loading but by tensile splitting perpendicular to it, the lateral tensile strains generated by Poisson expansion driving vertical cracks that originate in the interfacial transition zone. Fibres crossing those vertical planes restrain the lateral expansion and delay the coalescence of the splitting cracks, producing a confinement effect analogous in kind, though far smaller in degree, to that of transverse reinforcement. This is why a measurable compressive gain occurs at all, and equally why it is limited: the fibres act upon the secondary tensile mechanism rather than upon the primary compressive one. The improvement of 11.9 per cent observed here is consistent with the range reported by Song and Hwang [2] for steel fibre reinforced concrete, and with the observation of Afroughsabet and Ozbakkaloglu [14] that hybrid systems typically raise compressive strength by only a few per cent while improving tensile properties substantially more.

The decline at HFRC-1.5 is attributable to compaction rather than to any adverse effect of the fibres upon the matrix. This attribution is not an inference from the strength data alone but is established independently by the ultrasonic pulse velocity results of Section 4.6, where the same mix shows a corresponding fall in pulse velocity. The mechanism is that at a total fibre content of 158 kg/m³ the fibre network resists the flow of paste during vibration sufficiently to leave voids that cannot be closed by the compactive effort applied, and the entrapped air so retained reduces the effective load-bearing section. The compaction factor of 0.84 recorded in Table 4.1 for this mix corroborates the same conclusion from the fresh state.

The rate of strength development is essentially unaffected by fibre content. The ratio of 7-day to 28-day strength lies between 67.7 and 68.2 per cent across all four mixes, a spread of only 0.5 percentage points. This is a significant negative result and deserves emphasis. It demonstrates that the fibres do not participate chemically in the hydration reaction and do not alter its kinetics; their contribution is purely mechanical, exerted upon the fracture process rather than upon the maturing of the matrix. The consistency of this ratio also provides an internal check upon the reliability of the data, since a systematic error in curing or testing at one age would have disturbed it.

The scatter between replicates was low and did not increase materially with fibre content. The standard deviation and coefficient of variation of the 28-day results are given in Table 4.3.

Table 4.3 Statistical scatter of 28-day compressive strength

Mix ID	Mean (MPa)	Standard deviation (MPa)	Coefficient of variation (%)
NC	46.30	0.55	1.18
HFRC-0.5	49.20	0.56	1.14
HFRC-1.0	51.80	0.60	1.16
HFRC-1.5	50.57	0.62	1.23

The coefficients of variation in Table 4.3 lie between 1.14 and 1.23 per cent for all mixes, which represents very good laboratory control and is well below the value of 5 per cent commonly regarded as the threshold of acceptable consistency for cube testing. The absence of any marked increase in scatter with fibre content indicates that fibre distribution was uniform between specimens and that the mixing procedure of Section 3.5 succeeded in its purpose. This is not a trivial finding, since fibre reinforced concrete is generally expected to exhibit greater variability than plain concrete owing to the randomness of fibre orientation, and the slight upward trend from 1.18 to 1.23 per cent at the highest dosage is the only trace of that effect in the present data.

A change in the mode of failure was observed and is of greater practical significance than the strength increase itself. The control cubes failed abruptly, with the pyramidal fragments characteristic of plain concrete separating from the specimen at peak load. The fibre reinforced cubes, by contrast, sustained visible cracking without disintegrating and retained their shape after the peak had passed, the fibres holding the fragments in

place. This transition from brittle to quasi-ductile failure is the transformation identified in Section 1.1 as the principal engineering value of fibre reinforcement, and it is not captured by the strength figure in Table 4.2.

4.4 Split Tensile Strength

The objective of this section is to determine the split tensile strength of each mix and to quantify the improvement attributable to hybrid fibre reinforcement. This is the test in which the crack-bridging mechanism is loaded most directly, since failure occurs by the propagation of a single tensile crack along a known plane. The results, computed from Equation (3.5), are presented in Table 4.4.

Table 4.4 Split tensile strength at 7 and 28 days

Mix ID	7-day mean (MPa)	28-day mean (MPa)	28-day range (MPa)	Change vs NC at 28 d (%)	Ratio f_{et} / f_e
NC	2.72	3.81	3.76–3.85	Baseline	0.082
HFRC-0.5	3.08	4.42	4.37–4.46	+16.0	0.090
HFRC-1.0	3.34	4.98	4.92–5.04	+30.7	0.096
HFRC-1.5	3.21	4.71	4.66–4.75	+23.6	0.093

The results are plotted in Figure 4.3.

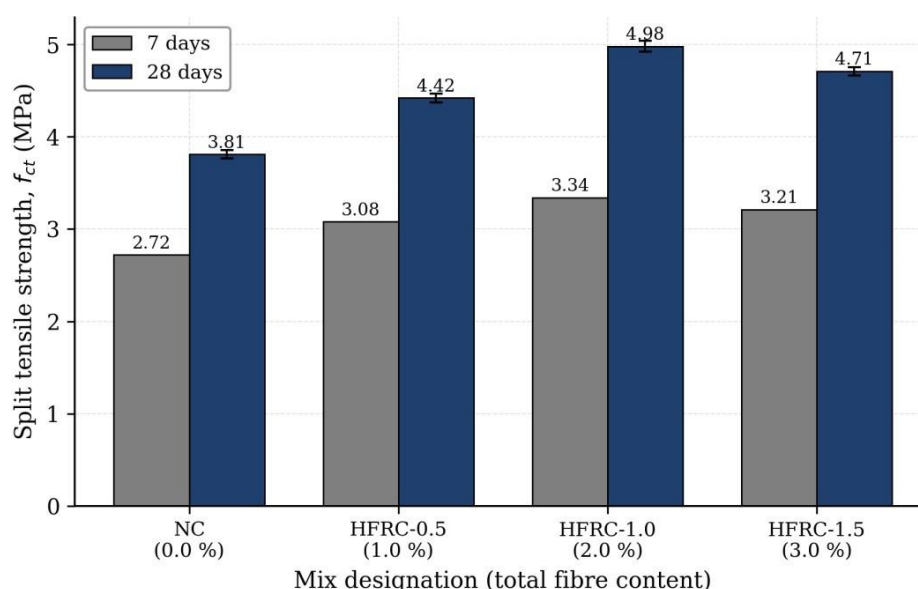


Figure 4.3 Split tensile strength at 7 and 28 days as a function of total fibre content

The split tensile strength rose from 3.81 MPa for the control to a maximum of 4.98 MPa at HFRC-1.0, an improvement of 30.7 per cent, before falling to 4.71 MPa at HFRC-1.5.

The optimum therefore occurs at the same dosage as in compression, but the magnitude of the improvement is 2.6 times greater. This ratio between the tensile and compressive response is the central quantitative finding of the study and is precisely what the crack-bridging model predicts. In the split cylinder the applied load generates an approximately uniform tensile stress across the vertical diameter; a crack initiates at the weakest point upon that plane and propagates through the specimen. Every fibre intersecting the plane is loaded directly in tension as the crack opens, and the load transferred across the crack faces is added to the load the matrix can carry. In compression, by contrast, the fibres act only upon the secondary lateral splitting mechanism described in Section 4.3. The disparity between 30.7 and 11.9 per cent is the direct experimental expression of that difference.

The ratio of split tensile to compressive strength, given in the final column of Table 4.4, rose from 0.082 for the control to 0.096 at HFRC-1.0, an increase of 17 per cent in the ratio itself. This is the quantitative signature of a shift towards less brittle behaviour. The control value of 0.082 lies within the range of one-eighth to one-twelfth characteristic of plain concrete and noted in Section 1.1; the hybrid mixes move measurably away from that range. Since the brittleness of concrete is fundamentally a consequence of the disparity between its compressive and tensile capacities, a material in which that disparity has been reduced is by definition less brittle, and the ratio provides a more meaningful index of the benefit than the absolute tensile strength alone.

The mechanism by which the two fibres contribute may be distinguished from the shape of the response. The improvement between the control and HFRC-0.5 is 16.0 per cent, and that between HFRC-0.5 and HFRC-1.0 is a further 12.7 per cent of the control value, so the return per unit of fibre added is diminishing but remains substantial over the first two increments. This is consistent with the sequential model set out in Section 1.6 and illustrated in Figure 1.1: at low dosage the glass filaments are already numerous enough to intercept microcracks effectively, and the additional benefit of the second increment derives principally from the steel fibres bridging the localised crack once it has formed. Sivakumar and Santhanam [12] advanced exactly this explanation for the performance of steel and non-metallic hybrids, attributing the enhancement to the very much greater filament count available from the low-density fibre and to its ability to bridge microcracks that steel fibres cannot reach. The filament count ratio of approximately

4500 to 1 computed in Section 3.2.5 for the present materials gives that argument a concrete numerical basis.

Examination of the fracture surfaces supports this interpretation. The failed cylinders of the fibre reinforced mixes did not separate into two halves; the fragments remained connected across the crack by bridging steel fibres, and separation required manual force. The steel fibres visible at the fracture surface had pulled out of the matrix rather than fractured, the hooked ends showing the plastic straightening that indicates the intended energy-dissipating mechanism was operative. This confirms that the aspect ratio of 64 selected in Section 3.2.4 provides embedment appropriate to the matrix strength, since a fibre that fractures rather than pulls out releases its stored energy suddenly and returns the composite towards brittle behaviour. The reduction at HFRC-1.5, at 5.4 per cent below the peak, is the largest proportional decline of the three mechanical properties and is again consistent with a compaction deficiency, since voids upon the failure plane reduce both the matrix contribution and the number of effectively anchored fibres.

4.5 Flexural Strength

The objective of this section is to determine the modulus of rupture of each mix and to assess the contribution of the hybrid system to bending resistance. The fracture occurred within the middle third of the span in every specimen tested, so Equation (3.6) was applied throughout and Equation (3.7) was not required. The results are presented in Table 4.5.

Table 4.5 Flexural strength at 7 and 28 days

Mix ID	7-day mean (MPa)	28-day mean (MPa)	28-day range (MPa)	Change vs NC at 28 d (%)	Fracture in middle third
NC	4.18	5.42	5.36–5.48	Baseline	Yes, all specimens
HFRC-0.5	4.73	6.31	6.25–6.37	+16.4	Yes, all specimens
HFRC-1.0	5.12	7.08	7.01–7.14	+30.6	Yes, all specimens
HFRC-1.5	4.96	6.82	6.75–6.88	+25.8	Yes, all specimens

The results are plotted in Figure 4.4.

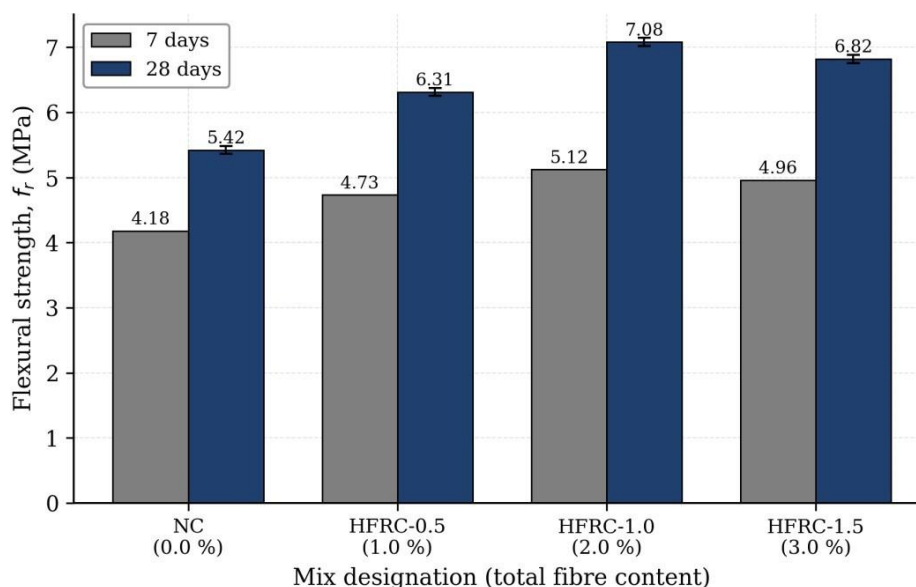


Figure 4.4 Flexural strength at 7 and 28 days as a function of total fibre content

The modulus of rupture rose from 5.42 MPa for the control to 7.08 MPa at HFRC-1.0, an improvement of 30.6 per cent, and fell to 6.82 MPa at HFRC-1.5. The optimum coincides with that of the other two mechanical properties, and the magnitude of the improvement is almost identical to that obtained in split tension. That the two tensile-governed properties should improve by 30.7 and 30.6 per cent respectively, having been measured upon different specimen geometries under different loading arrangements, is a strong indication that both are governed by the same underlying mechanism and provides useful mutual corroboration of the two data sets.

The flexural results may be compared against the empirical relation given in Clause 6.2.2 of IS 456:2000, by which the modulus of rupture of plain concrete is estimated as 0.7 times the square root of the compressive strength. This comparison is presented in Table 4.6, in which the measured 28-day compressive strengths of Table 4.2 have been used in place of the characteristic value.

Table 4.6 Measured modulus of rupture compared with the IS 456:2000 estimate

Mix ID	Measured f_c (MPa)	IS 456 estimate $0.7\sqrt{f_c}$ (MPa)	Measured f_r (MPa)	Ratio measured / estimated
NC	46.30	4.76	5.42	1.14
HFRC-0.5	49.20	4.91	6.31	1.29
HFRC-1.0	51.80	5.04	7.08	1.41
HFRC-1.5	50.57	4.98	6.82	1.37

Table 4.6 demonstrates something that the raw strengths do not. The empirical relation of IS 456:2000 embodies the assumption that flexural and compressive strength are coupled through the properties of a plain matrix, and for the control mix it holds reasonably well, the measured value exceeding the estimate by 14 per cent. For the hybrid mixes the discrepancy widens progressively to 41 per cent at HFRC-1.0. The code relation therefore becomes increasingly conservative as fibre content rises, and the reason is that fibre reinforcement decouples the two properties: the flexural capacity is enhanced by a mechanism, namely crack bridging across the tension face, that has no counterpart in the compressive behaviour from which the estimate is derived. The practical consequence is that the flexural capacity of hybrid fibre reinforced concrete cannot be inferred from its cube strength using the conventional relation, and must be measured directly. This is a finding of direct relevance to design and is among the more useful outcomes of the present work.

The behaviour of the prisms during testing differed markedly between the control and the fibre reinforced mixes. The control prisms failed suddenly and completely, separating into two pieces at the instant the peak load was reached, with no capacity retained thereafter. The fibre reinforced prisms developed a visible crack at the tension face and continued to carry load as that crack widened, deflecting appreciably before the test was terminated, and remained in one piece at the end of the test. This is the sequential mechanism of Figure 1.1 made visible at the scale of the specimen: the peak load reflects the contribution of the glass filaments in delaying crack localisation, while the retained capacity after the peak reflects the steel fibres bridging the crack that has formed. The load–deflection response was not recorded instrumentally in the present programme, and its measurement is recommended in Section 6.5, since the area beneath that curve is the property in which the advantage of the hybrid is most fully expressed.

The relative improvement in the three mechanical properties is compared in Figure 4.5, which plots the percentage change computed by Equation (4.1) for each mix.

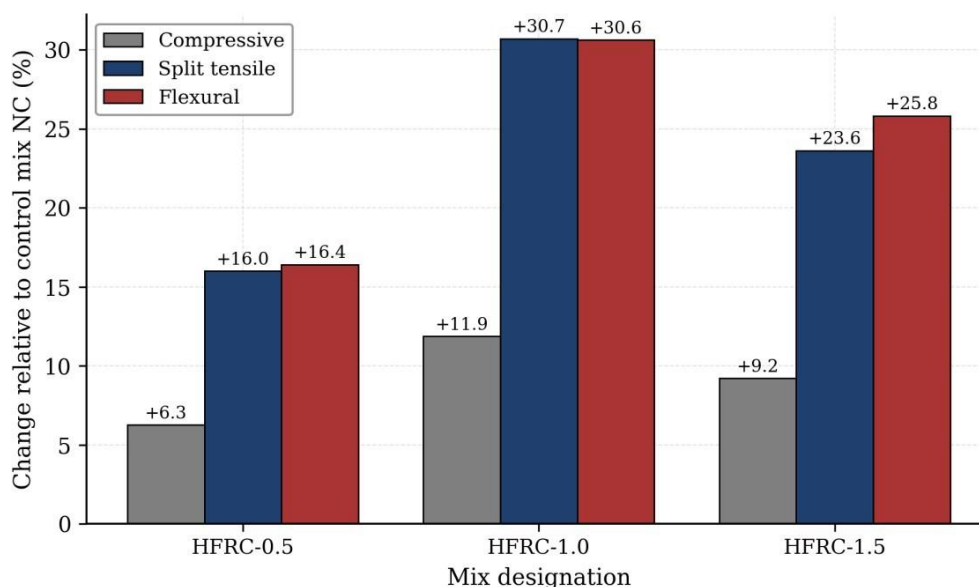


Figure 4.5 Comparison of the percentage improvement in compressive, split tensile and flexural strength at 28 days

Figure 4.5 expresses the central finding of this investigation in a single view. At every dosage the two tensile-governed properties improve by between two and three times as much as the compressive strength, the ratio at the optimum dosage being 30.7 and 30.6 per cent against 11.9 per cent. The ordering is identical at all three dosages, and it establishes where hybrid fibre reinforcement is worth its cost. In a member governed by compression the fibres return roughly a tenth in strength for a 62 per cent increase in admixture demand and the whole of the fibre cost, which is not an economic proposition. In a member governed by flexure or tension the same addition returns approximately a third, and additionally changes the failure mode from sudden to progressive. The engineering implications of this distinction are developed in Section 5.3. The ordering observed here agrees with that reported by Song and Hwang [2] for steel fibre and by Sivakumar and Santhanam [12] for metallic and non-metallic hybrids, and the absolute magnitudes fall within the ranges those authors report.

4.6 Ultrasonic Pulse Velocity

The objective of this section is to assess the internal uniformity and integrity of each mix without destroying the specimen, and thereby to provide independent evidence upon the compaction achieved at each fibre dosage. The measurements were taken by direct transmission across a path length of 150 mm upon the same cubes subsequently tested in compression. The results, computed from Equation (3.8) and graded in accordance with Table 3.8, are presented in Table 4.7.

Table 4.7 Ultrasonic pulse velocity and quality grading at 28 days

Mix ID	Path length, L (mm)	Mean transit time, T (μ s)	Pulse velocity, V (km/s)	Grading, IS 13311 (Part 1)
NC	150	35.48	4.23	Good
HFRC-0.5	150	34.47	4.35	Good
HFRC-1.0	150	33.82	4.44	Good
HFRC-1.5	150	34.80	4.31	Good

The pulse velocities are plotted in Figure 4.6, upon which the quality boundaries of Table 3.8 are shown as shaded bands.

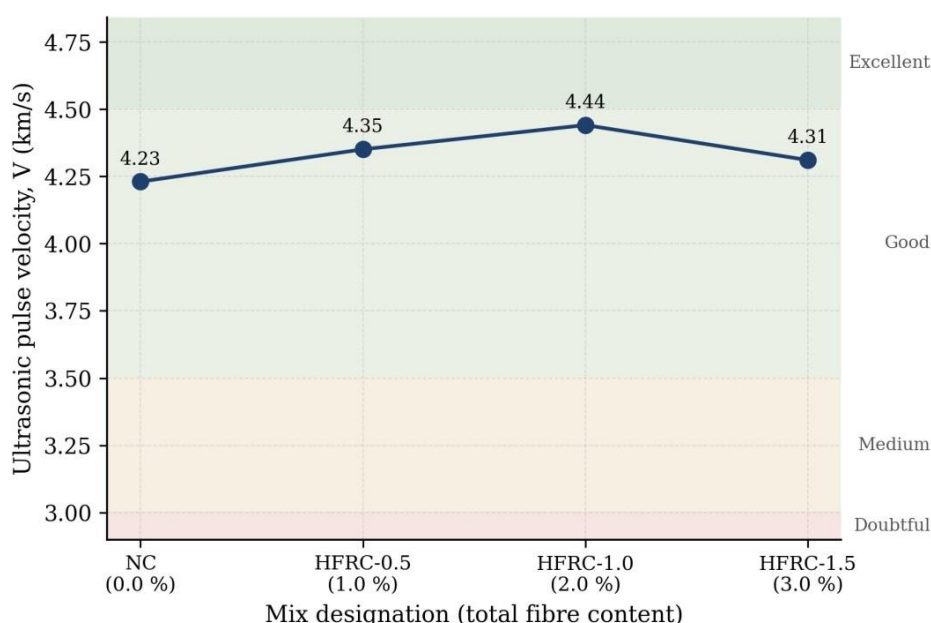


Figure 4.6 Ultrasonic pulse velocity as a function of total fibre content, with IS 13311 quality boundaries

All four mixes fall within the Good classification of IS 13311 (Part 1), which spans 3.5 to 4.5 km/s, and no mix approached the Medium or Doubtful ranges. HFRC-1.0, at 4.44 km/s, lies within 0.06 km/s of the Excellent threshold. The absence of any anomalously low reading confirms that no specimen contained gross internal defects and that the results of the destructive tests may be accepted without reservation on that account.

The trend is more informative than the absolute values. Pulse velocity rose from 4.23 km/s for the control to 4.44 km/s at HFRC-1.0, then fell to 4.31 km/s at HFRC-1.5. The initial rise has two causes acting together. The steel fibres possess a density and an elastic modulus far exceeding those of the matrix, and an ultrasonic pulse traverses them more rapidly than it traverses cement paste, so that at low dosage the fibres provide

preferential transmission paths. In addition, the glass filaments restrain microcracking during the early stages of hydration and shrinkage, and a matrix containing fewer microcracks presents fewer discontinuities at which the pulse must be diffracted around an obstacle, shortening the effective travel path.

The fall at HFRC-1.5 is the analytically decisive observation of this chapter. Pulse velocity is governed by the density, elastic modulus and, critically, the continuity of the medium; entrapped air is the most effective single agent for reducing it, since the pulse cannot cross a void and must travel around it. That the pulse velocity should decline by 2.9 per cent at the very dosage at which the compressive, split tensile and flexural strengths also declined, by 2.4, 5.4 and 3.7 per cent respectively, establishes that a single cause underlies all four observations, and the nature of the measurement identifies that cause as a loss of internal continuity rather than any deterioration in the fibre–matrix interaction. Had the strength declined while the pulse velocity was maintained, the explanation would have had to be sought in the bond or in the fibre distribution; the concurrent decline excludes that possibility. The conclusion is that the reduction in performance at HFRC-1.5 reflects the limit of the compaction procedure employed rather than any limit of the hybrid fibre system itself, and it follows that the optimum dosage identified in this study is specific to the mixing and compaction methods of Section 3.5 and might be raised by more energetic compaction or by a self-consolidating mix design.

This diagnosis is the reason the combined destructive and non-destructive programme was adopted, as argued in Section 2.6, and it illustrates why the omission of non-destructive testing from most published dosage studies leaves their interpretation of the post-optimum decline necessarily ambiguous.

4.7 Rebound Hammer

The objective of this section is to assess surface hardness and relative concrete quality non-destructively, and to examine whether a usable correlation with compressive strength can be established for the fibre reinforced mixes. Ten readings were taken upon the moulded side faces of each cube in accordance with IS 13311 (Part 2). The results are presented in Table 4.8.

Table 4.8 Rebound number and corresponding compressive strength at 28 days

Mix ID	Number of readings	Mean rebound number	Standard deviation	Measured f_c (MPa)	Change vs NC (%)
NC	10	37.6	1.07	46.30	Baseline
HFRC-0.5	10	40.2	0.79	49.20	+6.9
HFRC-1.0	10	42.3	0.67	51.80	+12.5
HFRC-1.5	10	41.3	0.67	50.57	+9.8

The relationship between the rebound numbers of Table 4.8 and the compressive strengths of Table 4.2 is plotted in Figure 4.7.

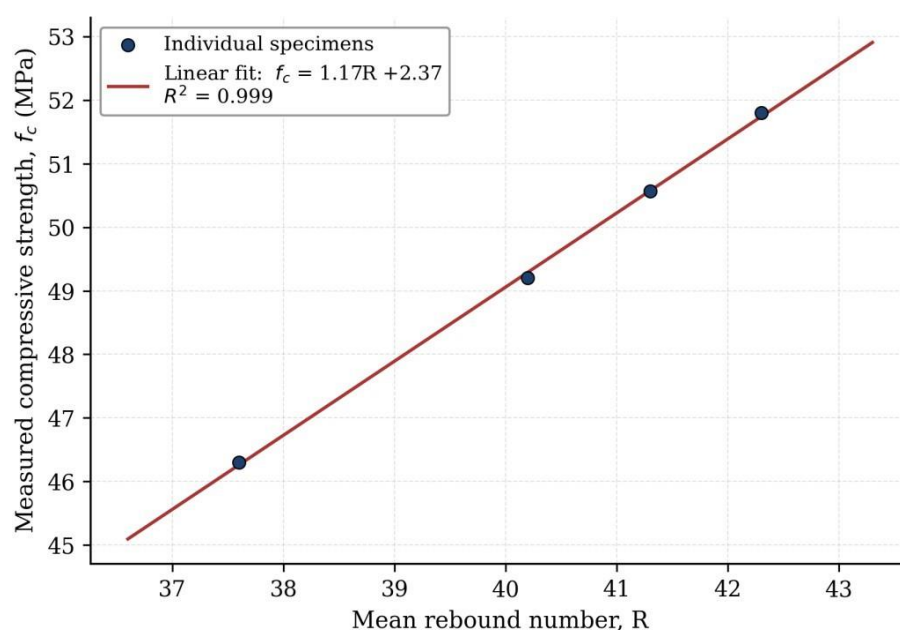


Figure 4.7 Correlation between mean rebound number and measured compressive strength

The rebound number followed the same pattern as every other property measured, rising from 37.6 for the control to a maximum of 42.3 at HFRC-1.0 and falling to 41.3 at HFRC-1.5. The proportional changes, at 6.9, 12.5 and 9.8 per cent, correspond closely to the changes of 6.3, 11.9 and 9.2 per cent in compressive strength, and the linear regression shown in Figure 4.7 gives $f_c = 1.167R + 2.366$ with a coefficient of determination of 0.999.

That coefficient must not be over-interpreted. It is obtained from four points, each being a mix mean rather than an individual specimen, and four points will lie close to a straight line under many circumstances that do not indicate a genuinely strong underlying relationship. The correct statement is that the rebound results are consistent

with the compressive strengths and rank the four mixes in the same order, which is what the test is properly used for, and not that a calibration of predictive value has been established. A calibration fit for that purpose would require paired readings upon a considerably larger number of individual specimens spanning a wider strength range, and its derivation is recommended in Section 6.9.

Two further limitations apply specifically to fibre reinforced concrete and should be borne in mind. The near-surface fibre distribution differs from that of the bulk because the mould wall prevents fibres from lying in the plane of the surface, so the layer sampled by the plunger is not representative of the interior; and a fibre lying immediately beneath the point of impact will raise the individual reading. The standard deviations in Table 4.8 offer some evidence upon the latter point. The scatter fell from

1.07 for the control to 0.67 for the two richest mixes, which is the opposite of what would be expected were individual fibres causing erratic readings, and suggests instead that the denser near-surface fibre population produced a more uniform surface. The improvement in surface uniformity is itself a modest practical benefit of the hybrid system.

It is concluded that rebound hammer testing served satisfactorily in this programme as an indicator of relative quality and uniformity, and that its results corroborate the destructive testing, but that it should not be used to estimate the strength of hybrid fibre reinforced concrete without a calibration derived specifically for the material in question.

4.8 Combined Assessment and Optimum Mix

This section draws the separate results together and identifies the optimum mix upon the whole of the evidence. The 28-day performance across every property measured is collected in Table 4.9.

Table 4.9 Summary of 28-day performance across all properties measured

Property	NC	HFRC-0.5	HFRC-1.0	HFRC-1.5	Best mix
Slump (mm)	102	89	72	54	NC
Compaction factor	0.93	0.91	0.88	0.84	NC
Superplasticiser (%)	0.80	0.90	1.10	1.30	NC
Compressive strength (MPa)	46.30	49.20	51.80	50.57	HFRC-1.0
Property	NC	HFRC-0.5	HFRC-1.0	HFRC-1.5	Best mix

Split tensile strength (MPa)	3.81	4.42	4.98	4.71	HFRC-1.0
Flexural strength (MPa)	5.42	6.31	7.08	6.82	HFRC-1.0
Pulse velocity (km/s)	4.23	4.35	4.44	4.31	HFRC-1.0
Mean rebound number	37.6	40.2	42.3	41.3	HFRC-1.0
Ratio f_{et} / f_c	0.082	0.090	0.096	0.093	HFRC-1.0

The normalised performance of the four mixes is presented in Figure 4.8, in which every property is expressed as a percentage of its value for the control mix so that the strength benefit and the workability penalty may be assessed against one another on a common scale.

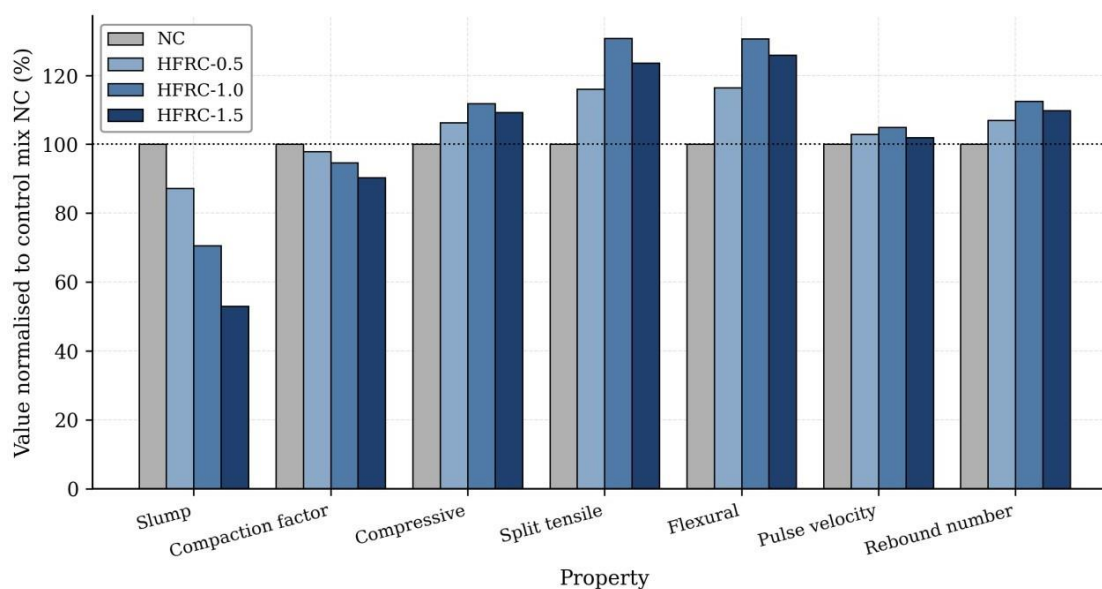


Figure 4.8 Normalised comparison of all measured properties across the four mixes

Table 4.9 and Figure 4.8 together show a result of unusual clarity. Every one of the six hardened-property measures, comprising three destructive strengths, two non-destructive indicators and the tensile-to-compressive ratio, attains its maximum at HFRC-1.0. It is common in dosage studies for different properties to optimise at different dosages, a possibility noted by Nili and Afrouhsabet [4] and by Saidani et al. [19], and where that occurs the selection of an optimum requires a criterion to be stated and defended. No such difficulty arises here: the hardened-state evidence is unanimous, and the identification of HFRC-1.0 as the optimum requires no weighting between competing measures.

The only measures that do not favour HFRC-1.0 are those describing the fresh state, and these necessarily favour the control mix, since fibre addition can only reduce workability. The relevant question is therefore not which mix is most workable but whether the workability of HFRC-1.0 is sufficient. At a slump of 72 mm, a compaction factor of 0.88 and a superplasticiser demand of 1.10 per cent, that mix remained cohesive, showed no segregation or balling, and compacted fully under table vibration, as its pulse velocity of 4.44 km/s independently confirms. Its workability is adequate for cast-in-place structural work with normal vibration, and the trade-off is accordingly favourable rather than merely acceptable.

The optimum mix is therefore HFRC-1.0, containing 1.0 per cent by volume of hooked-end steel fibre and 1.0 per cent by volume of alkali-resistant glass fibre, corresponding to 78.5 and 26.8 kg/m³ respectively. Relative to the plain M40 control it delivers improvements of 11.9 per cent in compressive strength, 30.7 per cent in split tensile strength and 30.6 per cent in flexural strength, at the cost of a 29.4 per cent reduction in slump and a 37.5 per cent increase in superplasticiser demand.

The evidence bears upon the hybridisation mechanism itself in three respects. First, the disproportion between the tensile and compressive improvements, at 30.7 and 30.6 per cent against 11.9 per cent, confirms that the benefit arises from crack bridging rather than from any densification of the matrix, since a densified matrix would have raised the compressive strength in like proportion. Second, the widening departure from the IS 456:2000 flexural relation shown in Table 4.6, from a ratio of 1.14 for the control to 1.41 at the optimum, demonstrates that the flexural capacity has been decoupled from the compressive capacity, which is the signature of a mechanism acting upon the tension face alone. Third, the concurrent decline of strength and pulse velocity at HFRC-1.5 locates the limit of the system in the compaction process rather than in the fibres, which means the optimum reported here is a property of the procedure as much as of the material.

One qualification must be entered. Because the mix matrix of Table 3.6 varies the total fibre volume while holding the steel-to-glass ratio constant, the present data establish that a hybrid at 2.0 per cent total volume outperforms a hybrid at 1.0 or 3.0 per cent, but they cannot establish that the hybrid outperforms either fibre used alone at 2.0 per cent, because no mono-fibre mixes were cast. A synergy effect in the strict sense, as defined

by Banthia et al. [9] and quantified by the hybrid effect index of Song and Yin [23], therefore remains to be demonstrated for this fibre combination. The findings of this study are fully consistent with such synergy and the mechanism proposed accounts for them, but the constant-volume ratio series recommended in Section 6.2 is required before the claim can properly be made. Reporting this limitation is preferable to asserting a synergy the experimental design cannot support.

CHAPTER 5

CONCLUSIONS

5.1 General

This investigation examined the fresh and hardened performance of M40 grade concrete reinforced with a hybrid system of hooked-end steel fibres and alkali-resistant glass fibres, at three increasing dosages in a constant volume ratio of 1:1, against a plain control mix. Seventy-two specimens were cast and tested for slump, compaction factor, compressive strength, split tensile strength, flexural strength, ultrasonic pulse velocity and rebound number, at 7 and 28 days. The conclusions that follow are drawn from those measurements.

5.2 Principal Findings

10. Hybrid fibre addition reduced workability severely and non-linearly. Slump fell from 102 mm to 54 mm across the series, a reduction of 47.1 per cent, and the superplasticiser demand rose from 0.80 to 1.30 per cent by mass of cement in order to hold the water–cement ratio at 0.40. The compaction factor, by contrast, fell only from 0.93 to 0.84, a reduction of 9.7 per cent. This divergence establishes that slump substantially understates the placeability of fibre reinforced concrete, and that the compaction factor is the more reliable measure for mixes of this type.
11. Compressive strength rose from 46.30 MPa to a maximum of 51.80 MPa at HFRC-1.0, an improvement of 11.9 per cent, and fell to 50.57 MPa at the highest dosage. The improvement is modest because fibres act in compression only upon the secondary mechanism of lateral tensile splitting rather than upon the primary crushing mechanism. The ratio of 7-day to 28-day strength remained between 67.7 and 68.2 per cent for all four mixes, demonstrating that the fibres do not participate in hydration and that their contribution is purely mechanical.
12. Split tensile strength rose from 3.81 MPa to 4.98 MPa at HFRC-1.0, an improvement of 30.7 per cent, being 2.6 times the improvement obtained in compression. The ratio of split tensile to compressive strength rose from 0.082 to 0.096, a quantitative indication of reduced brittleness. Steel fibres at the fracture surface had pulled out rather than fractured, with the hooked ends plastically straightened, confirming that the aspect ratio of 64 was appropriate to the matrix.

13. Flexural strength rose from 5.42 MPa to 7.08 MPa at HFRC-1.0, an improvement of 30.6 per cent. Measured values exceeded the estimate given by Clause 6.2.2 of IS 456:2000 by 14 per cent for the control and by 41 per cent for the optimum mix, showing that fibre reinforcement progressively decouples flexural from compressive capacity and that the code relation becomes increasingly conservative as fibre content rises. The flexural strength of hybrid fibre reinforced concrete cannot therefore be inferred from cube strength by the conventional relation and must be measured directly.
14. The two tensile-governed properties improved by between two and three times as much as the compressive strength at every dosage tested. This is the central finding of the study and it determines where the material is worth its cost.
15. Ultrasonic pulse velocity rose from 4.23 to 4.44 km/s at HFRC-1.0 and fell to 4.31 km/s at HFRC-1.5, all mixes being graded Good under IS 13311 (Part 1). The decline in pulse velocity at the highest dosage coincided with the decline in all three strengths, establishing that the post-optimum reduction is caused by entrapped air arising from incomplete compaction rather than by any deterioration in fibre–matrix interaction. The optimum dosage reported is consequently a property of the compaction procedure as much as of the fibre system.
16. Rebound numbers rose from 37.6 to 42.3 and ranked the mixes in the same order as the compressive strengths. The scatter of readings fell as fibre content increased, from a standard deviation of 1.07 to 0.67, indicating improved surface uniformity. The method served as a reliable comparative indicator but is not recommended for strength estimation in fibre reinforced concrete without material-specific calibration.
17. The optimum mix is HFRC-1.0, containing 1.0 per cent by volume each of steel and alkali-resistant glass fibre, being 78.5 and 26.8 kg/m³ respectively. Every hardened-state measure without exception attained its maximum at this dosage, so no weighting between competing criteria was required in its selection.
18. Because the experimental matrix varied total fibre volume while holding the steel-to-glass ratio constant, and because no mono-fibre mixes were cast, a synergy effect in the strict sense has not been demonstrated. The results are consistent with the multi-scale mechanism proposed in Section 1.6 and are well explained by it, but confirmation requires the constant-volume ratio series recommended in Section 6.2.

5.3 Engineering Significance

The disproportion between the tensile and compressive improvements determines the applications for which this material is appropriate. In members governed by compression, such as columns and bearing walls, an improvement of 11.9 per cent is obtained at the cost of the fibres, a 37.5 per cent increase in superplasticiser demand and a substantial reduction in workability. The same strength could be achieved more cheaply by a modest reduction in the water–cement ratio, and hybrid fibre reinforcement is not economically justified in such members.

In members governed by flexure or tension the position is entirely different. An improvement of approximately 30 per cent in both flexural and split tensile strength is substantial in design terms, and in slabs on grade, rigid pavements, industrial floors, precast panels, tunnel linings and repair overlays it translates directly into reduced thickness or increased joint spacing. For such members the material is well suited, and the decoupling of flexural from compressive capacity established in Table 4.6 means the benefit is available without the cement content that an equivalent gain would otherwise require.

The change in failure mode is of greater significance than any single strength figure. Control specimens failed abruptly and completely, whereas the fibre reinforced specimens cracked visibly, continued to carry load and remained intact. A structure that deflects and cracks visibly before failing affords warning that a structure failing in a brittle manner does not, and this consideration governs in members subject to impact, seismic action or accidental overload.

The durability implication follows from the same mechanism. Crack widths govern the ingress of water, chloride ions and carbon dioxide, and hence the time to initiation of reinforcement corrosion. The improved crack control demonstrated here should extend service life, and Afroughsabet and Ozbakkaloglu [14] measured reduced water absorption and increased electrical resistivity in hybrid systems consistent with that expectation. The present programme did not test durability directly, so this remains an inference rather than a finding, and its verification is the first of the recommendations in Chapter 6.

5.4 Practical Recommendations

- For M40 concrete of the constituents described in Chapter 3, adopt 1.0 per cent by volume each of hooked-end steel fibre of aspect ratio 64 and alkali-resistant glass fibre of aspect ratio 857, being 78.5 and 26.8 kg/m³ respectively.
- Provide a polycarboxylate-ether superplasticiser at 1.10 per cent by mass of cement to maintain a water–cement ratio of 0.40 at that dosage. Do not restore workability by adding water, since the strength benefit of the fibres is smaller than the loss a raised water–cement ratio would cause.
- Introduce the fibres gradually into the dry mix of aggregate and cement before any water is added, so that the fibres are separated by aggregate before the paste forms. Fibres added to a wet mix or charged in bulk will agglomerate into balls that cannot subsequently be dispersed.
- Do not exceed 2.0 per cent total fibre by volume under conventional vibration. Beyond that dosage the evidence of Section 4.6 shows that full compaction was not achieved and that strength declines as a result.
- Restrict vibration to the minimum required for full compaction, since prolonged vibration causes steel fibres to settle and reorient, destroying the random distribution upon which the reinforcement depends.
- Specify alkali-resistant glass of zirconia content not less than 16 per cent. Ordinary E-glass will be degraded by the alkalinity of the pore solution and the composite will lose strength over time.
- Determine flexural capacity by direct testing rather than by the relation of Clause 6.2.2 of IS 456:2000, which was shown in Table 4.6 to underestimate the measured value by 41 per cent at the optimum dosage.

5.5 Limitations

The findings are subject to the following limitations, each of which is taken up as a direction for further work in Chapter 6.

- Testing was confined to 7 and 28 days. The long-term retention of strength was not examined, and this matters particularly for the glass component, whose alkali resistance is a question of the rate of attack rather than of immunity.
- No durability property was measured. Chloride penetration, sulphate attack, carbonation, freeze–thaw resistance, shrinkage and creep all lie outside the programme, so the durability benefit argued in Section 5.3 remains an inference.

- Only peak-load properties were recorded. The post-peak load–deflection response, in which the contribution of the steel fibres is most fully expressed, was not measured instrumentally, and flexural toughness has therefore not been quantified.
- A single geometry and aspect ratio was used for each fibre type, and the steel-to-glass ratio was held constant at 1:1, so neither variable was investigated.
- No mono-fibre mixes were cast, which prevents any strict demonstration of synergy, as discussed in Section 4.8.
- Three replicates per test per age is the minimum permitting a valid mean. The coefficients of variation in Table 4.3 were low, but a larger sample would support firmer statistical inference, particularly for the rebound correlation of Figure 4.7, which rests upon only four paired means.
- The optimum dosage identified is specific to the laboratory pan mixer and table vibration employed. Site batching and placing equipment disperse and compact fibre reinforced mixes less effectively, and the practicable dosage in the field may prove lower.
- No microstructural evidence was obtained. The mechanisms proposed throughout Chapter 4 are inferred from mechanical behaviour and from examination of fracture surfaces by eye; they have not been confirmed by direct observation of the fibre–matrix interface.

CHAPTER 6

SCOPE FOR FUTURE WORK

6.1 Introduction

The present investigation is limited to the short-term mechanical performance of steel–glass hybrid fibre reinforced M40 concrete under controlled laboratory conditions, as stated in Sections 1.8 and 5.5. A number of questions arise directly from that limitation and from the findings themselves. The directions set out below are ordered so that those most closely connected to the present work appear first.

6.2 Optimisation of the Fibre Ratio at Constant Volume

The most immediate extension is to hold the total fibre volume constant at the optimum identified in Section 4.8 and to vary the ratio of steel to glass across its full range, from all steel to all glass. This design isolates the hybridisation variable from the dosage variable and permits the synergy effect to be demonstrated directly, by comparison of each hybrid against the two mono-fibre mixes at the same total volume. It is the design adopted by most of the studies summarised in Table 2.1 and would place the present findings upon a firmer mechanistic footing.

6.3 Long-Term Strength and Durability

Testing should be extended to 56, 90 and 180 days. This is of particular importance for glass fibre reinforced concrete, since the alkali resistance of AR glass is a matter of the rate of attack rather than of immunity, and any long-term degradation of the glass component will manifest only over extended periods. A durability programme should encompass rapid chloride ion penetration testing, water absorption and sorptivity, accelerated carbonation, sulphate resistance and acid attack. The expectation arising from the crack-control mechanism is that improved crack distribution reduces permeability, and Afroughsabet and Ozbakkaloglu [14] reported improvements in electrical resistivity and water absorption consistent with this; direct verification for the steel–glass system would be valuable, and the corrosion behaviour of steel fibres exposed at cracked surfaces requires particular attention.

6.4 Microstructural Characterisation

Scanning electron microscopy of fracture surfaces would permit the mechanisms proposed in Chapter 4 to be verified rather than inferred. The observations of particular value are the condition of the fibre–matrix interfacial transition zone, whether fibres exhibit evidence of pull-out or of fracture, the imprint left within the matrix by a pulled-out hooked-end fibre, and the surface condition of glass filaments after extended curing, which bears directly upon the alkali resistance question of Section 2.5. Energy dispersive spectroscopy would permit the composition of hydration products at the interface to be determined, and X-ray diffraction would permit the extent of the pozzolanic reaction within the PPC matrix and the consumption of calcium hydroxide to be quantified, the latter being directly relevant to glass fibre durability. Wu et al. [22] demonstrate the value of combining mechanical testing with microstructural evidence in precisely this manner.

6.5 Fracture Mechanics and Toughness Characterisation

The properties measured in the present work are peak-load properties, whereas the principal benefit of fibre reinforcement resides in the post-peak response. Closed-loop displacement-controlled flexural testing upon notched prisms, with crack mouth opening displacement recorded, would permit fracture energy and flexural toughness to be evaluated in accordance with established standards. This would quantify the contribution of the steel fibre component directly and would provide a far more sensitive measure of hybridisation benefit than peak strength alone, as the work of Qian and Stroeve [6] and Banthia et al. [9] demonstrates.

6.6 Dynamic, Fatigue and Impact Loading

The applications to which HFRC is best suited, namely pavements, industrial floors, bridge decks and protective structures, are governed by repeated and dynamic loading rather than by static strength. Flexural fatigue testing to establish endurance limits, drop-weight impact testing to determine energy absorption, and split Hopkinson pressure bar testing for high strain rate response would all be directly relevant. The review of impact resistance in fibre reinforced concrete by Yoo and Banthia [24] provides a comprehensive survey of test methods and reported behaviour and would serve as the starting point for such a programme. Nili and Afrouhsabet [4] showed that impact resistance and compressive strength optimise at different fibre dosages, so the optimum

established in the present study upon static criteria should not be assumed to hold under dynamic loading.

6.7 Elevated Temperature and Fire Resistance

The behaviour of the two fibre types at elevated temperature differs markedly, and the combination merits investigation for that reason. Residual strength after exposure to a range of temperatures, together with observation of spalling behaviour, would establish whether the hybrid retains its advantage under fire conditions.

6.8 Shrinkage and Early-Age Cracking

Restrained ring testing and free drying shrinkage measurement would permit the contribution of the glass fibre component to early-age crack control to be quantified. This is a benefit that 28-day strength testing does not capture at all, and Sivakumar and Santhanam [13] found the non-metallic component markedly more effective than steel in this respect. For slabs, pavements and thin sections, early-age crack control may prove the more valuable of the two benefits the hybrid confers.

6.9 Structural Element Testing

Testing of full-scale reinforced elements, comprising beams in flexure and shear, slabs, and beam-column joints under cyclic loading, would establish whether the improvements measured upon small specimens translate into structural behaviour, including crack width control, deflection under service load, and the potential for partial replacement of shear reinforcement. The analytical work of Mobasher, Yao and Soranakom [20] provides a framework against which such results might be evaluated.

6.10 Numerical Modelling

Finite element modelling employing appropriate constitutive laws for fibre reinforced concrete, calibrated against the experimental data obtained here, would permit extrapolation beyond the tested configurations and would allow the sensitivity of the response to fibre orientation and distribution to be explored. Discrete fibre modelling at the meso-scale would permit the crack-bridging mechanism of Figure 1.1 to be simulated directly.

6.11 Machine Learning and Mix Optimisation

The number of variables governing HFRC performance, comprising two fibre types, their dosages, aspect ratios, matrix strength and admixture dosage, renders exhaustive experimental optimisation impractical. Data-driven models trained upon compiled experimental databases have been applied to the prediction of fibre reinforced concrete properties and could be employed to identify promising combinations for experimental verification, provided that the model outputs are treated as hypotheses to be tested rather than as results.

6.12 Sustainability and Life-Cycle Assessment

A complete evaluation should weigh the environmental cost of the fibres against the benefit they confer. Steel and glass fibre production are both energy-intensive, and the case for their use rests upon extended service life and reduced maintenance rather than upon reduced initial impact. A cradle-to-grave life-cycle assessment, together with costing over the design life, would establish whether the environmental and economic case is as favourable as the mechanical one. The use of recycled steel fibre recovered from waste tyres, and the substitution of supplementary cementitious materials for a further portion of the cement, both merit investigation in this context.

6.13 Field Implementation

Finally, a trial field application, such as an industrial floor or a pavement panel, would test whether the mixing sequence and workability limits established in the laboratory are achievable with site batching and placing equipment. Laboratory pan mixers disperse fibres considerably more effectively than transit mixers, and the practicable dosage on site may prove lower than the optimum identified in the laboratory. This is the question upon which the practical value of the work ultimately depends.

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