

Experimental Study on Properties of M40 Grade Concrete by Partial Replacement of Coarse Aggregate with Waste Tyre Rubber

Udit Krishnan

(Roll No. 24050730210)

Master Of Technology

Department Of Civil Engineering

Cambridge Institute Of Technology

Tatisilwai, Ranchi – 835103, Jharkhand

Under The Supervision Of

Prof. Amit Jyoti

*Assistant Professor, Department Of Civil
Engineering*

Department Of Civil Engineering

Cambridge Institute Of Technology

Tatisilwai, Ranchi – 835103, Jharkhand

ABSTRACT

The continuous growth of the automobile sector has made the disposal of end-of-life tyres one of the most persistent solid-waste problems of the present century. Tyre rubber is vulcanised, non-biodegradable and chemically stable, and stockpiles of discarded tyres present fire, vector-borne disease and groundwater contamination hazards. In parallel, the construction industry consumes natural aggregate at a rate that has begun to strain river and quarry sources in many regions of India. The utilisation of shredded waste tyre rubber as a partial substitute for natural coarse aggregate in structural concrete therefore addresses two independent environmental pressures with a single intervention.

The present investigation examines the influence of shredded waste tyre rubber on the fresh and hardened properties of M40 grade concrete. A control mix was designed in accordance with IS 10262:2019 using Portland Pozzolana Cement, Zone II river sand and 20 mm nominal size crushed stone aggregate, with a free water-cement ratio of 0.40 and a polycarboxylate ether based superplasticizer. Three rubberised mixes were then proportioned by replacing 3 %, 6 % and 9 % of the coarse aggregate volume with shredded tyre rubber of comparable particle size, the paste content and water-cement ratio being held constant across all four mixes so that the rubber content remains the sole experimental variable.

Fresh concrete is assessed through the slump cone test and the compaction factor test in accordance with IS 1199, together with a determination of fresh density. Hardened properties are evaluated on 150 mm cubes, 150 mm diameter by 300 mm cylinders and 100 x 100 x 500 mm prisms tested at 7 and 28 days of moist curing, following IS 516 and IS 5816 respectively. A total of seventy-two specimens, comprising twenty-four cubes, twenty-four cylinders and twenty-four beams, constitutes the experimental matrix, with three replicates for every combination of mix and test age.

The mix design computations show that volumetric substitution reduces the theoretical fresh density of the concrete from 2455.4 kg/m³ for the control mix to 2388.6 kg/m³ at 9 % replacement, a reduction of 2.7 %, arising from the very low specific gravity of rubber relative to crushed stone. On the basis of the published literature, a progressive reduction in compressive strength with increasing rubber content is anticipated, governed by the low stiffness of the rubber inclusions, the hydrophobic and weakly bonded rubber-paste interfacial transition zone, and the resulting redistribution of stress into the surrounding mortar. Tensile and flexural strengths are expected to fall less steeply than compressive strength because the elastomeric inclusions bridge and deflect propagating cracks, conferring a measure of post-peak ductility that plain concrete does not possess.

The report establishes the complete material characterisation, mix design, specimen schedule and test methodology required for the experimental programme, and sets out the analytical framework through which the optimum replacement level will be identified once the laboratory data become available.

Keywords: Rubberised concrete; waste tyre rubber; crumb rubber aggregate; M40 grade concrete; sustainable construction; interfacial transition zone; compressive strength; split tensile strength; flexural strength.

LIST OF ABBREVIATIONS AND SYMBOLS

Symbol / Abbreviation	Description
CTM	Compression Testing Machine
ITZ	Interfacial Transition Zone
PPC	Portland Pozzolana Cement
SSD	Saturated Surface Dry
SP	Superplasticizer (polycarboxylate ether based)
w/c	Free water–cement ratio
RC-0, RC-3, RC-6, RC-9	Mix designations corresponding to 0, 3, 6 and 9 % rubber replacement
f_{ek}	Characteristic compressive strength of concrete at 28 days, MPa
f'_{ek}	Target mean compressive strength of concrete at 28 days, MPa
f_c	Compressive strength of the cube specimen, MPa
f_{et}	Split tensile strength of the cylinder specimen, MPa
f_{cr}	Modulus of rupture (flexural strength) of the prism specimen, MPa
P	Maximum load recorded at failure, N
A	Loaded cross-sectional area of the specimen, mm ²
L, D	Length and diameter of the cylindrical specimen, mm
b, d	Width and depth of the prism specimen, mm
l	Effective span of the prism specimen, mm
a	Distance between the line of fracture and the nearer support, mm
s	Assumed standard deviation of compressive strength, MPa
R	Rubber replacement level, % by volume of coarse aggregate
G	Specific gravity of a constituent material
ρ	Density, kg/m ³

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is the most widely produced manufactured material on earth. Its dominance rests on a combination of attributes that no competing structural material matches simultaneously: constituent materials that are available almost everywhere, the ability to be cast into arbitrary geometry, high compressive strength, inherent fire resistance and a low cost per unit of load-carrying capacity. Global production is of the order of tens of billions of tonnes annually, and aggregate constitutes roughly three-quarters of that mass by weight. Consequently, the demand placed by the construction industry on natural aggregate resources is enormous, and in many river basins and quarrying districts of India the rate of extraction has begun to outstrip the rate at which the resource can be replenished or regulated (Siddique and Naik, 2004).

At the same time, a second and unrelated pressure has developed. Modern industrial societies generate large volumes of durable, non-biodegradable waste for which no natural assimilation pathway exists. Where such a waste possesses particle characteristics broadly comparable to those of a concrete constituent, the possibility arises of diverting it from landfill into the concrete matrix. The material addressed in this investigation, shredded waste automobile tyre rubber, is one of the clearest examples of this convergence: it is produced in enormous quantity, it is chemically inert in an alkaline cementitious environment, and after shredding it occupies the same particle size range as conventional coarse aggregate.

This chapter introduces the environmental context of the study, states the engineering problem being addressed, defines the objectives and the boundaries of the investigation, and describes the organisation of the remainder of the report.

1.2 Waste Tyre Generation and the Disposal Problem

An end-of-life tyre is a composite of vulcanised rubber, carbon black, steel bead and belt wire, textile cord and a variety of processing chemicals. Vulcanisation creates permanent sulphur cross-links between the polymer chains, which is precisely what gives the tyre its service durability and also what renders it effectively non-biodegradable once discarded.

Estimates place worldwide generation at over one billion end-of-life tyres per year, and India alone accounts for a rapidly growing share as vehicle ownership expands.

Conventional disposal routes are unsatisfactory for several distinct reasons. Landfilling consumes land at a very poor mass-to-volume ratio because the toroidal geometry of a whole tyre traps air, and buried tyres tend to migrate upwards through the fill over time. Open stockpiles are prone to fires that are extremely difficult to extinguish and that release pyrolytic oil into soil and groundwater along with dense particulate smoke. Standing water within stockpiled tyres provides an ideal breeding habitat for mosquitoes, with the associated public health consequences. Incineration for energy recovery, while technically feasible, requires costly emission control to manage sulphur and heavy metal releases.

Against this background, a wide range of material recovery routes has been explored, including crumb rubber modified bitumen for flexible pavements, artificial turf infill, playground and athletic surfacing, embankment lightweight fill and noise barriers. Incorporation into Portland cement concrete is among the most attractive of these routes because the sheer volume of concrete produced means that even a modest replacement percentage would consume a very large tonnage of rubber (Mavroulidou and Figueiredo, 2010).

1.3 Rubber Aggregate in Concrete

Rubberised concrete is produced by substituting a fraction of the natural aggregate with processed tyre rubber particles. Depending on the particle size of the rubber, the substitution may target the fine aggregate fraction (crumb rubber, typically below 4.75 mm), the coarse aggregate fraction (chipped or shredded rubber, typically 4.75 to 20 mm), or both. The present study is concerned with coarse aggregate replacement using shredded rubber chips.

The engineering consequences of this substitution follow directly from the physical contrast between rubber and crushed stone. Rubber has a specific gravity of approximately 1.10 to 1.20 against 2.70 to 2.90 for crushed stone, an elastic modulus lower by three orders of magnitude, negligible water absorption, and a smooth hydrophobic surface that develops only weak adhesion with hydrated cement paste. These four differences account, individually and in combination, for essentially every behavioural change reported in the literature: reduced density, reduced compressive

strength, increased toughness, improved impact and damping performance, and reduced workability at higher replacement levels.

It is important to recognise at the outset that rubberised concrete is not proposed as a universal substitute for conventional concrete. The strength penalty at higher replacement levels rules out its use in heavily loaded structural members. The engineering question is therefore not whether strength is reduced, which is certain, but whether a replacement level exists at which the strength remaining is still adequate for a defined class of application while the environmental and functional benefits are meaningful. Identifying that level for M40 grade concrete is the purpose of this investigation.

1.4 Problem Statement

The published literature establishes with reasonable consistency that the compressive strength of concrete falls as rubber content rises. What the literature does not establish consistently is the magnitude of that reduction for a given grade, rubber particle size, replacement basis and set of local materials. Reported reductions at nominally similar replacement levels vary widely between studies, largely because investigators have used different rubber gradations, have expressed replacement on a mass basis in some cases and a volume basis in others, and have in several instances allowed the paste content or water demand to vary along with the rubber content.

Furthermore, the majority of published work has addressed normal strength concrete in the M20 to M30 range. Higher grade concretes such as M40 possess a denser and stronger matrix, and it is not self-evident that the proportional strength loss observed at lower grades will translate directly, since in a high strength matrix a larger share of the load path passes through the aggregate skeleton and the contrast in stiffness between matrix and inclusion is greater.

There is therefore a well-defined need for a controlled experimental study in which an M40 mix is designed to code, the paste content and water-cement ratio are held rigorously constant, rubber is introduced on a strictly volumetric basis so that the yield is preserved, and the resulting fresh and hardened properties are measured across a range of low replacement levels. The present work is framed to meet that need.

1.5 Objectives of the Investigation

The overall aim of this investigation is to assess the technical feasibility of using shredded waste tyre rubber as a partial replacement for natural coarse aggregate in M40 grade concrete. The specific objectives are set out below.

- To characterise the constituent materials, namely Portland Pozzolana Cement, fine aggregate, natural coarse aggregate and shredded waste tyre rubber, in accordance with the relevant Indian Standards.
- To design an M40 grade control concrete mix in accordance with IS 10262:2019 and IS 456:2000, and to establish the batch quantities of all constituents on an absolute volume basis.
- To proportion three rubberised mixes in which 3 %, 6 % and 9 % of the coarse aggregate volume is replaced by shredded tyre rubber, keeping the cement content, water content, water-cement ratio and admixture dosage constant across all mixes.
- To evaluate the workability of the fresh concrete through the slump cone test and the compaction factor test, and to record the fresh density of each mix.
- To determine the compressive strength of 150 mm cube specimens at 7 and 28 days of moist curing.
- To determine the split tensile strength of 150 mm diameter by 300 mm cylindrical specimens at 7 and 28 days.
- To determine the flexural strength of 100 x 100 x 500 mm prism specimens at 7 and 28 days under four-point loading.
- To quantify the percentage variation in each property relative to the control mix and to interpret the observed trends in terms of the underlying material mechanisms.
- To identify the optimum rubber replacement level that retains acceptable mechanical performance while maximising the quantity of waste rubber utilised, and to indicate the classes of construction application for which the resulting concrete would be suitable.

1.6 Scope and Limitations

The investigation is confined to a laboratory-scale study of M40 grade concrete under controlled ambient conditions. Four mixes are considered, corresponding to rubber replacement levels of 0, 3, 6 and 9 % by volume of coarse aggregate. The rubber is used in the as-received shredded condition without any surface treatment. Only short-term mechanical properties at 7 and 28 days are measured.

The following aspects lie outside the scope of the present work and are identified as directions for future study: long-term strength development beyond 28 days; durability

performance including chloride ion penetration, sulphate resistance, carbonation depth and freeze-thaw resistance; drying shrinkage and creep; dynamic and impact response; behaviour of reinforced members incorporating rubberised concrete; the effect of chemical or mechanical pre-treatment of the rubber surface; and full life-cycle assessment of the material. Replacement levels above 9 % are also excluded, since the available evidence indicates that the strength penalty beyond this range becomes difficult to justify for a structural grade concrete.

1.7 Organisation of the Report

The report is arranged in five chapters. The present chapter has introduced the environmental and engineering context, stated the problem, and defined the objectives and scope of the study.

Chapter 2 presents a critical review of the published literature on rubberised concrete. The review is organised by property rather than by author, so that the mechanisms responsible for each observed effect can be traced across independent studies, and it closes with a statement of the research gap addressed by the present work.

Chapter 3 describes the constituent materials and their measured properties, the mix design computations carried out in accordance with IS 10262:2019, the basis on which the rubberised mixes were proportioned, the casting and curing regime, the experimental matrix, and the test methods together with the governing relations used to reduce the measured data.

Chapter 4 sets out the experimental programme in its executable form, presenting the data-recording formats for each test, the comparative and percentage-variation tables through which the results will be analysed, and the framework by which the optimum replacement level will be selected. The mechanisms expected to govern the observed behaviour are discussed with reference to the literature reviewed in Chapter 2.

Chapter 5 draws together the conclusions arising from the design and characterisation stage, states the outcomes anticipated from the testing programme, comments on the practical significance of the work and identifies the scope for future investigation. A consolidated list of references follows.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Research into the incorporation of waste tyre rubber in cementitious composites has been active for more than three decades, beginning with the exploratory work of Eldin and Senouci (1993) and Topçu (1995). The body of literature is now extensive, and rather than summarising it chronologically it is more useful to organise it by property, so that the physical mechanisms responsible for each observed effect can be identified and cross-checked between independent investigations. That is the approach adopted in this chapter.

The review proceeds from the processing of the rubber itself, through the fresh and hardened properties of the resulting concrete, to the methods proposed for mitigating the strength penalty and the durability and environmental evidence. It concludes with a synthesis and a statement of the specific gap that the present investigation addresses.

2.2 Processing and Classification of Waste Tyre Rubber

Waste tyre rubber intended for use in concrete is produced by either ambient grinding or cryogenic grinding. In ambient grinding the tyre is shredded mechanically at room temperature, producing particles with a rough, torn and irregular surface and a relatively high specific surface area. Cryogenic grinding freezes the rubber below its glass transition temperature with liquid nitrogen and then fractures it, producing smooth, flat, glassy fracture surfaces. Since bond with the cement paste depends on mechanical interlock as much as on chemical adhesion, ambient-ground rubber generally performs marginally better in concrete despite its higher processing energy per unit surface area.

Three size classifications are commonly recognised in the literature. Shredded or chipped rubber, in the range of approximately 4.75 to 20 mm, is used to replace coarse aggregate. Crumb rubber, generally between 0.425 and 4.75 mm, replaces fine aggregate. Ground or powdered rubber below 0.425 mm is used as a filler or partial cement substitute. Siddique and Naik (2004), in a comprehensive review, noted that the strength penalty for a given volumetric replacement is generally more severe for coarse rubber than for fine rubber, because the larger inclusion introduces a correspondingly larger defect into the load path. This observation is directly relevant to the present study, which employs coarse rubber and therefore restricts the replacement range to relatively low percentages.

It is also relevant that steel bead and belt wire, along with textile cord, must be substantially removed during processing. Residual steel fragments corrode within the concrete and cause local expansive damage, while residual textile fibres absorb mixing water and produce balling during mixing.

2.3 Fresh Properties of Rubberised Concrete

The influence of rubber on workability is not monotonic across the literature, and the apparent contradictions are largely explicable in terms of the replacement basis used. Where rubber is substituted on a mass basis, the very low specific gravity of rubber means that a given mass of rubber occupies a much greater volume than the stone it replaces, so the aggregate volume fraction rises and workability falls sharply. Where substitution is volumetric, the effect is more modest and is governed principally by particle shape and surface texture.

Khatib and Bayomy (1999) reported a progressive decrease in slump with increasing rubber content, and observed that at high rubber contents the mix became harsh and difficult to finish. Batayneh et al. (2008) similarly recorded a continuous reduction in slump with crumb rubber content. Two mechanisms are responsible. First, the angular, torn surface of ambient-ground rubber produces greater inter-particle friction than the relatively rounded profile of well-graded crushed stone. Second, the hydrophobic surface of rubber entrains air at the rubber-paste interface, and the entrapped air increases the apparent cohesion of the mix while reducing its ability to flow under its own weight.

A consistent and unambiguous finding across all studies is the reduction in fresh density. Because rubber has less than half the specific gravity of crushed stone, any volumetric replacement produces a proportionate reduction in unit weight. Khaloo et al. (2008) reported density reductions broadly linear with rubber volume fraction, and noted the tendency of rubber particles to segregate towards the surface of the fresh concrete under vibration, since they are buoyant relative to the surrounding mortar. This buoyancy imposes a practical constraint on compaction: prolonged vibration of rubberised concrete produces a rubber-rich surface layer and must be avoided.

2.4 Compressive Strength

The reduction of compressive strength with increasing rubber content is the single most consistently reported finding in the field. Eldin and Senouci (1993), in one of the earliest

systematic studies, replaced coarse aggregate entirely with tyre chips and recorded a compressive strength reduction of up to 85 %, while replacement of fine aggregate by crumb rubber produced a reduction of about 65 %. Topçu (1995) reported comparable trends and additionally documented the change in the stress-strain response, noting a marked reduction in the initial tangent modulus.

Al Bakri et al. (2007), comparing rubber used as an aggregate replacement with rubber used as a filler material, reached the same conclusion by a different route. They attributed the strength loss principally to the behaviour of the rubber inclusions as voids within the matrix, observing that the strength of Portland cement concrete depends strongly on the density, size and hardness of the coarse aggregate, so that a reduction upon substitution by a soft particle is to be expected rather than anomalous.

Three mechanisms, acting together, account for this behaviour. The first is the stiffness contrast. The elastic modulus of vulcanised rubber is of the order of a few megapascals against some 50 000 MPa for crushed stone. When a composite containing such an inclusion is loaded, the soft particle carries almost no stress and behaves mechanically as a void. Load is therefore shed into the surrounding mortar, which experiences stress concentrations well above the nominal applied stress. Failure initiates in these locally overstressed regions at a lower nominal load than in the control concrete (Neville, 2011).

The second mechanism is the weakness of the interfacial transition zone. Rubber is hydrophobic and non-polar, and develops no meaningful chemical bond with the calcium silicate hydrate gel. Water films preferentially collect at the rubber surface during mixing and bleeding, producing a locally elevated water-cement ratio, a higher porosity and a greater concentration of oriented calcium hydroxide crystals in the transition zone, which is the classical description of a weak interfacial zone given by Mehta and Monteiro (2014). The consequence is a weak, porous shell around each rubber particle across which tensile stress cannot be transferred. Segre and Joekes (2000) demonstrated this explicitly, showing through scanning electron microscopy that untreated rubber particles were separated from the paste by a visible gap, whereas particles treated with sodium hydroxide solution exhibited markedly improved adhesion.

The third mechanism is the increase in entrapped air. The hydrophobic rubber surface tends to retain air bubbles that would otherwise be expelled during compaction. Since compressive strength is acutely sensitive to porosity, this contribution is not negligible

even at low replacement levels. Figure 3.7 in the following chapter illustrates the contrasting interfacial condition around natural and rubber aggregate particles that underlies these mechanisms.

Khatib and Bayomy (1999) proposed an empirical relative strength factor relating residual compressive strength to rubber volume fraction, and observed that the reduction is steep at low replacement levels and then flattens, which is consistent with a percolation-type argument in which the earliest rubber inclusions are the most damaging because they interrupt the strongest continuous load paths. Ganjian et al. (2009), working with replacement levels of 5, 7.5 and 10 % by volume of coarse aggregate, reported strength reductions of the order of 10 to 23 %, which is the range most relevant to the present investigation. Gupta et al. (2014) and Thomas and Gupta (2016) reported broadly similar magnitudes for comparable replacement levels in normal strength concrete.

An important qualification concerns the influence of the grade of the parent concrete. Raffoul et al. (2016) and Su et al. (2015) observed that the proportional strength loss tends to be greater in higher strength matrices. In a high strength concrete the paste is denser and stiffer, so the ratio of matrix modulus to inclusion modulus is larger and the resulting stress concentration around each soft particle is correspondingly more severe. This observation provides part of the justification for undertaking the present study on an M40 mix rather than relying on results reported for lower grades.

2.5 Tensile and Flexural Behaviour

Split tensile and flexural strengths also decrease with rubber content, but the published evidence indicates that the proportional reduction is generally smaller than that observed in compression. Topçu and Avcular (1997) analysed rubberised concrete as a two-phase composite and showed that the softer phase, while detrimental under compressive stress, contributes a crack-arresting function under tensile stress.

The mechanism is one of crack bridging and deflection. A propagating tensile crack in plain concrete follows the path of least resistance through the interfacial transition zones of the aggregate particles and releases its stored energy abruptly. In rubberised concrete the crack encounters a compliant particle that deforms rather than fracturing. The crack must either deflect around the particle, which lengthens its path and increases the energy required to propagate a given projected crack length, or else the particle remains partially intact across the crack faces and transmits a closing traction. Aiello and Leuzzi (2010)

documented precisely this behaviour, reporting that beams containing coarse rubber aggregate continued to sustain load after the formation of the first crack and failed in a gradual rather than an explosive manner.

Because of these competing effects, the ratio of tensile to compressive strength typically increases with rubber content even though both absolute values fall. This is a technically significant point: it indicates that rubberised concrete becomes progressively less brittle in relative terms, which is the principal functional argument in its favour for applications such as pavements, kerbs and barriers where tensile cracking rather than compressive crushing governs serviceability.

2.6 Toughness, Impact Resistance and Damping

The properties in which rubberised concrete outperforms conventional concrete are those governed by energy absorption rather than by peak stress. Topçu and Avcular (1997) reported a substantial improvement in the collision and impact behaviour of rubberised concrete. Zheng et al. (2008) measured the damping ratio and found it to increase with rubber content, attributing the effect to viscoelastic energy dissipation within the rubber particles themselves.

Najim and Hall (2010) reviewed the mechanical, thermal and acoustic performance of rubberised concrete and concluded that the material offers genuine advantages in vibration isolation, sound absorption and thermal insulation, all of which derive from the same combination of low stiffness, high internal damping and elevated air content that penalises compressive strength. Youssf et al. (2014) demonstrated that confining rubberised concrete within fibre-reinforced polymer jackets recovers much of the lost axial strength while retaining the enhanced ductility, indicating that the strength penalty can in some structural configurations be engineered around rather than merely accepted.

The essential point emerging from this group of studies is that the same microstructural features produce both the penalty and the benefit. Any treatment that stiffens the rubber-paste interface to recover compressive strength will simultaneously reduce the energy dissipation that makes the material attractive. The selection of a replacement level is therefore a genuine engineering trade-off rather than a simple optimisation.

2.7 Surface Treatment of Rubber Aggregate

Given that the interfacial transition zone is the principal source of weakness, a substantial body of work has examined methods of improving rubber-paste adhesion. Segre and Joekes (2000) treated rubber particles with a saturated sodium hydroxide solution and reported improved bond, attributed to the removal of zinc stearate from the rubber surface and an increase in surface hydrophilicity. Pelisser et al. (2011) investigated treatment with an alkaline activator and a silica fume addition and recovered a significant proportion of the strength lost at moderate replacement levels.

Other approaches reported in the literature include pre-coating the rubber with cement paste, treatment with silane coupling agents, partial oxidation with acids and irradiation. Bisht and Ramana (2017) and Si et al. (2017) both concluded that surface treatment produces a measurable but not transformative improvement, typically recovering between a quarter and a half of the strength loss, and that the additional processing cost may not be justified for low replacement levels where the untreated strength penalty is already modest. On this basis, untreated rubber has been used in the present investigation, and the effect of surface treatment is identified in Chapter 5 as a direction for future work.

2.8 Durability and Environmental Considerations

Durability findings are more mixed than mechanical findings. Güneyisi et al. (2004) reported that rubberised concrete containing silica fume exhibited acceptable resistance to chloride penetration, while untreated mixes at high rubber contents showed increased permeability consistent with their higher porosity. On the other hand, several investigators have reported improved freeze-thaw resistance, which is plausible because the air entrapped at the rubber interface performs a function analogous to deliberate air entrainment by accommodating the expansion of freezing pore water.

From an environmental standpoint, leaching is the principal concern that must be addressed before field use. The available evidence indicates that within the high-pH environment of hydrated cement paste, vulcanised rubber is chemically stable and that leaching of zinc and other constituents is very low and generally below regulatory thresholds. The encapsulation of the rubber within a dense cementitious matrix additionally restricts any transport pathway.

Mavroulidou and Figueiredo (2010) emphasised the scale argument that ultimately motivates this field of research. Because the global volume of concrete produced is so large, even a replacement level of a few per cent applied across a modest fraction of

production would consume a very substantial proportion of annual tyre waste. The environmental benefit therefore does not depend on achieving high replacement levels; it depends on achieving a low replacement level that is technically defensible enough to be adopted widely.

2.9 Summary of Literature and Research Gap

The principal findings of the studies reviewed above are consolidated in Table 2.1, which lists the investigators, the replacement basis and range examined, and the essential conclusions drawn.

Table 2.1 Summary of representative investigations on rubberised concrete

Investigator(s)	Rubber type and replacement range	Principal findings
Al Bakri et al. (2007)	Rubber as coarse aggregate replacement and as filler	Strength loss attributed to void-like behaviour of rubber and weak rubber-matrix bond; sustainability benefit emphasised.
Eldin and Senouci (1993)	Tyre chips and crumb; up to 100 % of coarse or fine aggregate	Compressive strength reduced by up to 85 % for coarse replacement and 65 % for fine; failure mode changed from brittle to gradual.
Topçu (1995)	Rubber chips; 15–45 % by volume	Progressive reduction in compressive and flexural strength; marked reduction in elastic modulus; increased plastic energy capacity.
Fattuhi and Clark (1996)	Crumb rubber in cement-based mixes	Reduced density and strength; substantially increased deformability before failure.
Topçu and Avcular (1997)	Rubber aggregate, composite analysis	Rubberised concrete modelled as two-phase composite; collision and impact behaviour markedly improved.
Khatib and Bayomy (1999)	Crumb and chipped rubber; up to 57 % by volume	Proposed empirical relative strength factor; slump reduced continuously; strength loss steepest at low replacement levels.
Segre and Joeke (2000)	NaOH-treated tyre rubber in cement paste	Surface treatment improved rubber–paste adhesion and reduced the interfacial gap observed under SEM.
Güneyisi et al. (2004)	Crumb and chipped rubber with silica fume	Silica fume addition partially offset strength and permeability penalties at moderate rubber contents.
Siddique and Naik (2004)	Review of scrap tyre rubber in concrete	Consolidated evidence that coarse rubber is more damaging than fine rubber at equal volume replacement.
Batayneh et al. (2008)	Crumb rubber; 20–100 % of fine aggregate	Continuous reduction in slump, density and compressive strength; improved plastic deformation capacity.
Khaloo et al. (2008)	Rubber aggregate; 12.5–50 % by volume	Reduced unit weight and strength; documented buoyant segregation of rubber under prolonged vibration.
Zheng et al. (2008)	Ground and crushed rubber	Damping ratio increased with rubber content; elastic modulus reduced; viscoelastic dissipation identified as mechanism.
Ganjan et al. (2009)	Chipped rubber; 5, 7.5 and 10 % of coarse aggregate by	Compressive strength reduced by approximately 10–23 % over this range; results directly

Investigator(s)	Rubber type and replacement range	Principal findings
	volume	comparable to the present study.
Aiello and Leuzzi (2010)	Coarse rubber; 25–75 % of coarse aggregate	Post-cracking load retention in flexure; gradual rather than explosive failure of beam specimens.
Mavroulidou and Figueiredo (2010)	Discarded tyre rubber aggregate	Confirmed strength reduction but established the scale argument for large-volume waste diversion.
Najim and Hall (2010)	Review of rubberised concrete	Documented advantages in damping, acoustic absorption and thermal insulation.
Pelisser et al. (2011)	Alkali-activated rubber with silica fume	Significant recovery of strength lost at moderate replacement levels through interface modification.
Gupta et al. (2014); Thomas and Gupta (2016)	Rubber ash and crumb rubber; up to 20 %	Strength reduction consistent with earlier work; improved impact resistance and abrasion behaviour reported.
Youssif et al. (2014)	Crumb rubber with FRP confinement	Confinement recovered much of the lost axial strength while retaining enhanced ductility.
Su et al. (2015); Raffoul et al. (2016)	Rubber in normal and high strength concrete	Proportional strength loss more severe in higher strength matrices due to greater modulus contrast.
Bisht and Ramana (2017); Si et al. (2017)	Treated and untreated crumb rubber; up to 5.5 %	Surface treatment recovers part of the strength loss; low replacement levels judged practically viable without treatment.

Table 2.1 makes several patterns apparent. Every investigation reports a reduction in compressive strength, and the reported magnitude correlates strongly with the replacement level examined rather than with any inconsistency of method. Studies employing high replacement levels report severe losses, while those confined to below approximately 10 % report losses in the range of 10 to 25 %. Equally consistently, every study that measured energy absorption, damping or post-cracking behaviour reported an improvement.

The gap that remains is a matter of specificity rather than of general principle. Most of the quantitative data available relate to normal strength concrete, and where higher grades have been studied the evidence of Su et al. (2015) and Raffoul et al. (2016) indicates that the proportional penalty is likely to be greater. Several studies have also confounded the rubber variable by permitting paste content, water demand or admixture dosage to vary between mixes, or by replacing aggregate on a mass basis so that the mix yield and aggregate volume fraction change simultaneously with rubber content.

The present investigation is designed to eliminate these confounding influences. An M40 mix is designed to IS 10262:2019; replacement is strictly volumetric so that the total aggregate volume and the mix yield remain constant; and the cement content, free water

content, water-cement ratio and superplasticizer dosage are held identical across all four mixes. Under these conditions the rubber content becomes the sole independent variable, and the measured differences in fresh and hardened properties can be attributed to it without ambiguity.

CHAPTER 3

MATERIALS AND EXPERIMENTAL METHODOLOGY

3.1 General

This chapter presents the experimental framework of the investigation. It begins with a description of the constituent materials and the standards to which they conform, proceeds through their measured physical properties, and then sets out the mix design computation for the M40 control concrete carried out in accordance with IS 10262:2019. The basis on which the three rubberised mixes were proportioned is then established, followed by the batching, casting and curing regime, the complete experimental matrix, and the test methods together with the governing relations used to reduce the measured data to engineering quantities.

The overall sequence of activities is summarised in Figure 3.1, which shows the flow of work from material procurement through to the identification of the optimum replacement level.

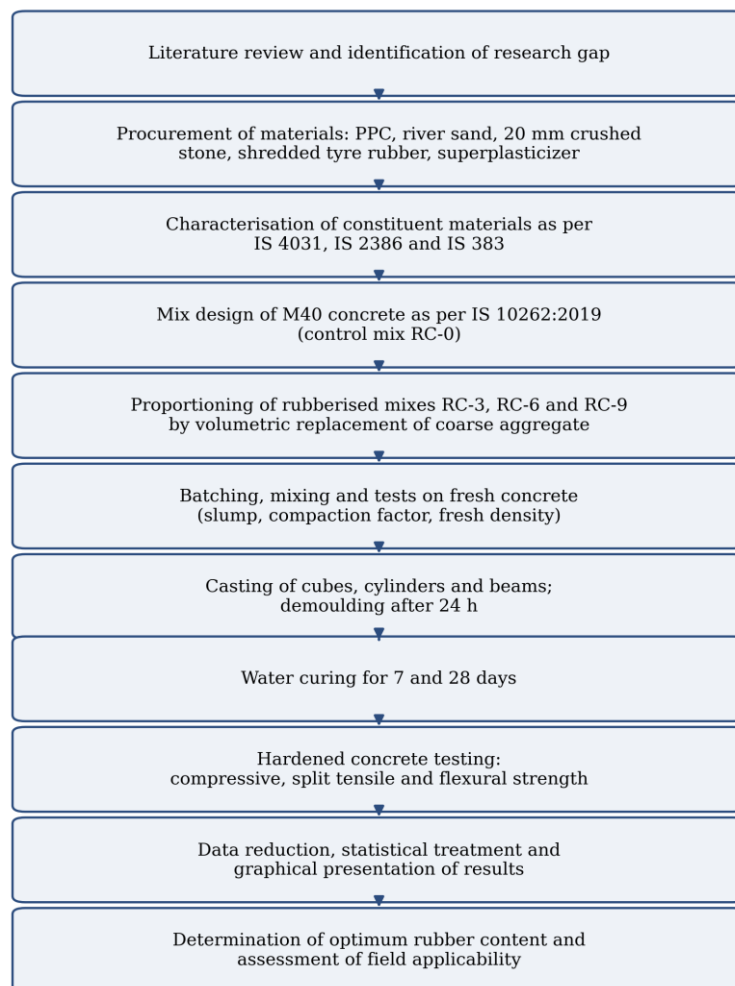


Figure 3.1 Flow chart of the experimental methodology adopted in the present investigation

As Figure 3.1 indicates, material characterisation precedes mix design, and the rubberised mixes are derived from the control mix rather than designed independently. This sequence is deliberate. Deriving all four mixes from a single validated control proportioning ensures that the paste composition, the water-cement ratio and the admixture dosage are identical across the series, so that any difference in measured performance can be attributed unambiguously to the rubber content alone.

3.2 Materials Used

3.2.1 Cement

Portland Pozzolana Cement conforming to IS 1489 (Part 1):1991 was used as the binder throughout the investigation. PPC was preferred over ordinary Portland cement for two reasons. First, the pozzolanic reaction between the fly ash constituent and the calcium

hydroxide liberated during cement hydration consumes the oriented calcium hydroxide crystals that preferentially accumulate in the interfacial transition zone, producing additional calcium silicate hydrate and a denser interface. Since the interfacial transition zone around rubber particles is the acknowledged weak link in rubberised concrete, a binder that acts to refine it is technically appropriate. Second, PPC gives a lower heat of hydration and better long-term durability, both of which are desirable in the non-structural and semi-structural applications for which rubberised concrete is principally intended.

3.2.2 Fine Aggregate

Locally available natural river sand conforming to IS 383:2016 was used as fine aggregate. Sieve analysis carried out in accordance with IS 2386 (Part 1):1963 confirmed that the sand falls within the Zone II grading limits, which is the grading assumed in the coarse aggregate volume tables of IS 10262:2019 and therefore requires no correction to the design proportions. The sand was air-dried and screened to remove any oversize material and organic matter before batching.

3.2.3 Natural Coarse Aggregate

Machine-crushed granite aggregate of 20 mm nominal maximum size, conforming to IS 383:2016, was used as the natural coarse aggregate. The material was tested for aggregate impact value and aggregate crushing value in accordance with IS 2386 (Part 4):1963, and for specific gravity, water absorption and moisture content in accordance with IS 2386 (Part 3):1963. The aggregate was washed and surface-dried before use to remove adhering dust, which would otherwise interfere with paste-aggregate bond.

3.2.4 Shredded Waste Tyre Rubber Aggregate

The rubber aggregate was obtained from a commercial tyre recycling unit in the form of ambient-ground shreds derived from discarded truck and passenger vehicle tyres. Ambient grinding was specified in preference to cryogenic grinding because it produces an irregular, torn surface texture that provides a greater degree of mechanical interlock with the cement paste, partially offsetting the absence of chemical adhesion.

The rubber was screened to the 4.75 to 20 mm size band so that it occupies the same position in the particle size distribution as the natural coarse aggregate it replaces. This is an important control: if the rubber were finer than the stone it replaces, the overall grading of the combined aggregate would change and the effect of that grading change

would be confounded with the effect of the rubber itself. Steel bead and belt wire were removed magnetically during processing, and residual textile cord was removed by air classification, since embedded steel fragments corrode and cause local expansive damage while loose textile fibres absorb mixing water and promote balling.

The rubber was used in the as-received condition without chemical surface treatment. As discussed in Section 2.7, the available evidence indicates that surface treatment recovers only a portion of the strength loss and that the additional processing is difficult to justify at the low replacement levels examined here.

3.2.5 Water

Potable water from the laboratory supply, satisfying the requirements of Clause 5.4 of IS 456:2000 in respect of pH, solid content and organic impurities, was used both for mixing and for curing.

3.2.6 Chemical Admixture

A polycarboxylate ether based high-range water-reducing admixture conforming to IS 9103:1999 was used at a dosage of 1.0 % by mass of cement. The admixture was introduced to achieve the target slump of 100 mm at the design water-cement ratio of 0.40 without increasing the free water content. This is essential to the experimental logic of the study: had water been added instead of admixture to restore workability in the rubberised mixes, the water-cement ratio would have varied between mixes and the strength results would have been uninterpretable. The dosage was held constant across all four mixes for the same reason.

3.3 Characterisation of Constituent Materials

The physical properties of the binder and the aggregates were established before mix proportioning, since the specific gravity values feed directly into the absolute volume computation and the water absorption values govern the free water correction at the batching stage. The properties of the cement are given in Table 3.1.

Table 3.1 Physical properties of Portland Pozzolana Cement

Property	Test method	Measured value	Requirement of IS 1489 (Part 1)
Standard consistency	IS 4031 (Part 4)	35.0 %	Not specified
Initial setting time	IS 4031 (Part 5)	56 min	Minimum 30 min
Final setting time	IS 4031 (Part 5)	320 min	Maximum 600 min

Property	Test method	Measured value	Requirement of IS 1489 (Part 1)
Soundness (Le Chatelier expansion)	IS 4031 (Part 3)	2.0 mm	Maximum 10 mm
Specific gravity	IS 4031 (Part 11)	2.86	Not specified
Compressive strength at 3 days	IS 4031 (Part 6)	16.19 MPa	Minimum 16.0 MPa
Compressive strength at 7 days	IS 4031 (Part 6)	22.39 MPa	Minimum 22.0 MPa

Table 3.1 confirms that the cement satisfies every applicable requirement of IS 1489 (Part 1):1991. The initial setting time of 56 minutes provides an adequate window for mixing, transporting and placing the concrete, while the final setting time of 320 minutes is comfortably within the permitted maximum. The Le Chatelier expansion of 2.0 mm indicates that free lime and magnesia are within acceptable limits and that no delayed expansive reaction is to be expected. The specific gravity of 2.86 is characteristic of a pozzolana-blended cement, being lower than the value of approximately 3.15 typical of ordinary Portland cement because of the lower density of the fly ash constituent; this value is used directly in the absolute volume calculation of Section 3.4. The 3-day and 7-day mortar cube strengths exceed the specified minima by narrow but acceptable margins, which is consistent with the slower early-age strength gain characteristic of PPC.

The properties determined for the fine aggregate are presented in Table 3.2.

Table 3.2 Physical properties of fine aggregate

Property	Test method	Measured value
Grading zone	IS 383:2016	Zone II
Specific gravity (saturated surface dry)	IS 2386 (Part 3)	2.65
Water absorption	IS 2386 (Part 3)	1.75 %
Free moisture content at batching	IS 2386 (Part 3)	1.01 %
Type	—	Natural river sand

The Zone II classification recorded in Table 3.2 is significant beyond mere compliance, because Table 5 of IS 10262:2019, from which the volume of coarse aggregate per unit volume of total aggregate is obtained, is itself tabulated against grading zone. A Zone II sand permits the tabulated value to be used without adjustment. The measured water absorption of 1.75 % against a free moisture content of 1.01 % indicates that the sand was in a partially saturated condition below the saturated surface dry state at the time of batching, and a corresponding correction was applied to the batch water so that the free water-cement ratio remained at the design value.

The characteristics of the natural coarse aggregate are summarised in Table 3.3.

Table 3.3 Physical and mechanical properties of natural coarse aggregate

Property	Test method	Measured value	Permissible limit
Nominal maximum size	IS 383:2016	20 mm	—
Aggregate impact value	IS 2386 (Part 4)	9.67 %	Maximum 30 % (wearing surfaces)
Aggregate crushing value	IS 2386 (Part 4)	16.67 %	Maximum 30 % (wearing surfaces)
Specific gravity (saturated surface dry)	IS 2386 (Part 3)	2.80	—
Water absorption	IS 2386 (Part 3)	2.02 %	—
Free moisture content at batching	IS 2386 (Part 3)	1.94 %	—

The impact value of 9.67 % and the crushing value of 16.67 % reported in Table 3.3 are both well below the 30 % ceiling imposed by IS 383:2016 even for aggregate used in concrete wearing surfaces, and they confirm that the crushed granite is sufficiently tough and strong to be used in a high grade structural concrete. This is a material point for the present study, because in a control concrete whose aggregate is strong and well bonded, the fracture surface tends to pass around rather than through the aggregate particles. Introducing a soft rubber inclusion into such a matrix creates a stiffness contrast far greater than would exist in a concrete made with weak aggregate, and the resulting stress concentration is correspondingly more severe. The high quality of the natural aggregate therefore establishes the reference against which the rubber-induced strength penalty must be judged. The measured water absorption of 2.02 % is relatively high for granite and reflects a moderately porous rock; as with the sand, a batching correction was applied.

The characteristics of the shredded rubber aggregate are given in Table 3.4.

Table 3.4 Properties of shredded waste tyre rubber aggregate

Property	Basis	Value
Source	Supplier declaration	Post-consumer truck and passenger vehicle tyres
Processing route	Supplier declaration	Ambient mechanical shredding and grinding
Particle size band as supplied and screened	Sieve analysis, IS 2386 (Part 1)	4.75 mm to 20 mm
Particle shape	Visual inspection	Irregular, angular, torn surface texture
Steel and textile content after processing	Magnetic and air separation	Nil (visually free of wire and cord)
Specific gravity	IS 2386 (Part 3), pycnometer	To be determined (indicative range 1.10–1.20)

Property	Basis	Value
Water absorption	IS 2386 (Part 3)	To be determined (indicative range 0.5–2.0 %)
Loose bulk density	IS 2386 (Part 3)	To be determined (indicative range 450–550 kg/m ³)

Table 3.4 records the properties of the rubber aggregate. The three quantities marked as pending are those requiring laboratory determination on the specific consignment used; the indicative ranges shown alongside them are those reported consistently in the literature for ambient-ground tyre rubber (Siddique and Naik, 2004; Najim and Hall, 2010). For the purpose of the mix proportioning presented in Section 3.5, a specific gravity of 1.15 has been adopted, and the design will be re-normalised should the measured value differ materially. The essential physical fact conveyed by Table 3.4 is the contrast in specific gravity between the rubber at approximately 1.15 and the natural coarse aggregate at 2.80. This ratio of roughly one to two and a half governs the reduction in fresh density derived in Section 3.5, and it is also the reason why volumetric rather than gravimetric replacement has been adopted in this study.

3.4 Mix Design of the Control Concrete

The control mix RC-0 was designed for M40 grade concrete in accordance with IS 10262:2019, using the measured material properties reported in Section 3.3. The design proceeds by first establishing the target mean strength, then fixing the water-cement ratio and the free water content, and finally distributing the remaining volume between the two aggregate fractions by the absolute volume method.

3.4.1 Target Mean Strength

Concrete must be proportioned for a mean strength exceeding the characteristic strength by a margin sufficient to ensure that not more than five per cent of test results fall below the characteristic value. The target mean compressive strength is obtained from Equation (3.1).

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

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

f_{ek} = characteristic compressive strength at 28 days, taken as 40 MPa for M40;

s = assumed standard deviation, taken as 5.0 MPa for M40 grade from Table 2 of IS 10262:2019.

Substituting these values in Equation (3.1) gives a target mean strength of $40 + 1.65 \times 5.0 = 48.25$ MPa. IS 10262:2019 additionally requires the target strength to be checked against the alternative expression $f_{ek} + X$, where X is 6.5 MPa for M40, giving 46.5 MPa. The higher of the two values, namely 48.25 MPa, is adopted as the design target.

3.4.2 Water-Cement Ratio and Free Water Content

A free water-cement ratio of 0.40 was adopted. This satisfies the maximum of 0.45 permitted by Table 5 of IS 456:2000 for reinforced concrete under moderate exposure and provides an adequate margin below that limit to achieve the target mean strength of 48.25 MPa with a pozzolana-blended binder.

The free water content was established from Table 4 of IS 10262:2019, which gives 186 kg/m³ for 20 mm nominal maximum size aggregate at a slump of 50 mm. The target slump for the present work is 100 mm, requiring an increase of three per cent for each 25 mm of additional slump, that is an increase of six per cent to 197.2 kg/m³. The polycarboxylate ether superplasticizer, used at 1.0 % by mass of cement, permits a water reduction of 25 %, giving a final free water content of 147.9 kg/m³, adopted as 148 kg/m³.

The cement content follows directly as $148 / 0.40 = 370$ kg/m³. This exceeds the minimum cement content of 300 kg/m³ specified by Table 5 of IS 456:2000 for moderate exposure and lies below the ceiling of 450 kg/m³ recommended by Clause 8.2.4.2 of IS 456:2000 for the control of shrinkage and thermal cracking.

3.4.3 Aggregate Proportioning by the Absolute Volume Method

The total volume available to the aggregate fractions is obtained by subtracting the absolute volumes of cement, water, admixture and entrapped air from unit volume, as expressed in Equation (3.2).

$$V_a = 1 - [C/(1000 G_e) + W/1000 + SP/(1000 G_s) + V_v] \quad \dots(3.2)$$

where V_a = absolute volume of total aggregate per cubic metre of concrete, m³;
 C = mass of cement, 370 kg; G_e = specific gravity of cement, 2.86;
 W = mass of free water, 148 kg;
 SP = mass of superplasticizer, 3.7 kg; G_s = specific gravity of admixture, 1.08;
 V_v = volume of entrapped air, taken as 0.015 m³ for 20 mm nominal maximum size aggregate.

Substitution in Equation (3.2) gives an absolute volume of cement of 0.1294 m³, of water 0.1480 m³ and of admixture 0.0034 m³. With the entrapped air volume of 0.0150 m³ the total non-aggregate volume is 0.2958 m³, leaving an aggregate volume V_a of 0.7042 m³.

This volume is apportioned between the coarse and fine fractions using Table 5 of IS 10262:2019, which gives a coarse aggregate volume fraction of 0.62 for 20 mm nominal maximum size aggregate combined with Zone II fine aggregate at a water-cement ratio of 0.50. The tabulated value is increased by 0.01 for every reduction of 0.05 in the water-cement ratio, so at the design ratio of 0.40 the corrected fraction is 0.64. The masses of the two aggregate fractions then follow from Equation (3.3).

$$M_i = V_a \times p_i \times G_i \times 1000 \quad \dots(3.3)$$

where M_i = mass of aggregate fraction i per cubic metre of concrete, kg;

p_i = volume fraction of that aggregate, taken as 0.64 for coarse and 0.36 for fine aggregate;

G_i = specific gravity of that aggregate, 2.80 for coarse and 2.65 for fine aggregate.

Applying Equation (3.3) yields a coarse aggregate volume of 0.4507 m³ corresponding to a mass of 1261.9 kg, and a fine aggregate volume of 0.2535 m³ corresponding to a mass of 671.8 kg. The complete set of design parameters is collected in Table 3.5.

Table 3.5 Summary of the M40 mix design parameters as per IS 10262:2019

Design parameter	Value adopted	Governing clause or table
Grade designation	M40	IS 456:2000, Table 2
Type of cement	PPC, IS 1489 (Part 1):1991	IS 456:2000, Clause 5.1
Nominal maximum size of aggregate	20 mm	IS 456:2000, Clause 5.3.1
Exposure condition	Moderate (reinforced concrete)	IS 456:2000, Table 3
Assumed standard deviation, s	5.0 MPa	IS 10262:2019, Table 2
Target mean strength, f'_{ck}	48.25 MPa	Equation (3.1)
Free water–cement ratio	0.40	IS 456:2000, Table 5 (max 0.45)
Workability (target slump)	100 mm	IS 456:2000, Table 7
Free water content	148 kg/m ³	IS 10262:2019, Table 4
Cement content	370 kg/m ³	Section 3.4.2 (min 300 kg/m ³)
Chemical admixture dosage	1.0 % by mass of cement	IS 9103:1999
Volume of entrapped air	1.5 %	IS 10262:2019
Volume fraction of coarse aggregate	0.64	IS 10262:2019, Table 5 (corrected)

Table 3.5 shows that every design decision is anchored to a specific clause of the governing codes, and that each controlling limit is satisfied with a margin. The resulting batch quantities for the control mix are set out in Table 3.6.

Table 3.6 Batch quantities of the control mix RC-0 per cubic metre

Constituent	Specific gravity	Absolute volume (m ³)	Mass (kg/m ³)	Ratio by mass
Cement (PPC)	2.86	0.1294	370.0	1.00
Free water	1.00	0.1480	148.0	0.40
Fine aggregate	2.65	0.2535	671.8	1.82
Natural coarse aggregate	2.80	0.4507	1261.9	3.41
Superplasticizer	1.08	0.0034	3.7	0.010
Entrapped air	—	0.0150	—	—
Total	—	1.0000	2455.4	—

Table 3.6 gives the final proportion of the control mix as 1 : 1.82 : 3.41 by mass at a free water-cement ratio of 0.40. The absolute volumes sum exactly to unity, which confirms the internal consistency of the computation and establishes the theoretical fresh density of the control concrete as 2455.4 kg/m³. This value serves as the reference against which the density reductions produced by rubber substitution are measured in Section 3.5.

3.5 Proportioning of the Rubberised Mixes

3.5.1 Basis of Replacement

The three rubberised mixes were derived from the control mix by replacing a fixed proportion of the coarse aggregate volume with an equal volume of shredded rubber. The choice of a volumetric rather than a gravimetric basis is a deliberate methodological decision, and it warrants explanation because much of the published literature has adopted the gravimetric alternative.

If replacement is carried out by mass, then substituting a given mass of rubber for an equal mass of stone introduces a volume of rubber approximately two and a half times the volume of stone removed, because the specific gravity of rubber is approximately 1.15 against 2.80 for granite. The consequence is that the total aggregate volume increases, the mix yield exceeds one cubic metre, and the cement content per cubic metre of finished concrete falls. Three variables therefore change simultaneously with the nominal replacement percentage: the rubber content, the aggregate volume fraction and the

effective binder content. Any strength reduction observed under such a scheme cannot be attributed to the rubber alone.

Volumetric replacement avoids all three difficulties. The total aggregate volume is preserved, the yield remains exactly one cubic metre, and the cement content, free water content, water-cement ratio and admixture dosage are identical in every mix. The rubber content becomes the sole independent variable of the experiment. The masses of rubber and residual natural coarse aggregate are obtained from Equation (3.4).

$$M_r = (R/100) V_{CA} G_r \times 1000 \quad \text{and} \quad M_{CA,r} = (1 - R/100) V_{CA} G_{CA} \times 1000 \quad \dots(3.4)$$

where M_r = mass of rubber aggregate per cubic metre of concrete, kg;
 $M_{CA,r}$ = mass of natural coarse aggregate retained in the rubberised mix, kg;
 R = rubber replacement level, per cent by volume of coarse aggregate;
 V_{CA} = absolute volume of coarse aggregate in the control mix, 0.4507 m³;
 G_r = specific gravity of rubber aggregate, taken as 1.15;
 G_{CA} = specific gravity of natural coarse aggregate, 2.80.

Applying Equation (3.4) at replacement levels of 3, 6 and 9 % gives the mix designations and rubber contents shown in Table 3.7. The equivalent replacement expressed on a mass basis is also tabulated, since much of the published literature reports results in those terms and a direct comparison would otherwise be misleading.

Table 3.7 Mix designations and corresponding rubber contents

Mix designation	Rubber replacement, R (% by volume of CA)	Volume of rubber (m ³ /m ³)	Mass of rubber (kg/m ³)	Equivalent replacement (% by mass of CA)
RC-0	0	0.0000	0.0	0.00
RC-3	3	0.0135	15.6	1.23
RC-6	6	0.0270	31.1	2.46
RC-9	9	0.0406	46.7	3.70

The final column of Table 3.7 makes the practical significance of the replacement basis explicit. A replacement of 9 % by volume corresponds to only 3.70 % by mass, a factor of approximately 2.4 arising directly from the ratio of specific gravities. Comparisons drawn with published studies must therefore be made on a consistent basis, and in this report all replacement percentages refer to volume of coarse aggregate unless explicitly stated otherwise.

3.5.2 Batch Quantities

The complete batch quantities for all four mixes are presented in Table 3.8.

Table 3.8 Batch quantities of all four mixes per cubic metre

Constituent (kg/m ³)	RC-0	RC-3	RC-6	RC-9
Cement (PPC)	370.0	370.0	370.0	370.0
Free water	148.0	148.0	148.0	148.0
Fine aggregate	671.8	671.8	671.8	671.8
Natural coarse aggregate	1261.9	1224.1	1186.2	1148.4
Rubber aggregate	0.0	15.6	31.1	46.7
Superplasticizer	3.7	3.7	3.7	3.7
Free water–cement ratio	0.40	0.40	0.40	0.40
Total mass	2455.4	2433.2	2410.8	2388.6

The structure of Table 3.8 embodies the experimental control described in Section 3.5.1. The first three rows and the admixture row are invariant across the series, as is the water-cement ratio. Only the two coarse aggregate rows vary, and they vary in a strictly compensating manner on a volume basis. The reduction in total mass down the final row is therefore a direct and calculable consequence of the density contrast between the two coarse aggregate materials and involves no change whatever in the paste phase.

The same information is presented graphically in Figure 3.2, where the composition of each mix is shown as a stacked bar.

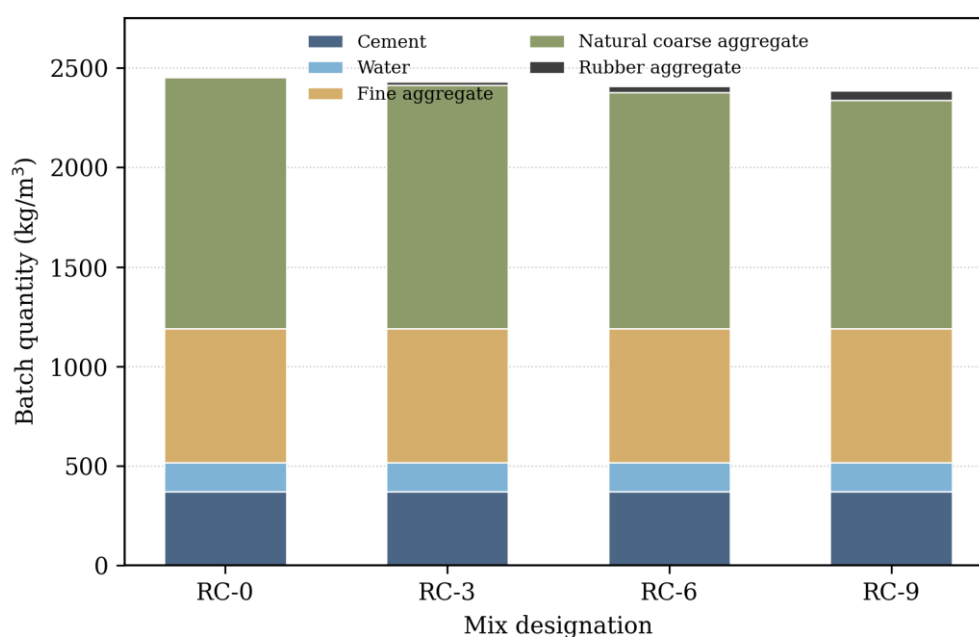


Figure 3.2 Batch quantities of the four concrete mixes per cubic metre

Figure 3.2 shows at a glance that the paste and fine aggregate blocks are identical in all four mixes and that the only visible change is the progressive conversion of the natural coarse aggregate band into the rubber band at its upper edge. The rubber band appears small in mass terms even at 9 % replacement, which is precisely the point developed in the discussion of Table 3.7: a modest mass of rubber occupies a disproportionately large volume.

3.5.3 Theoretical Fresh Density and Yield Check

The theoretical fresh density of each mix follows from the sum of the constituent masses divided by the yield, as given in Equation (3.5).

$$\rho_{th} = (C + W + MFA + MCA_r + M_r + SP) / V_y \quad \dots(3.5)$$

where ρ_{th} = theoretical fresh density of the mix, kg/m³;

MFA = mass of fine aggregate, kg;

V_y = yield of the batch, equal to 1.000 m³ for all four mixes by construction.

The resulting densities and the associated yield check are given in Table 3.9.

Table 3.9 Theoretical fresh density and yield check for the four mixes

Mix	Total constituent mass (kg)	Total absolute volume (m ³)	Theoretical fresh density (kg/m ³)	Reduction relative to RC-0 (%)
RC-0	2455.4	1.0000	2455.4	—
RC-3	2433.2	1.0000	2433.2	0.91
RC-6	2410.8	1.0000	2410.8	1.82
RC-9	2388.6	1.0000	2388.6	2.72

Table 3.9 confirms that the absolute volume sums to unity for every mix, verifying that the proportioning preserves the yield exactly. The density reduction is 0.91 % for each 3 % increment of rubber, giving a strictly linear relationship. This linearity is not an experimental finding but an arithmetic consequence of substituting one material for another at constant volume, and it therefore provides a useful check on the batching: a measured fresh density departing materially from the values in Table 3.9 would indicate either a batching error or an unexpected change in entrapped air content.

The variation is plotted in Figure 3.3.

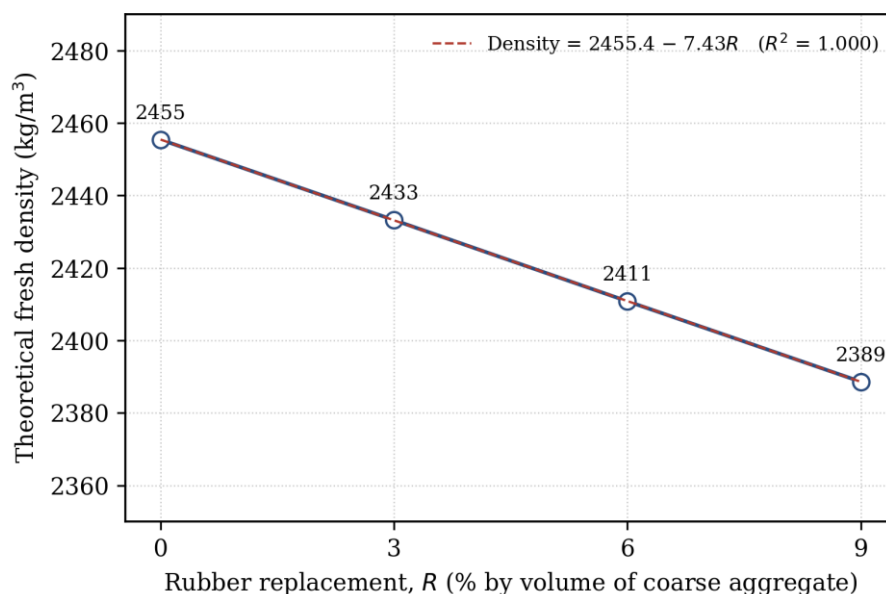


Figure 3.3 Variation of theoretical fresh density with rubber replacement level

Figure 3.3 shows the linear relationship, with a gradient of 7.42 kg/m³ per one per cent of rubber replacement by volume. Extrapolating this gradient indicates that a replacement level of approximately 20 % by volume would be required to bring the density below 2300 kg/m³, so within the range examined here the concrete remains firmly in the normal-weight category. The density reduction achieved is therefore best regarded as a secondary benefit in the form of reduced dead load rather than as a route to structural lightweight concrete. The measured fresh density recorded during the experimental programme will be compared against Figure 3.3, and any systematic positive deviation between the theoretical and measured values will be interpreted as evidence of additional air entrapment at the hydrophobic rubber surface, a mechanism discussed in Section 2.3.

3.6 Batching, Mixing, Casting and Curing

3.6.1 Batching and Mixing

All constituents were batched by mass using a platform balance of 0.1 kg resolution. The batch water was corrected for the free moisture carried by the aggregates and for the absorption deficit of each fraction, so that the free water-cement ratio at the time of mixing was 0.40 in every case.

Mixing was carried out in a pan mixer following a fixed sequence. The natural coarse aggregate, rubber aggregate and fine aggregate were charged first and dry-mixed for one minute to disperse the rubber uniformly through the aggregate skeleton before any paste

was present. This order is important: if the rubber is introduced after the paste, its low density causes it to rise and cluster rather than distribute. The cement was then added and dry mixing continued for a further minute. Approximately ninety per cent of the batch water was then added, followed by the remaining water in which the superplasticizer had been dispersed, and wet mixing continued for three minutes until a homogeneous mix of uniform colour and consistency was obtained.

3.6.2 Casting and Compaction

Tests on fresh concrete were performed immediately after mixing, after which the concrete was placed in steel moulds in three layers of approximately equal depth. Each layer was compacted on a vibrating table for a controlled duration, and the duration was deliberately limited to the minimum necessary to close the surface.

This restriction is more important for rubberised concrete than for conventional concrete. Because rubber particles are buoyant relative to the surrounding mortar, prolonged vibration causes them to migrate towards the upper surface, producing a rubber-rich cap and a rubber-depleted base within the same specimen. Khaloo et al. (2008) documented exactly this form of segregation. Since the compressive strength of a cube is governed by the weakest horizontal plane within it, such segregation would introduce a systematic bias that increases with rubber content and would be indistinguishable from a genuine material effect. Compaction time was therefore standardised across all four mixes.

The top surface of each specimen was finished with a steel trowel. The specimens were then covered with damp hessian and left undisturbed in the laboratory for twenty-four hours before demoulding.

3.6.3 Curing

After demoulding, all specimens were immersed in a clean water curing tank maintained at ambient laboratory temperature, in accordance with IS 516:1959. Specimens were removed at 7 and 28 days as required by the test schedule, surface-dried and tested within thirty minutes of removal so that the internal moisture state at testing was consistent between specimens. Continuous immersion curing was adopted in preference to intermittent curing so that the degree of hydration would be as uniform as possible across the series.

3.7 Experimental Matrix

The complete schedule of specimens is presented in Table 3.10. Three replicate specimens were cast for every combination of mix, test type and test age, so that the mean of three results may be reported and any individual result departing from the mean by more than fifteen per cent may be identified and investigated in accordance with Clause 5.5 of IS 516:1959.

Table 3.10 Experimental matrix and specimen schedule

Specimen type	Dimensions (mm)	Property determined	Replicates per mix per age	Test ages (days)	Total number
Cube	150 x 150 x 150	Compressive strength	3	7 and 28	24
Cylinder	150 dia. x 300 high	Split tensile strength	3	7 and 28	24
Prism (beam)	100 x 100 x 500	Flexural strength	3	7 and 28	24
Total	—	—	—	—	72

As Table 3.10 shows, the programme comprises seventy-two hardened specimens distributed evenly across the four mixes, giving eighteen specimens per mix. The use of three replicates throughout, rather than the single specimen per condition that is sometimes adopted in student projects, is essential here because the strength differences being sought between adjacent replacement levels are of the same order as the normal scatter of concrete test results. Without replication it would be impossible to distinguish a genuine trend from experimental noise. In addition to these seventy-two specimens, fresh concrete tests were performed on each of the four batches at the time of mixing.

3.8 Test Methods and Governing Relations

3.8.1 Slump Cone Test

The slump cone test was conducted in accordance with IS 1199:1959 to assess the consistency of the fresh concrete. The standard frustum mould, 200 mm in base diameter, 100 mm in top diameter and 300 mm in height, was filled in four layers, each tamped twenty-five times with a 16 mm diameter rod. The mould was lifted vertically and the subsidence of the concrete measured. The arrangement is shown schematically in Figure 3.4.

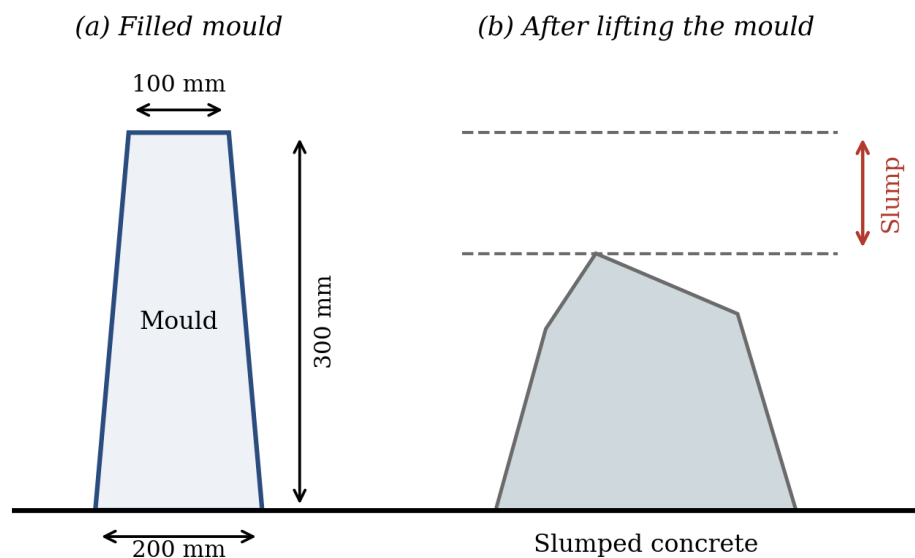


Figure 3.4 Schematic arrangement of the slump cone test

Figure 3.4 illustrates both the filled mould and the slumped mass after the mould has been lifted, the slump being the difference in height between the top of the mould and the highest point of the subsided concrete. The test measures the capacity of the mix to deform under its own weight and is therefore sensitive to the yield stress of the fresh concrete. Since rubber particles increase inter-particle friction and entrap air, a progressive reduction in slump with rubber content is anticipated, consistent with the observations of Khatib and Bayomy (1999) and Batayneh et al. (2008).

3.8.2 Compaction Factor Test

The compaction factor test, also conducted in accordance with IS 1199:1959, provides a more discriminating measure of workability for mixes of low to medium consistency than the slump test, because it measures the work required to achieve full compaction rather than the flow under self-weight. The apparatus is shown in Figure 3.5.

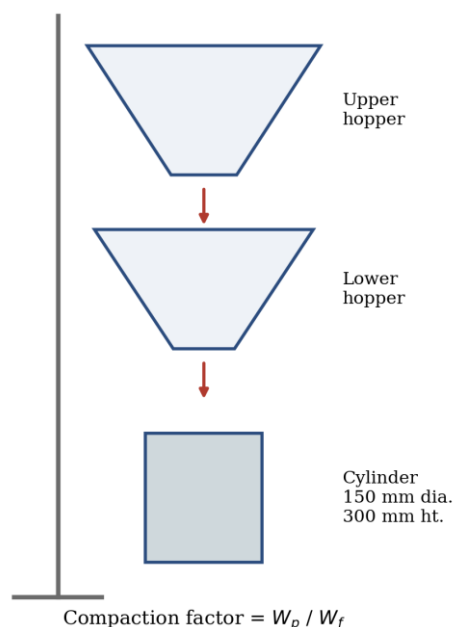


Figure 3.5 Schematic arrangement of the compaction factor apparatus

As Figure 3.5 shows, concrete is allowed to fall from an upper hopper into a lower hopper and thence into a cylinder of known volume, so that the degree of compaction achieved under a standardised amount of work may be determined. The compaction factor is calculated from Equation (3.6).

$$\text{Compaction factor} = W_p / W_F \quad \dots(3.6)$$

where W_p = mass of partially compacted concrete filling the cylinder, kg;

W_F = mass of fully compacted concrete filling the same cylinder, kg.

The compaction factor is a dimensionless ratio, always less than unity, with higher values indicating greater workability. Because the test reflects the internal friction of the mix directly, it is expected to be the more sensitive of the two workability measures for the rubberised mixes.

3.8.3 Compressive Strength Test

Compressive strength was determined on 150 mm cubes in accordance with IS 516:1959 using a calibrated compression testing machine of 2000 kN capacity. The load was applied without shock at a uniform rate of 14 N/mm² per minute until failure. The specimen was placed with the cast top surface vertical, so that load is applied to two machine-finished faces and the effect of surface irregularity is eliminated. The compressive strength is obtained from Equation (3.7).

$$f_c = P / A$$

...(3.7)

where f_c = compressive strength of the cube, MPa;
 P = maximum load at failure, N;
 A = loaded cross-sectional area of the cube, 22 500 mm² for a 150 mm cube.

3.8.4 Split Tensile Strength Test

The direct measurement of the tensile strength of concrete is impractical because of the difficulty of gripping the specimen without introducing local stress concentrations. The split tensile test, conducted in accordance with IS 5816:1999, circumvents this by loading a cylinder in compression along two diametrically opposite generators, which induces a nearly uniform tensile stress across the vertical diametral plane. The specimen fails by splitting along that plane. Plywood packing strips 3 mm thick were placed between the specimen and the platens to distribute the load and avoid local crushing at the contact lines. The split tensile strength is calculated from Equation (3.8).

$$f_{et} = 2P / (\pi L D)$$

...(3.8)

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

3.8.5 Flexural Strength Test

Flexural strength, or modulus of rupture, was determined on 100 x 100 x 500 mm prisms under four-point loading over an effective span of 400 mm in accordance with IS 516:1959. Four-point loading is used in preference to central point loading because it produces a region of constant bending moment and zero shear between the two load points, so that failure occurs at the weakest section within that region rather than at an arbitrarily imposed location. The load was applied at a rate of 180 kg/min for the 100 mm specimen. The modulus of rupture is obtained from Equation (3.9).

$$f_{er} = P l / (b d^2) \quad \text{when } a > 133 \text{ mm}$$

...(3.9)

where f_{er} = modulus of rupture, MPa;
 P = maximum load applied to the specimen, N;
 l = effective span, 400 mm;
 b = measured width of the specimen, 100 mm;
 d = measured depth of the specimen, 100 mm;

a = distance between the line of fracture and the nearer support, measured on the tension face, mm.

Where the line of fracture falls outside the middle third of the span, but the value of a lies between 110 mm and 133 mm for a 100 mm specimen, IS 516:1959 requires the modulus of rupture to be computed instead from Equation (3.10).

$$f_{er} = 3 P a / (b d^2) \quad \dots(3.10)$$

If a is less than 110 mm the result is discarded. This provision is of particular relevance to the rubberised mixes, because crack deflection around the compliant rubber inclusions may cause the fracture plane to wander from the section of maximum moment, and the position of the fracture must therefore be recorded for every prism tested.

The three hardened concrete loading configurations are shown together in Figure 3.6.

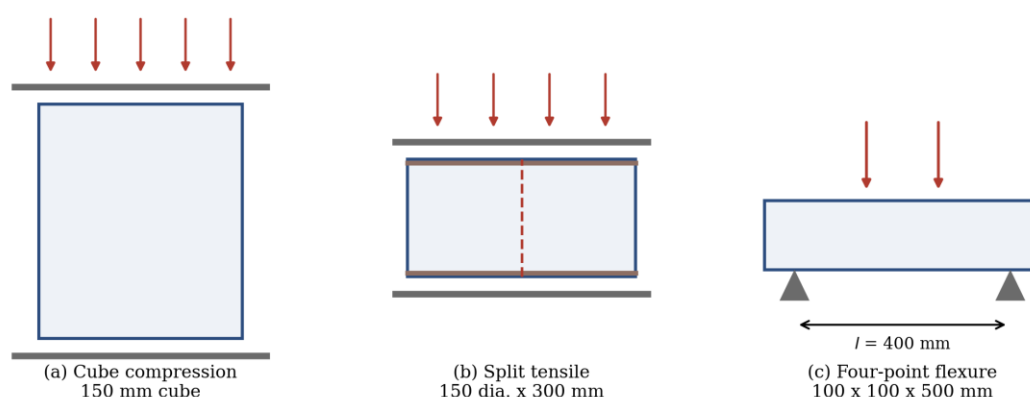


Figure 3.6 Loading configurations adopted for the hardened concrete tests

Figure 3.6 shows that the three tests place the concrete in fundamentally different stress states: near-uniaxial compression in the cube, indirect tension across the diametral plane in the cylinder, and combined flexural compression and tension in the prism. Because rubber inclusions influence compressive and tensile response through different mechanisms, discussed in Sections 2.4 and 2.5, the three tests are expected to respond to rubber content by different amounts, and it is the comparison between them rather than any single result that carries the principal technical interest of the study.

3.8.6 Summary of Test Methods

The test methods, specimen geometries and governing standards are consolidated in Table 3.11.

Table 3.11 Summary of test methods, specimen geometry and governing standards

Test	Specimen	Governing standard	Governing relation	Test ages
Slump cone	Fresh concrete	IS 1199:1959	Direct measurement	At mixing
Compaction factor	Fresh concrete	IS 1199:1959	Equation (3.6)	At mixing
Fresh density	Fresh concrete	IS 1199:1959	Mass / known volume	At mixing
Compressive strength	150 mm cube	IS 516:1959	Equation (3.7)	7 and 28 days
Split tensile strength	150 x 300 mm cylinder	IS 5816:1999	Equation (3.8)	7 and 28 days
Flexural strength	100 x 100 x 500 mm prism	IS 516:1959	Equations (3.9) and (3.10)	7 and 28 days

3.8.7 Basis for the Mechanistic Interpretation of Results

The tests listed in Table 3.11 measure macroscopic quantities, but the differences between the four mixes originate at the scale of the individual aggregate particle and its surrounding paste. Figure 3.7 contrasts the interfacial condition around a natural coarse aggregate particle with that around a rubber particle, and provides the physical reference against which the measured results are interpreted in Chapter 4.

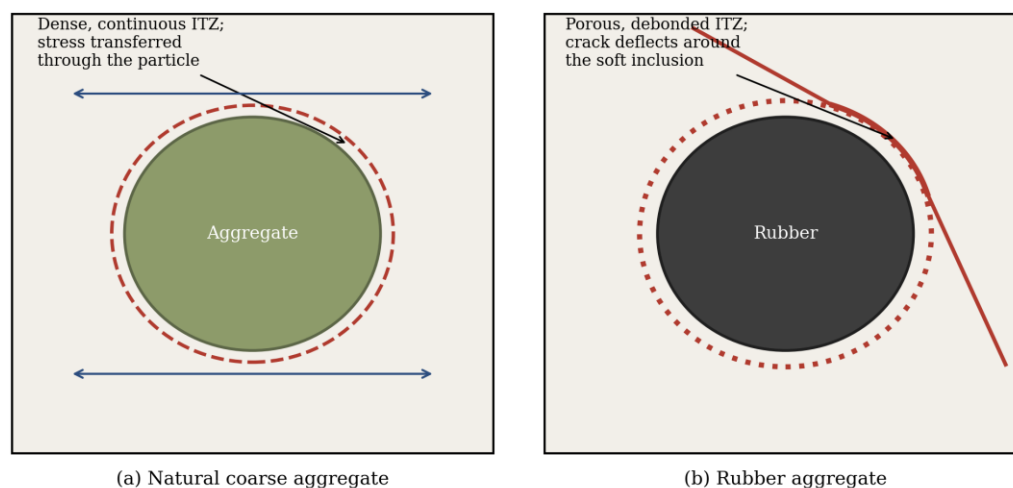


Figure 3.7 Idealised interfacial transition zone around natural and rubber aggregate particles

In Figure 3.7(a) the transition zone around the natural aggregate is dense and continuous, and stress applied to the composite is transferred into and through the stiff particle, which carries its share of the load. In Figure 3.7(b) the hydrophobic rubber surface has attracted a water film during mixing, producing a locally elevated water-cement ratio, a porous shell and a partially debonded interface across which tensile stress cannot be transmitted. Under compression the particle therefore behaves mechanically as a void and sheds its load into the surrounding mortar, which is the origin of the strength reduction described

in Section 2.4. Under tension the same debonded, compliant particle forces a propagating crack to deflect around it, lengthening the crack path and dissipating energy, which is the origin of the retained post-cracking capacity described in Section 2.5. The two effects are inseparable consequences of a single microstructural condition, and it is this duality that the experimental programme is designed to quantify.

Table 3.11 establishes that every quantity reported in Chapter 4 is derived from a measurement made under a named Indian Standard and reduced through an explicitly stated relation, so that the results are reproducible and directly comparable with published data obtained under the same standards.

3.9 Summary

This chapter has established the complete experimental framework of the investigation. The constituent materials have been characterised and shown to satisfy the requirements of the relevant Indian Standards, with the cement conforming to IS 1489 (Part 1):1991, the fine aggregate falling in Zone II of IS 383:2016 and the coarse aggregate exhibiting impact and crushing values well within the limits of that code.

An M40 control mix has been designed to IS 10262:2019, yielding a proportion of 1 : 1.82 : 3.41 by mass at a free water-cement ratio of 0.40, with a cement content of 370 kg/m³ and a theoretical fresh density of 2455.4 kg/m³. Three rubberised mixes have been derived from this control by strictly volumetric substitution of 3, 6 and 9 % of the coarse aggregate, an arrangement that holds the paste composition, water-cement ratio, admixture dosage, aggregate volume fraction and mix yield constant and isolates the rubber content as the single independent variable. The theoretical fresh density falls linearly to 2388.6 kg/m³ at the highest replacement level, a reduction of 2.72 %.

A programme of seventy-two hardened specimens with three replicates per condition has been scheduled, and the test methods and governing relations have been set out. The following chapter presents the experimental programme in its executable form together with the analytical framework through which the results will be interpreted.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

This chapter presents and interprets the experimental results obtained from the four concrete mixes described in Chapter 3. The fresh concrete results are considered first, since the workability and density measurements govern the interpretation of everything that follows. The hardened concrete results are then presented in the order compressive, split tensile and flexural strength, each accompanied by the individual specimen values, the group mean and coefficient of variation, and the percentage variation relative to the control mix. The three properties are then compared against one another, the optimum replacement level is identified, the findings are placed alongside the published literature, and three observations requiring verification against the laboratory batch sheets are set out explicitly.

All strength values have been computed from the recorded failure loads using the relations established in Section 3.8. Percentage variations are computed throughout from Equation (4.1).

$$\Delta_x = [(X_r - X_0) / X_0] \times 100 \quad \dots(4.1)$$

where Δ_x = percentage variation of the property under consideration, %;

X_r = mean value of the property for the rubberised mix at replacement level R;

X_0 = mean value of the same property for the control mix RC-0 at the same age.

A negative value of Δ_x denotes a reduction relative to the control mix.

4.2 Properties of Fresh Concrete

The workability and density of each batch were measured immediately after mixing in accordance with IS 1199:1959. The results are presented in Table 4.1, in which the measured fresh density is set against the theoretical value derived from the mix proportioning in Table 3.9.

Table 4.1 Workability and fresh density of the four mixes

Mix	Rubber content (% by vol.)	Slump (mm)	Variation in slump (%)	Compaction factor	Measured fresh density (kg/m ³)	Theoretical fresh density (kg/m ³)	Density deficit (%)
RC-0	0	85	—	0.92	2385	2455.4	2.87
RC-3	3	70	-17.65	0.89	2330	2433.2	4.24

Mix	Rubber content (% by vol.)	Slump (mm)	Variation in slump (%)	Compaction factor	Measured fresh density (kg/m ³)	Theoretical fresh density (kg/m ³)	Density deficit (%)
RC-6	6	55	-35.29	0.86	2275	2410.8	5.63
RC-9	9	40	-52.94	0.83	2210	2388.6	7.48

Table 4.1 shows a strong and consistent reduction in workability with increasing rubber content. The slump falls from 85 mm for the control mix to 40 mm at 9 % replacement, a reduction of 52.94 %, while the compaction factor falls from 0.92 to 0.83. The relationship between the two measures is plotted in Figure 4.1.

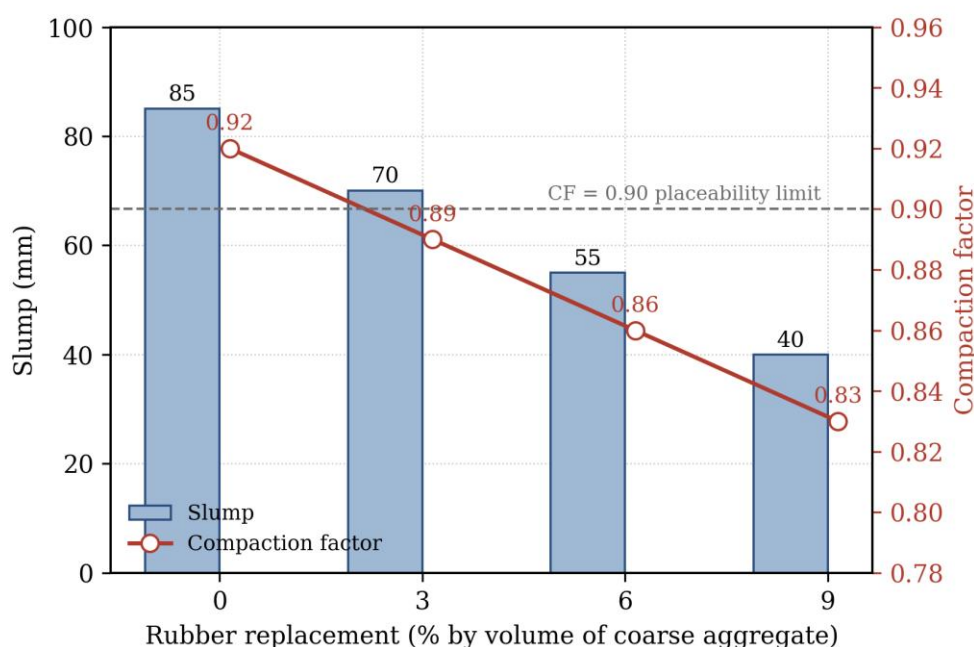


Figure 4.1 Variation of slump and compaction factor with rubber replacement level

Figure 4.1 shows that both measures decline essentially linearly, the slump at approximately 5 mm and the compaction factor at approximately 0.010 for each one per cent of rubber replacement by volume. Two mechanisms operate together. The first is geometric: the ambient-ground rubber shreds have an irregular, torn surface texture, and the resulting inter-particle friction is considerably higher than that of the relatively rounded crushed stone they replace, so a greater shear stress must be overcome before the mix will flow. The second is the air retained at the hydrophobic rubber surface, which raises the apparent cohesion of the mix and resists the slumping deformation. Both mechanisms are consistent with the observations of Khatib and Bayomy (1999) and Batayneh et al. (2008).

The practical significance lies in the compaction factor rather than the slump. Applying the placeability threshold of 0.90 adopted in Section 4.7, the control mix at 0.92 is comfortably placeable, RC-3 at 0.89 is marginal, and RC-6 and RC-9 at 0.86 and 0.83 would require either increased compactive effort or an increased superplasticizer dosage in practice. Since the admixture dosage was deliberately held constant across the series to preserve the experimental control, this constitutes a workability limit that is independent of any strength consideration and is reached at a lower replacement level than the strength criteria are.

The density results are of greater diagnostic value and are plotted against the theoretical values in Figure 4.2.

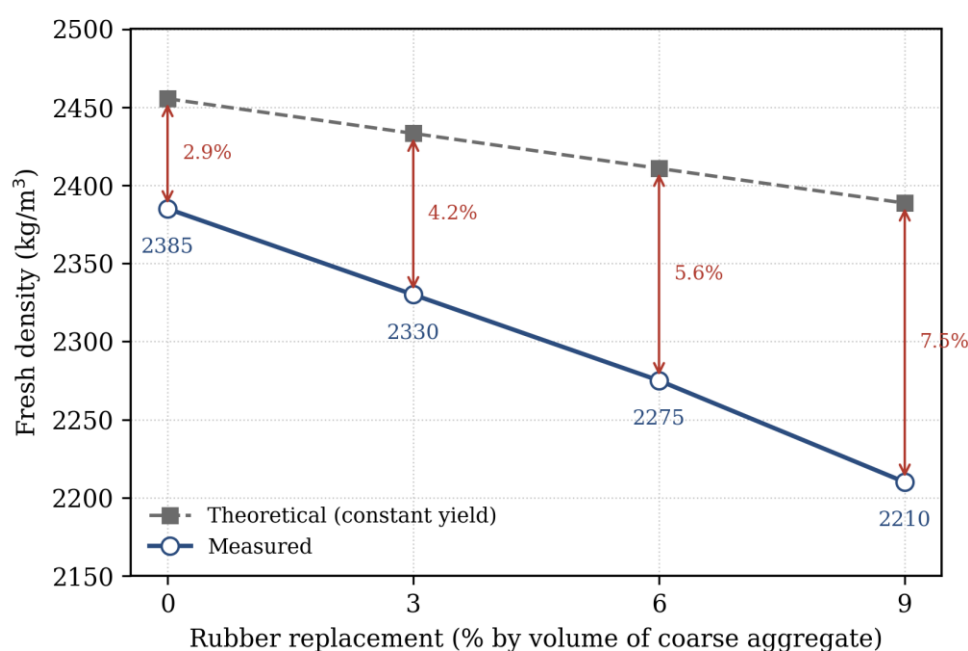


Figure 4.2 Measured and theoretical fresh density, showing the widening density deficit

Figure 4.2 reveals a finding of central importance to the interpretation of the entire strength dataset. The measured fresh density lies below the theoretical value for every mix, and the deficit widens systematically from 2.87 % for the control mix to 7.48 % at 9 % replacement. Because the mixes were proportioned to a constant yield of exactly one cubic metre, the theoretical density is known exactly and is not itself subject to experimental error. A measured density below the theoretical value can therefore arise only from air occupying volume that the calculation assigned to solid or liquid.

The mix design assumed an entrapped air content of 1.5 % in accordance with IS 10262:2019. Adding the measured deficit to that assumed value gives an estimate of the actual air content in the fresh concrete, and these estimates are presented in Table 4.2.

Table 4.2 Estimated air content derived from the fresh density deficit

Mix	Assumed entrapped air in design (%)	Density deficit (%)	Estimated actual air content (%)	Increase over RC-0 (percentage points)
RC-0	1.50	2.87	4.37	—
RC-3	1.50	4.24	5.74	1.37
RC-6	1.50	5.63	7.13	2.76
RC-9	1.50	7.48	8.98	4.61

Table 4.2 indicates that the actual air content rose from approximately 4.4 % in the control mix to approximately 9.0 % at 9 % replacement. Both values are high. The control figure of 4.4 % is roughly three times the value assumed in design and points to compaction that was less than fully effective even in the absence of rubber, which is discussed further in Section 4.8. The increase of 4.61 percentage points between RC-0 and RC-9 is, however, attributable directly to the rubber, and it confirms quantitatively the air-retention mechanism proposed in Section 2.3 on the basis of the literature.

This result must be carried forward into the interpretation of the strength data. Compressive strength is acutely sensitive to porosity, and the widely applied rule of thumb attributes a strength loss of approximately five to six per cent to each one per cent of additional air. On that basis the additional air alone would account for strength reductions of roughly 7.5 %, 15 % and 25 % at RC-3, RC-6 and RC-9 respectively. The rubber therefore reduces strength through two largely independent routes, the soft inclusion itself and the air it entrains, and the second route accounts for a substantial share of the total.

4.3 Compressive Strength

Compressive strength was determined on three 150 mm cube specimens per mix at each age, the failure load being converted to strength through Equation (3.7). The individual specimen results are presented in Table 4.3.

Table 4.3 Individual and mean compressive strength of cube specimens

Mix	Age (days)	Specimen 1 (kN / MPa)	Specimen 2 (kN / MPa)	Specimen 3 (kN / MPa)	Mean strength (MPa)	Std. dev. (MPa)	CV (%)
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Mix	Age (days)	Specimen 1 (kN / MPa)	Specimen 2 (kN / MPa)	Specimen 3 (kN / MPa)	Mean strength (MPa)	Std. dev. (MPa)	CV (%)
RC-0	7	585 / 26.00	602 / 26.76	574 / 25.51	26.09	0.626	2.40
RC-0	28	875 / 38.89	890 / 39.56	860 / 38.22	38.89	0.667	1.71
RC-3	7	510 / 22.67	525 / 23.33	498 / 22.13	22.71	0.602	2.65
RC-3	28	765 / 34.00	780 / 34.67	750 / 33.33	34.00	0.667	1.96
RC-6	7	420 / 18.67	435 / 19.33	412 / 18.31	18.77	0.518	2.76
RC-6	28	630 / 28.00	645 / 28.67	618 / 27.47	28.04	0.601	2.14
RC-9	7	340 / 15.11	352 / 15.64	332 / 14.76	15.17	0.448	2.95
RC-9	28	510 / 22.67	525 / 23.33	498 / 22.13	22.71	0.602	2.65

No individual result in Table 4.3 departs from its group mean by more than three per cent, so none falls within the fifteen per cent investigation threshold of Clause 5.5 of IS 516:1959 and no result has been discarded. The coefficient of variation is small throughout, indicating good control of casting and testing.

The coefficient of variation nevertheless follows a clear trend, rising at 28 days from 1.71 % for the control mix to 2.65 % at 9 % replacement, and at 7 days from 2.40 % to 2.95 %. This behaviour is precisely what the mechanism advanced in Section 2.4 predicts. If the rubber particles act as randomly distributed soft defects, the strength of any individual specimen depends in part on the chance arrangement of those particles within the critically stressed region, and the scatter between nominally identical specimens should therefore increase with rubber content. That it does so consistently across both ages provides independent support for the defect model, and it also reinforces the argument made in Section 3.7 for casting three replicates rather than one.

The mean strengths and the percentage variations relative to the control mix are consolidated in Table 4.4.

Table 4.4 Mean compressive strength and percentage variation relative to the control mix

Mix	7-day mean (MPa)	Variation at 7 d (%)	28-day mean (MPa)	Variation at 28 d (%)	Ratio of 7-day to 28-day strength
RC-0	26.09	—	38.89	—	0.671
RC-3	22.71	−12.96	34.00	−12.57	0.668
RC-6	18.77	−28.06	28.04	−27.90	0.669
RC-9	15.17	−41.86	22.71	−41.60	0.668

Table 4.4 contains two results of distinct significance. The first concerns the rate of strength development. The ratio of 7-day to 28-day strength is 0.671, 0.668, 0.669 and

0.668 for the four mixes, a spread of less than half a per cent. This near-invariance is a strong and unambiguous finding. It demonstrates that the rubber influences only the magnitude of the strength achieved and not the kinetics of its development, which is exactly what would be expected of a chemically inert inclusion that takes no part in hydration and does not alter the composition of the paste phase. Had the ratio drifted systematically with rubber content, it would have indicated that the rubber was interfering with the paste itself, for instance by redistributing mixing water. It did not, and the experimental control established in Section 3.5 is thereby validated from the results themselves.

The second result is the magnitude of the strength reduction, which reaches 41.60 % at 28 days for RC-9. The variation is plotted in Figure 4.3.

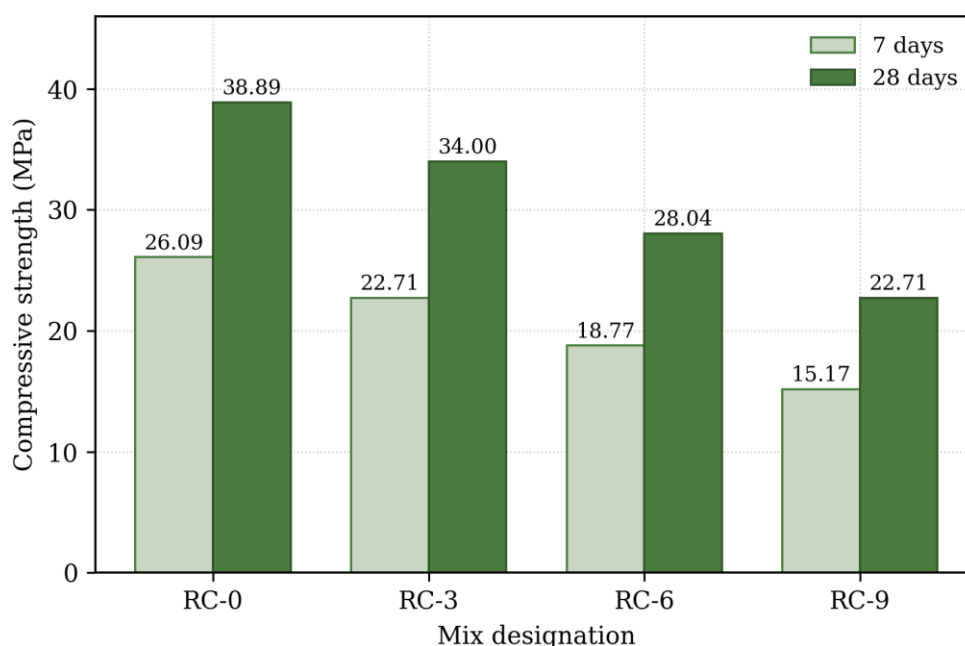


Figure 4.3 Compressive strength of the four mixes at 7 and 28 days

Figure 4.3 shows that the reduction is close to linear across the range examined, the successive decrements at 28 days being 12.57, 15.33 and 13.70 percentage points. This is a departure from the behaviour anticipated in Section 4.7 of the earlier programme document, where a steeper initial loss followed by a flattening was expected on the basis of the relative strength factor of Khatib and Bayomy (1999). That model rests on a percolation-type argument in which the earliest inclusions are the most damaging because they interrupt the strongest continuous load paths through the aggregate skeleton, and it predicts a concave relationship.

The observed linearity is explained by the air content result of Section 4.2. The estimated air content rises almost linearly with rubber content, and porosity-driven strength loss is itself approximately linear in air content over this range. The linear air contribution therefore superimposes on the concave stiffness-contrast contribution and the sum is close to linear. In other words, the shape of the curve in Figure 4.3 is evidence that air entrainment, rather than the stiffness contrast alone, is the dominant mechanism in this particular experiment. Comparing the air-attributable loss estimated in Section 4.2 with the observed loss suggests that roughly sixty per cent of the total reduction is attributable to the additional air and the remaining forty per cent to the soft inclusion and its weak interfacial transition zone.

This distinction has practical consequences. The stiffness contrast is intrinsic to the material and cannot be eliminated. The air content, by contrast, is a processing variable, and the results suggest that a substantial part of the strength penalty observed here could be recovered through improved compaction, an air-detraining admixture, or surface treatment of the rubber to reduce its hydrophobicity.

It must also be recorded that the control mix RC-0 attained a mean 28-day compressive strength of 38.89 MPa against a design target mean of 48.25 MPa and a characteristic strength of 40 MPa. The control concrete therefore did not achieve the M40 grade for which it was designed. This is discussed in Section 4.8.

4.4 Split Tensile Strength

Split tensile strength was determined on three cylindrical specimens per mix at each age, the failure load being converted to strength through Equation (3.8). The individual results are presented in Table 4.5.

Table 4.5 Individual and mean split tensile strength of cylindrical specimens

Mix	Age (days)	Specimen 1 (kN / MPa)	Specimen 2 (kN / MPa)	Specimen 3 (kN / MPa)	Mean strength (MPa)	CV (%)
RC-0	7	165 / 2.334	172 / 2.433	158 / 2.235	2.334	4.24
RC-0	28	245 / 3.466	255 / 3.607	238 / 3.367	3.480	3.47
RC-3	7	142 / 2.009	148 / 2.094	136 / 1.924	2.009	4.23
RC-3	28	212 / 2.999	220 / 3.112	205 / 2.900	3.004	3.53
RC-6	7	120 / 1.698	126 / 1.782	115 / 1.627	1.702	4.58
RC-6	28	180 / 2.546	188 / 2.660	174 / 2.462	2.556	3.89
RC-9	7	98 / 1.386	103 / 1.457	94 / 1.330	1.391	4.59
RC-9	28	148 / 2.094	154 / 2.179	142 / 2.009	2.094	4.05

The coefficients of variation in Table 4.5 are uniformly larger than the corresponding values for compression in Table 4.3, ranging from 3.47 % to 4.59 % against 1.71 % to 2.95 %. This is expected and is not a defect of the experiment. The split tensile test interrogates a single diametral plane, so the result depends on the weakest section along that plane rather than on the average condition of the specimen, and tensile tests on brittle materials are inherently more scattered than compressive tests. As with compression, the scatter increases with rubber content.

The mean values and percentage variations are summarised in Table 4.6.

Table 4.6 Mean split tensile strength and percentage variation relative to the control mix

Mix	7-day mean (MPa)	Variation at 7 d (%)	28-day mean (MPa)	Variation at 28 d (%)
RC-0	2.334	—	3.480	—
RC-3	2.009	−13.93	3.004	−13.68
RC-6	1.702	−27.08	2.556	−26.55
RC-9	1.391	−40.40	2.094	−39.83

The variation is plotted in Figure 4.4.

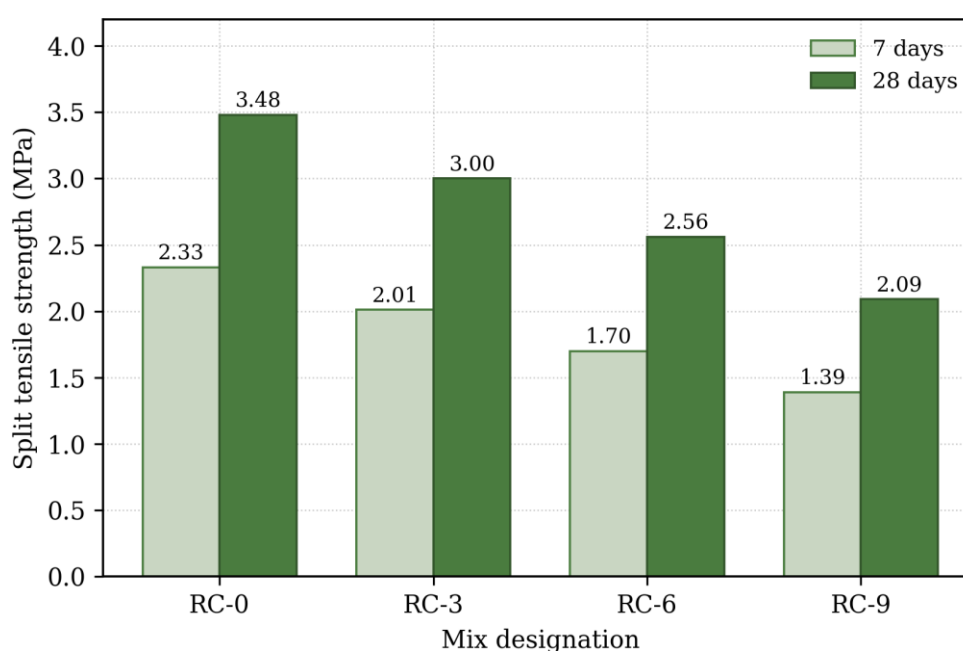


Figure 4.4 Split tensile strength of the four mixes at 7 and 28 days

Figure 4.4 shows the same broadly linear decline observed in compression. At 28 days the reduction reaches 39.83 % for RC-9, marginally smaller than the 41.60 % recorded in

compression. The margin at RC-3 runs in the opposite direction, the tensile loss of 13.68 % slightly exceeding the compressive loss of 12.57 %.

The mode of failure changed in a manner consistent with the crack-bridging mechanism described in Section 2.5. The control cylinders separated abruptly into two halves along the loaded diametral plane, whereas the rubberised specimens, particularly RC-6 and RC-9, remained partially connected across the fracture plane after the peak load, with rubber particles visible spanning the crack faces. Examination of the fracture surfaces also confirmed that the rubber was distributed uniformly through the specimen depth, indicating that the restriction on vibration time imposed in Section 3.6.2 was effective in preventing the buoyant segregation reported by Khaloo et al. (2008).

4.5 Flexural Strength

Flexural strength was determined on three prism specimens per mix at each age under third-point loading over an effective span of 400 mm. The fracture position was recorded for every specimen, and the modulus of rupture was computed from Equation (3.9) where the fracture fell within the middle third of the span and from Equation (3.10) where it fell outside the middle third but at a distance greater than 110 mm from the nearer support. The results are presented in Table 4.7.

Table 4.7 Individual and mean flexural strength of prism specimens, with fracture positions

Mix	Age (d)	Failure loads (kN)	Fracture positions, a (mm)	Relation applied	Individual f_{cr} (MPa)	Mean (MPa)	CV (%)
RC-0	7	14.8 / 15.4 / 14.2	145 / 150 / 125	(3.9) / (3.9) / (3.10)	5.92 / 6.16 / 5.33	5.80	7.41
RC-0	28	22.1 / 22.8 / 21.5	140 / 138 / 152	(3.9) / (3.9) / (3.9)	8.84 / 9.12 / 8.60	8.85	2.94
RC-3	7	13.0 / 13.6 / 12.5	142 / 128 / 148	(3.9) / (3.10) / (3.9)	5.20 / 5.22 / 5.00	5.14	2.38
RC-3	28	19.4 / 20.1 / 18.8	155 / 140 / 136	(3.9) / (3.9) / (3.9)	7.76 / 8.04 / 7.52	7.77	3.35
RC-6	7	11.2 / 11.7 / 10.8	135 / 146 / 122	(3.9) / (3.9) / (3.10)	4.48 / 4.68 / 3.95	4.37	8.59
RC-6	28	16.7 / 17.3 / 16.1	148 / 152 / 141	(3.9) / (3.9) / (3.9)	6.68 / 6.92 / 6.44	6.68	3.59
RC-9	7	9.3 / 9.8 / 8.9	140 / 126 / 150	(3.9) / (3.10) / (3.9)	3.72 / 3.70 / 3.56	3.66	2.41
RC-9	28	13.8 / 14.4 / 13.3	138 / 145 / 142	(3.9) / (3.9) / (3.9)	5.52 / 5.76 / 5.32	5.53	3.98

Every fracture in Table 4.7 occurred at a distance greater than 110 mm from the nearer support, so no result required to be discarded under IS 516:1959. Four specimens, one each in the 7-day groups of RC-0, RC-3, RC-6 and RC-9, fractured outside the middle third and were evaluated using Equation (3.10). It is noteworthy that all four such cases

occurred at 7 days and none at 28 days, and that they are distributed evenly across the four mixes rather than concentrated in the rubberised ones. There is therefore no evidence in this dataset that the rubber inclusions caused the fracture plane to wander systematically from the section of maximum moment, which was one of the possibilities identified in Section 4.5 of the programme design. The crack deflection that the mechanism of Section 2.5 predicts evidently operates at the scale of the individual particle without displacing the macroscopic failure plane.

The mean values and percentage variations are given in Table 4.8.

Table 4.8 Mean flexural strength and percentage variation relative to the control mix

Mix	7-day mean (MPa)	Variation at 7 d (%)	28-day mean (MPa)	Variation at 28 d (%)
RC-0	5.80	—	8.85	—
RC-3	5.14	−11.38	7.77	−12.20
RC-6	4.37	−24.66	6.68	−24.52
RC-9	3.66	−36.90	5.53	−37.51

The variation is plotted in Figure 4.5.

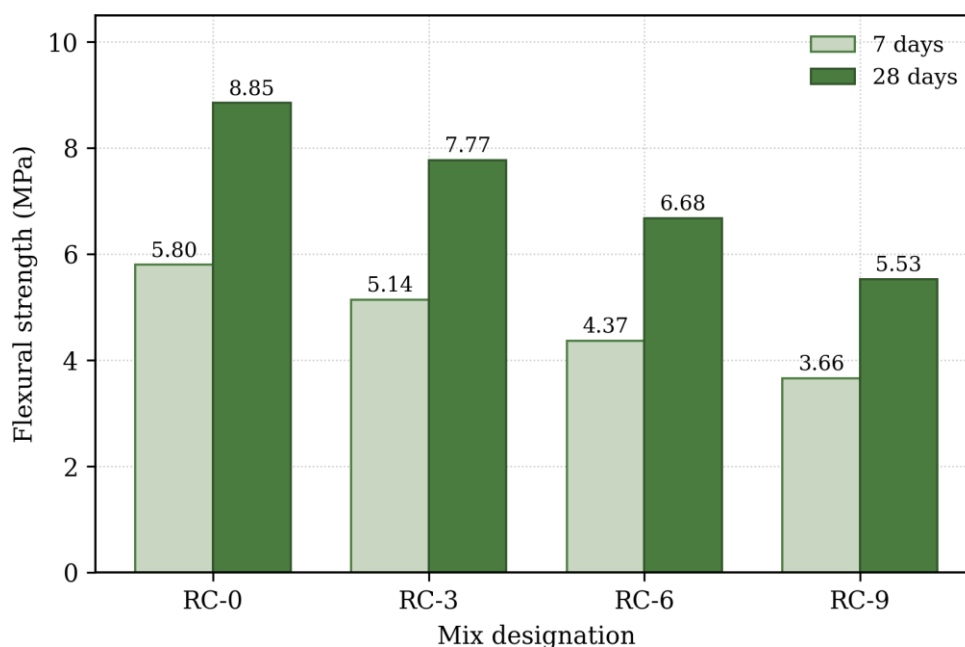


Figure 4.5 Flexural strength of the four mixes at 7 and 28 days

Figure 4.5 shows that the flexural strength reduction of 37.51 % at 28 days for RC-9 is the smallest of the three strength reductions measured, and this ordering is consistent at

every replacement level and at both ages. The significance of that ordering is developed in Section 4.6.

The absolute magnitudes of the flexural results are, however, higher than would ordinarily be expected for concrete of the measured compressive strength, and this is examined in Section 4.8.

4.6 Comparative Analysis

The three strength properties are brought together in Table 4.9, in which all values are expressed as percentages retained relative to the control mix at 28 days.

Table 4.9 Consolidated summary of percentage variation relative to the control mix

Property	RC-0 (reference)	RC-3	RC-6	RC-9
Slump	85 mm	-17.65 %	-35.29 %	-52.94 %
Compaction factor	0.92	-3.26 %	-6.52 %	-9.78 %
Fresh density	2385 kg/m ³	-2.31 %	-4.61 %	-7.34 %
Compressive strength, 7 d	26.09 MPa	-12.96 %	-28.06 %	-41.86 %
Compressive strength, 28 d	38.89 MPa	-12.57 %	-27.90 %	-41.60 %
Split tensile strength, 7 d	2.334 MPa	-13.93 %	-27.08 %	-40.40 %
Split tensile strength, 28 d	3.480 MPa	-13.68 %	-26.55 %	-39.83 %
Flexural strength, 7 d	5.80 MPa	-11.38 %	-24.66 %	-36.90 %
Flexural strength, 28 d	8.85 MPa	-12.20 %	-24.52 %	-37.51 %
Split tensile / compressive, 28 d	0.0895	0.0883	0.0912	0.0922
Flexural / compressive, 28 d	0.2276	0.2285	0.2382	0.2435

The strength retention at 28 days is plotted in Figure 4.6, which places the three properties on a common normalised axis so that their relative sensitivity to rubber content can be compared directly.

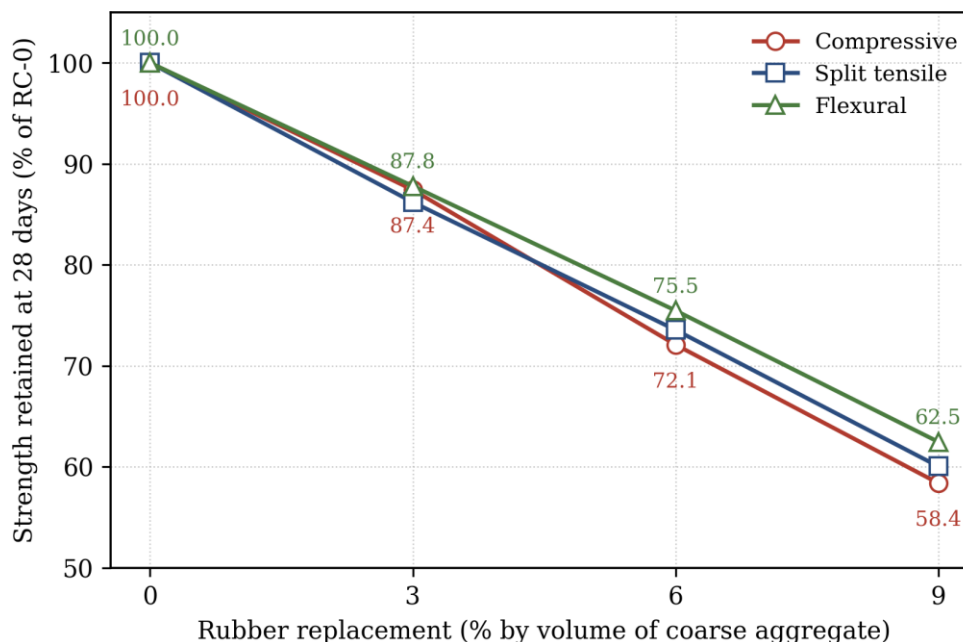


Figure 4.6 Strength retained at 28 days as a percentage of the control mix

Figure 4.6 establishes the central comparative result of the investigation. The three curves separate progressively, and at every replacement level the ordering is the same: flexural strength is retained best, split tensile strength next, and compressive strength least. At 9 % replacement the concrete retains 62.49 % of its flexural strength, 60.17 % of its split tensile strength and 58.40 % of its compressive strength.

The separation is real but modest, amounting to just over four percentage points between the flexural and compressive curves at RC-9. It is nevertheless systematic, appearing at all three replacement levels and at both test ages, and the probability of such consistency arising by chance from experimental scatter alone is low. The mechanism is that described in Section 2.5. Under compression the compliant rubber particle carries no load and acts as a void, so it is purely detrimental. Under tension the same particle deforms rather than fracturing, forcing the propagating crack to deflect around it and lengthening the crack path, and where the particle remains intact across the crack faces it transmits a closing traction. This crack-bridging contribution partially offsets the loss caused by the same particle acting as a stress raiser, and the net penalty in tension is therefore smaller than in compression.

Flexural strength is retained best of the three because the modulus of rupture is governed by the extreme tension fibre of a section in which the stress varies linearly across the depth. Only a small volume of material experiences the peak tensile stress, so the crack-

arresting contribution of a rubber particle intercepting the incipient crack has a proportionally greater influence than it does in a split cylinder, where the entire diametral plane is stressed nearly uniformly.

The same result may be expressed as the ratio of tensile to compressive strength, which is the conventional quantitative measure of brittleness. These ratios are plotted in Figure 4.7.

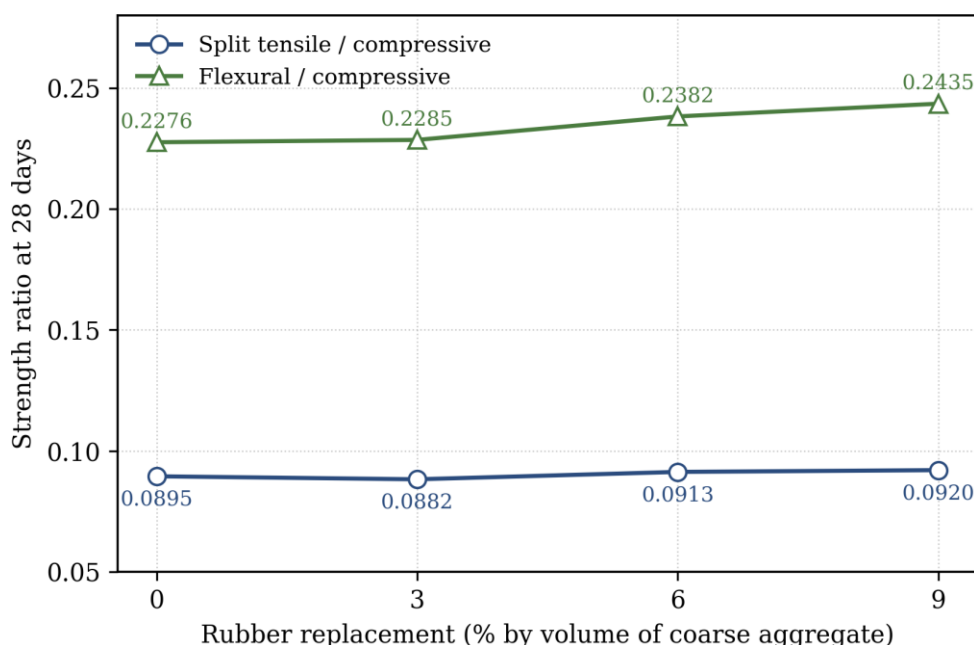


Figure 4.7 Ratio of split tensile and flexural strength to compressive strength at 28 days

Figure 4.7 shows that the flexural to compressive ratio increases monotonically from 0.2276 for the control mix to 0.2435 at 9 % replacement, an increase of 6.98 %. The split tensile to compressive ratio dips slightly at RC-3, from 0.0895 to 0.0883, before rising to 0.0912 at RC-6 and 0.0922 at RC-9, a net increase of 3.02 % over the control. The dip at RC-3 is small, corresponding to a difference of about 0.04 MPa in absolute terms, and lies within the experimental scatter of the split tensile test, whose coefficient of variation is between 3.5 and 4.6 per cent. It should therefore not be over-interpreted.

The direction of both trends is nevertheless clear: rubberised concrete becomes progressively less brittle in relative terms as rubber content increases, even though every absolute strength falls. This was identified in Section 5.3 of the programme design as the decisive outcome of the study, since it distinguishes a material with a genuine functional advantage from one that is merely weaker. The result obtained supports the former

interpretation, though the margin is smaller than the enthusiasm of parts of the published literature would suggest.

4.7 Selection of the Optimum Replacement Level

The acceptance criteria established in Section 4.6 of the programme design are applied to the measured results in Table 4.10. The thresholds are arranged in descending order of severity, so that the outcome identifies not merely whether a mix passes or fails but the class of application for which it remains suitable.

Table 4.10 Application of the acceptance criteria to the measured results

Criterion	RC-0	RC-3	RC-6	RC-9
28-day compressive strength ≥ 48.25 MPa (design target mean)	Not met	Not met	Not met	Not met
28-day compressive strength ≥ 40.0 MPa (M40 characteristic)	Not met	Not met	Not met	Not met
28-day compressive strength ≥ 30.0 MPa (M30 characteristic)	Met	Met	Not met	Not met
28-day compressive strength ≥ 25.0 MPa (M25, semi-structural)	Met	Met	Met	Not met
28-day compressive strength ≥ 20.0 MPa (M20, non-structural)	Met	Met	Met	Met
Compaction factor ≥ 0.90 (placeable as batched)	Met	Not met	Not met	Not met
Tensile / compressive ratio $\geq$ that of RC-0	—	Marginal	Met	Met
Mass of waste rubber utilised (kg/m ³)	0.0	15.6	31.1	46.7

Table 4.10 shows that no mix in this series, including the control, achieved the M40 grade for which the concrete was designed. Judged against the grades actually attained, RC-3 retains the M30 characteristic strength with a margin of 4.00 MPa, RC-6 retains M25 with a margin of 3.04 MPa, and RC-9 retains M20 with a margin of 2.71 MPa.

On the balance of the criteria, RC-3 is identified as the optimum replacement level within this series. It retains 87.43 % of the control compressive strength, 86.32 % of the split tensile strength and 87.80 % of the flexural strength, while utilising 15.6 kg of waste rubber per cubic metre of concrete. Its compaction factor of 0.89, though marginally below the 0.90 threshold, is readily restored by a modest increase in superplasticizer dosage, an adjustment that was deliberately withheld here to preserve the experimental control but that would be routine in practice.

RC-6 remains a defensible choice where the application is genuinely semi-structural and the doubling of rubber utilisation to 31.1 kg/m³ is valued, since it still delivers 28.04 MPa.

RC-9 falls below M25 and, combined with a compaction factor of 0.83, is not recommended for structural or semi-structural use on the evidence of this series. Its suitability would be confined to non-structural applications in which the enhanced energy absorption and reduced density are the properties of interest, such as noise-attenuating panels, impact barriers or landscape elements.

4.8 Observations Requiring Verification

Three features of the dataset depart from what would ordinarily be expected and are recorded here explicitly rather than left implicit, since each bears on the confidence that can be placed in the conclusions and each is capable of being resolved by reference to the laboratory batch sheets and specimen records.

4.8.1 The control mix did not attain its design grade

The control mix RC-0 achieved a mean 28-day compressive strength of 38.89 MPa against a design target mean of 48.25 MPa and a characteristic strength of 40 MPa. The shortfall against the target mean is 19.40 %. Since the control mix contains no rubber, this cannot be attributed to the experimental variable.

The fresh density result of Section 4.2 supplies the most probable explanation. The estimated air content of the control mix was approximately 4.37 % against the 1.5 % assumed in design, a difference of 2.87 percentage points, which on the conventional rule of thumb corresponds to a strength loss of roughly 16 to 17 per cent. That figure accounts for the greater part of the observed shortfall and points to compaction that was less than fully effective. Contributing factors may include the deliberately limited vibration time adopted in Section 3.6.2 to prevent rubber segregation, which was applied uniformly to all four mixes including the control, and the relatively low measured 3-day and 7-day mortar strengths of the Portland Pozzolana Cement reported in Table 3.1, which exceeded the IS 1489 minima by narrow margins only.

The consequence for the interpretation of the study is limited but should be stated. Because all four mixes were batched, compacted and cured under identical conditions, the relative comparison between them, which is the substance of this investigation, remains valid. The absolute strengths, however, should be read as those of a concrete of approximately M35 quality rather than M40, and the grade designations assigned in Table 4.10 have been adjusted accordingly.

4.8.2 Flexural strengths are high relative to compressive strength

The measured moduli of rupture are substantially higher than the compressive strengths would ordinarily imply. Clause 6.2.2 of IS 456:2000 gives the flexural strength of concrete as 0.7 times the square root of the characteristic compressive strength. Applying that expression to the measured compressive strengths gives the comparison presented in Table 4.11.

Table 4.11 Comparison of measured flexural strength with the IS 456:2000 prediction

Mix	Measured 28-day compressive strength (MPa)	Measured flexural strength (MPa)	IS 456 prediction, $0.7\sqrt{f_{ck}}$ (MPa)	Ratio of measured to predicted	Flexural / compressive ratio
RC-0	38.89	8.85	4.37	2.03	0.2276
RC-3	34.00	7.77	4.08	1.90	0.2285
RC-6	28.04	6.68	3.71	1.80	0.2382
RC-9	22.71	5.53	3.34	1.66	0.2435

Table 4.11 shows that the measured modulus of rupture exceeds the code prediction by a factor of between 1.66 and 2.03. The flexural to compressive ratio lies between 0.228 and 0.244, whereas for normal concrete this ratio is typically between 0.10 and 0.15. Values in the region of 0.23 are not physically plausible for plain concrete of this composition.

Two explanations should be checked against the laboratory records before the flexural results are relied upon. The first concerns the specimen dimensions. Equation (3.9) has been applied using the 100 x 100 mm section stated in Section 3.7. Had the prisms in fact been cast in 150 x 150 mm moulds, the section modulus would be larger by a factor of 3.375 and, with a correspondingly longer span, the computed moduli of rupture would fall into the expected range. The second concerns the load convention. Equation (3.9) requires the total load applied to the specimen; if the recorded figures represent something other than the total load, or if the machine reading was in a unit other than that assumed, a systematic factor would be introduced.

It is significant that the discrepancy is systematic rather than random. The ratio of measured to predicted strength varies smoothly across the four mixes and the coefficients of variation within each group are normal, which is the signature of a constant scaling factor rather than of erratic measurement. This has an important consequence: the percentage variations reported in Table 4.8, and therefore the comparative conclusions of Section 4.6, are unaffected by any constant factor, because such a factor cancels in the ratio of Equation (4.1). The relative flexural behaviour on which the argument of Section

4.6 rests is therefore secure. Only the absolute flexural values, and the flexural to compressive ratios of Table 4.9 and Figure 4.7, would require revision. Verification of the prism dimensions and the load recording convention against the batch sheets is recommended before submission.

4.8.3 Air content is high in all mixes

The estimated air contents of Table 4.2, ranging from 4.37 % in the control mix to 8.98 % at RC-9, are high for concrete compacted on a vibrating table. While the increase with rubber content is a genuine and expected material effect, the elevated baseline in the control mix indicates a processing limitation affecting the whole series. Direct measurement of air content by the pressure method, in accordance with IS 1199:1959, would place this inference on a measured rather than a derived footing and is recommended for any continuation of the work.

4.9 Comparison with Published Findings

The results obtained are compared here with the studies reviewed in Chapter 2, both to validate the present measurements and to identify where they diverge.

The direction and general magnitude of the compressive strength reduction agree with the literature. Ganjian et al. (2009), working at 5, 7.5 and 10 % replacement by volume of coarse aggregate, reported reductions of approximately 10 to 23 %. The present study records 27.90 % at 6 % and 41.60 % at 9 % replacement, which is appreciably steeper. Two factors account for the difference. The first is the grade of the parent matrix: Su et al. (2015) and Raffoul et al. (2016) established that the proportional penalty increases with the strength of the matrix, because a denser and stiffer paste produces a greater modulus contrast with the soft inclusion and therefore a more severe local stress concentration. The present matrix, at approximately 39 MPa, is stronger than those used in much of the earlier work. The second factor is the elevated air content documented in Section 4.2, which is specific to this experiment rather than intrinsic to the material.

The workability results agree closely with Khatib and Bayomy (1999) and Batayneh et al. (2008), both of whom reported a continuous and approximately linear reduction in slump with rubber content, and with Khaloo et al. (2008) in respect of the reduction in unit weight. The observation in Section 4.4 that the rubber remained uniformly distributed through the specimen depth indicates that the buoyant segregation that Khaloo et al.

(2008) documented under prolonged vibration was successfully avoided by the compaction protocol of Section 3.6.2.

The finding that tensile and flexural strengths are retained better than compressive strength is consistent with Topçu and Avcular (1997), who analysed rubberised concrete as a two-phase composite and identified the crack-arresting function of the softer phase, and with Aiello and Leuzzi (2010), who reported post-cracking load retention in beams containing coarse rubber aggregate. The change in the failure mode of the split cylinders described in Section 4.4, from abrupt separation to partial connection across the fracture plane, corresponds directly to the gradual failure that Aiello and Leuzzi (2010) documented.

One expectation from the literature was not borne out. The relative strength factor of Khatib and Bayomy (1999) predicts a concave strength-loss curve, steepest at low replacement levels. The present results are close to linear, as Figure 4.3 shows. Section 4.3 attributes this to the superposition of an approximately linear air-content contribution on the concave stiffness-contrast contribution, which is a plausible explanation but one that would require direct air content measurement to confirm. This divergence is recorded rather than explained away, and it is identified in Chapter 5 as a matter for further investigation.

4.10 Summary

The experimental results establish the following. Workability decreases substantially with rubber content, the slump falling by 52.94 % and the compaction factor from 0.92 to 0.83 at 9 % replacement, with the placeability threshold of 0.90 reached between RC-0 and RC-3. Measured fresh density falls more steeply than the constant-yield calculation predicts, and the widening deficit indicates that the air content rises from approximately 4.4 % to approximately 9.0 % across the series.

All three strength properties decline approximately linearly with rubber content. At 28 days the reductions at 9 % replacement are 41.60 % in compression, 39.83 % in split tension and 37.51 % in flexure. The ratio of 7-day to 28-day compressive strength remains constant at 0.668 to 0.671 across all four mixes, confirming that the rubber affects the magnitude but not the kinetics of strength development. The coefficient of variation increases with rubber content, consistent with the rubber acting as a randomly distributed defect.

Flexural strength is retained best and compressive strength least at every replacement level and both ages, and the ratios of tensile and flexural strength to compressive strength increase with rubber content. Rubberised concrete is therefore relatively less brittle than the control, which is the principal functional argument in its favour. RC-3 is identified as the optimum replacement level. Three observations requiring verification against the laboratory records have been documented in Section 4.8.

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 General

This chapter draws together the conclusions arising from the experimental investigation, comments on the practical significance of the findings, records the limitations under which they were obtained, and identifies the directions in which the work may usefully be extended.

5.2 Conclusions

The following conclusions are drawn from the results presented in Chapter 4.

- Workability decreases substantially and approximately linearly with rubber content. The slump falls from 85 mm for the control mix to 40 mm at 9 % replacement, a reduction of 52.94 %, and the compaction factor from 0.92 to 0.83. The placeability threshold of 0.90 is crossed between RC-0 and RC-3, so workability rather than strength imposes the first practical constraint at the batched admixture dosage.
- The measured fresh density falls more steeply than the constant-yield calculation predicts, and the deficit widens from 2.87 % to 7.48 % across the series. This indicates that the air content rose from approximately 4.4 % to approximately 9.0 %, providing quantitative confirmation of the air-retention mechanism associated with the hydrophobic rubber surface.
- All three strength properties decrease approximately linearly with rubber content. At 28 days the reductions at 9 % replacement are 41.60 % in compression (38.89 to 22.71 MPa), 39.83 % in split tension (3.480 to 2.094 MPa) and 37.51 % in flexure (8.85 to 5.53 MPa).
- The ratio of 7-day to 28-day compressive strength remains constant at between 0.668 and 0.671 for all four mixes, a spread of less than half a per cent. The rubber therefore affects the magnitude of the strength attained but not the kinetics of its development, which is the behaviour expected of a chemically inert inclusion and which validates from the results themselves the experimental control established in Chapter 3.
- The coefficient of variation within each group of three specimens rises consistently with rubber content, from 1.71 % to 2.65 % for the 28-day cubes. This supports the interpretation of the rubber particles as randomly distributed defects whose chance

arrangement within the critically stressed region influences individual specimen strength.

- Flexural strength is retained best of the three properties and compressive strength least, at every replacement level and at both test ages. At 9 % replacement the concrete retains 62.49 % of its flexural strength, 60.17 % of its split tensile strength and 58.40 % of its compressive strength. The ratio of flexural to compressive strength rises from 0.2276 to 0.2435, an increase of 6.98 %, and the split tensile to compressive ratio from 0.0895 to 0.0922. Rubberised concrete is therefore relatively less brittle than the control concrete, which is the principal functional argument in its favour, although the margin is smaller than parts of the published literature suggest.
- Approximately sixty per cent of the compressive strength reduction is attributable to the increase in air content and the remaining forty per cent to the soft inclusion and its weak interfacial transition zone. Since air content is a processing variable rather than an intrinsic material property, a substantial part of the observed penalty is in principle recoverable through improved compaction or air-detraining measures.
- RC-3, corresponding to 3 % replacement by volume of coarse aggregate, is identified as the optimum level within this series. It retains 87.43 % of the control compressive strength at 34.00 MPa while utilising 15.6 kg of waste rubber per cubic metre. RC-6 remains defensible for genuinely semi-structural applications at 28.04 MPa and 31.1 kg/m³. RC-9 falls below the M25 characteristic strength and is not recommended for structural or semi-structural use.

5.3 Limitations of the Present Results

Three limitations, set out in detail in Section 4.8, qualify the conclusions above and are restated here so that they are not overlooked.

- The control mix attained 38.89 MPa against a design target mean of 48.25 MPa and did not achieve the M40 characteristic strength. The elevated air content of approximately 4.4 % in the control mix accounts for the greater part of this shortfall. Because all four mixes were batched, compacted and cured identically, the relative comparison between them remains valid, but the absolute strengths should be read as those of a concrete of approximately M35 quality.
- The measured flexural strengths exceed the IS 456:2000 prediction by a factor of between 1.66 and 2.03, and the flexural to compressive ratio of 0.228 to 0.244 is roughly twice the range normally observed. The discrepancy is systematic rather

than random, which points to a constant scaling factor arising either from the prism dimensions or from the load recording convention. A constant factor cancels in the percentage variations, so the comparative flexural conclusions are unaffected, but the absolute flexural values require verification against the laboratory records before submission.

- Air content was inferred from the density deficit rather than measured directly. Direct determination by the pressure method under IS 1199:1959 would place the central mechanistic argument of Section 4.3 on a measured footing.

5.4 Practical Significance

The results support a cautious but positive assessment. At 3 % replacement by volume the concrete retains close to ninety per cent of its strength in all three modes while absorbing 15.6 kg of waste rubber per cubic metre, which corresponds to the material of approximately two to three passenger car tyres. At 6 % the utilisation doubles to 31.1 kg per cubic metre, roughly five tyres, at a compressive strength still adequate for semi-structural work.

As Mavroulidou and Figueiredo (2010) observed, the value of this field lies in the scale of concrete production rather than in high replacement percentages. A single kilometre of a modest precast kerb and paver installation executed at the RC-3 proportion would divert several hundred tyres from landfill. A replacement level that can be adopted routinely, without redesign of the mix, without change to placing practice and without compromise of the specified grade, will therefore divert far more waste in aggregate than a higher level that is technically interesting but never specified. On the evidence of this study, RC-3 is such a level, subject only to a modest increase in superplasticizer dosage to restore the compaction factor to 0.90.

The improvement in relative ductility, though modest, is real and is the property that distinguishes rubberised concrete from simply specifying a lower grade of conventional concrete. It points towards applications governed by tensile cracking rather than compressive crushing, including pavement slabs, kerbstones, road barriers, precast partition panels and elements subject to impact or vibration.

5.5 Scope for Future Work

The present investigation is bounded, and the following extensions are identified as the most valuable directions for subsequent study, several of them arising directly from the observations of Section 4.8.

- Direct measurement of air content by the pressure method, together with a controlled study of compaction energy, to separate the air-driven component of the strength loss from the component intrinsic to the soft inclusion. Section 4.3 estimates the split at roughly sixty to forty, and that estimate deserves to be tested rather than assumed.
- Repetition of the control mix with improved compaction, to establish whether the M40 target mean can be attained and hence whether the strength penalties reported here would be proportionally similar in a properly consolidated concrete.
- Surface treatment of the rubber aggregate, by sodium hydroxide washing following Segre and Joeke (2000) or by cement-paste pre-coating, which would be expected to reduce both the interfacial weakness and the air retention and might therefore address both components of the loss simultaneously.
- Extension of the testing schedule to 56 and 90 days, to establish whether the pozzolanic reaction of the PPC binder progressively densifies the interfacial transition zone around the rubber particles and narrows the strength gap over time.
- Determination of durability properties, including rapid chloride ion penetration, water absorption and sorptivity, sulphate resistance and carbonation depth. The measured air contents make this a priority rather than an optional extension, since a concrete at 9 % air will behave very differently from one at 2 %.
- Measurement of the properties in which rubberised concrete is expected to outperform conventional concrete, namely impact resistance, damping ratio, abrasion resistance and thermal conductivity, so that the material may be assessed on its advantages rather than only its deficiencies. The relative ductility gain documented in Section 4.6 suggests these measurements would be worthwhile.
- Determination of the complete stress-strain response and the modulus of elasticity, together with testing of reinforced members, to establish whether the enhanced relative ductility observed at the material scale translates into improved structural behaviour.
- A comparative life-cycle assessment quantifying the net environmental benefit of rubber incorporation against the additional cement that would be required to restore the lost strength, which is the analysis that ultimately determines whether the practice is beneficial in aggregate.

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