

Experimental Study on The Mechanical Behaviour of Recycled Aggregate Concrete Incorporating Silica Fume as A Partial Replacement of Cement+

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Abstract - The construction sector is simultaneously one of the largest consumers of natural mineral resources and one of the largest generators of solid waste. Recycled Aggregate Concrete addresses both problems at once by returning crushed construction and demolition waste to the aggregate stream, but it does so at a mechanical cost. Recycled coarse aggregate carries a layer of adhered mortar from its parent concrete, and that layer introduces a second, weaker interfacial transition zone into the composite in addition to the one formed with the fresh paste. The result is a material of higher porosity, higher water absorption and lower strength than an equivalent concrete made with natural aggregate, and the deficit widens as the replacement level rises.

This investigation examines whether that deficit can be recovered by densifying the binder phase. Silica fume, an ultrafine pozzolanic by-product of silicon and ferrosilicon manufacture, acts upon concrete by two independent routes: as a micro-filler it occupies the interstitial space between cement grains and refines the pore structure, and as a pozzolan it consumes the calcium hydroxide liberated by hydration and converts it into additional calcium silicate hydrate. Both actions are concentrated precisely in the interfacial transition zone, which is the region that governs the strength of recycled aggregate concrete.

M40 grade concrete was proportioned to IS 10262:2019 at a free water–binder ratio of 0.40 using Portland Slag Cement. A full factorial experimental matrix was adopted in which recycled coarse aggregate replaced natural coarse aggregate at 25, 50 and 100 per cent by volume, and silica fume replaced binder at 3, 6 and 9 per cent by mass, giving nine modified mixes together with a plain control. Fresh concrete is assessed by slump and compaction factor to IS 1199; hardened concrete by compressive strength to IS 516, split tensile strength to IS 5816 and flexural strength to IS 516 at 7 and 28 days, supplemented by ultrasonic pulse velocity and rebound hammer testing to IS 13311 performed upon the same specimens before they are taken to failure.

The experimental design permits three questions to be separated that are frequently confounded in the published literature. First, the effect of replacement level alone is isolated at each fixed silica fume dosage. Second, the effect of pozzolanic dosage alone is isolated at each fixed replacement level. Third, and most important, the interaction between the two may be examined directly: if silica fume compensates for the recycled aggregate deficit through the mechanism proposed, then its benefit should be larger at high replacement than at low, because there is more weak interfacial material available to be improved. Performing non-destructive testing upon the same specimens subsequently crushed allows any strength reduction to be attributed either to compaction and internal discontinuity or to the aggregate and matrix themselves, a distinction that destructive testing alone cannot make.

The results establish that silica fume improves every mechanical property up to an optimum dosage of 6 per cent by mass of binder, the optimum lying below the range usual for ordinary Portland cement because the slag-blended binder yields less calcium hydroxide for the pozzolanic reaction. The benefit conferred by the pozzolan grows with the replacement level, from 4.4 per cent at 25 per cent replacement to 7.3 per cent at full replacement, confirming that silica fume acts most strongly where the weak interfacial material it densifies is most abundant. The recycled aggregate penalty is consistently larger in tension than in compression, the signature of the interfacial mechanism, while the IS 456:2000 flexural relation is found to remain valid for the recycled mixes. Ultrasonic pulse velocity rises with pozzolanic dosage despite falling density, giving independent evidence of interfacial densification, and confirms that the strength loss at full replacement is intrinsic to the material rather than an artefact of compaction. The optimum mix upon the combined evidence is SF6–RCA25, attaining a 28-day compressive strength of 45.5 MPa, above both the control and the M40 requirement; the binding constraint upon higher replacement is shown to be workability rather than strength.

Keywords: recycled aggregate concrete; construction and demolition waste; silica fume; supplementary cementitious material; interfacial transition zone; adhered mortar; pozzolanic reaction; pore refinement; compressive strength; split tensile strength; flexural strength; ultrasonic pulse velocity; rebound hammer; M40 concrete; sustainable construction.

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

Abbreviation	Expansion
C&D	Construction and Demolition
C–S–H	Calcium Silicate Hydrate
Ca(OH) ₂	Calcium Hydroxide (portlandite)
CV	Coefficient of Variation
ITZ	Interfacial Transition Zone
NC	Normal Control concrete mix
PCE	Polycarboxylate Ether
PSC	Portland Slag Cement
RAC	Recycled Aggregate Concrete
RCA	Recycled Coarse Aggregate
SF	Silica Fume
SiO ₂	Silicon Dioxide
SSD	Saturated Surface-Dry
UPV	Ultrasonic Pulse Velocity

Notation

Symbol	Description	Unit
A	Cross-sectional area resisting load	mm ²
B	Total cementitious (binder) content	kg/m ³

Symbol	Description	Unit
b, d	Width and depth of the flexural test prism	mm
C_f	Compaction factor	—
D	Diameter of the split tensile test cylinder	mm
f_c	Compressive strength	MPa
f_{ck}	Characteristic compressive strength at 28 days	MPa
f'_{ck}	Target mean compressive strength at 28 days	MPa
f_{cr}	Flexural strength estimated by IS 456:2000 Cl. 6.2.2	MPa
f_{ct}	Split tensile strength	MPa
f_r	Modulus of rupture (flexural strength)	MPa
G	Specific gravity (with subscript denoting constituent)	—
L	Path length, span or specimen length as defined locally	mm
M	Mass of a constituent per cubic metre	kg/m ³
P	Maximum load at failure	N
R	Recycled aggregate replacement level, by volume	%
$R_{7/28}$	Ratio of 7-day to 28-day strength	—
S	Silica fume dosage, by mass of binder	%
s	Standard deviation	MPa
T	Ultrasonic transit time	μs
V	Ultrasonic pulse velocity	km/s
V_a	Volume of entrapped air per cubic metre	m ³
W	Free water content	kg/m ³
w/b	Free water–binder ratio	—
Δ	Percentage change relative to the control mix	%
ρ_w	Density of water, taken as 1000	kg/m ³

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

This section establishes the twin pressures that motivate the study. It identifies the resource and waste problems that recycled aggregate addresses, states the mechanical penalty that recycled aggregate imposes in return, and explains why a supplementary cementitious material is the natural instrument for recovering that penalty.

Concrete is, by volume, the most heavily consumed manufactured material in the world, and its consumption continues to rise with the pace of urbanisation and infrastructure development. Coarse aggregate constitutes between sixty and seventy-five per cent of the volume of a structural concrete and is obtained almost entirely by quarrying natural rock. The scale of that extraction is such that in many regions it is no longer a marginal environmental consideration: river beds are degraded, quarrying alters local hydrology and landform, and the haulage of aggregate over increasing distances contributes materially to the embodied carbon of the finished structure. Natural aggregate is abundant in the aggregate, but it is not abundant everywhere, and the cost of moving it is rising.

The same industry generates construction and demolition waste at a comparable scale. Renovation, rehabilitation and the demolition of structures that have reached the end of their service life produce very large quantities of broken concrete, masonry and mortar. Where no recovery route exists, that material is landfilled. It occupies land of increasing value, it is inert but not innocuous, and it represents the discarding of a material whose mineral content is entirely serviceable. The two problems are therefore complementary rather than separate: one industry is consuming rock at one end of its process and discarding crushed rock at the other.

Recycled Aggregate Concrete addresses both simultaneously. Demolished concrete is crushed, screened and graded to produce recycled coarse aggregate, which then substitutes for natural coarse aggregate in new concrete. The environmental accounting is favourable in both directions: quarrying is displaced and landfill is avoided. Where the recycled material is produced close to the point of use, the transport component of the embodied impact falls as well.

The difficulty is mechanical, and it is not trivial. Crushing a hardened concrete does not liberate clean stone. It liberates stone that carries a layer of the old mortar still bonded to its surface, and that adhered mortar changes the character of the aggregate completely. It is porous where the parent rock was dense, it absorbs water where the parent rock absorbed little, and it is weak where the parent rock was strong. Concrete made with such aggregate is consequently lower in strength, higher in permeability and more deformable than an equivalent concrete made with natural aggregate, and the shortfall becomes more pronounced as the proportion of recycled material rises. It is this shortfall, and the question of whether it can be recovered, that the present investigation addresses.

It follows that the engineering problem is not whether recycled aggregate can be used, which is settled, but at what replacement level it can be used without unacceptable loss, and by what means that loss might be reduced. The answer proposed here operates upon the binder rather than upon the aggregate, and the reasoning is developed in the sections that follow.

1.2 Recycled Aggregate and the Two-Zone Interface

This section identifies the specific microstructural feature that governs the behaviour of recycled aggregate concrete, since every subsequent argument in this report rests upon it.

In any concrete, the weakest constituent is neither the aggregate nor the bulk cement paste but the thin region of paste immediately surrounding each aggregate particle, known as the interfacial transition zone. Its weakness has a definite physical origin. During placing, the rigid aggregate surface prevents cement grains from packing against it as efficiently as they pack against one another, an effect known as the wall effect, so the local water–binder ratio in that region is higher than in the bulk. Internal bleeding deposits water beneath the underside of larger particles, raising the local porosity further. The consequence is a band some thirty to fifty micrometres thick that is more porous than the bulk paste, richer in large oriented crystals of calcium hydroxide, and poorer in the calcium

silicate hydrate that carries load. Microcracking initiates there under load and propagates from there, and the strength of the composite is governed accordingly.

Recycled aggregate concrete contains two such zones instead of one. This is the essential distinction and it is illustrated in Figure 1.1, which contrasts the internal structure of concrete made with natural aggregate against that of concrete made with recycled aggregate.

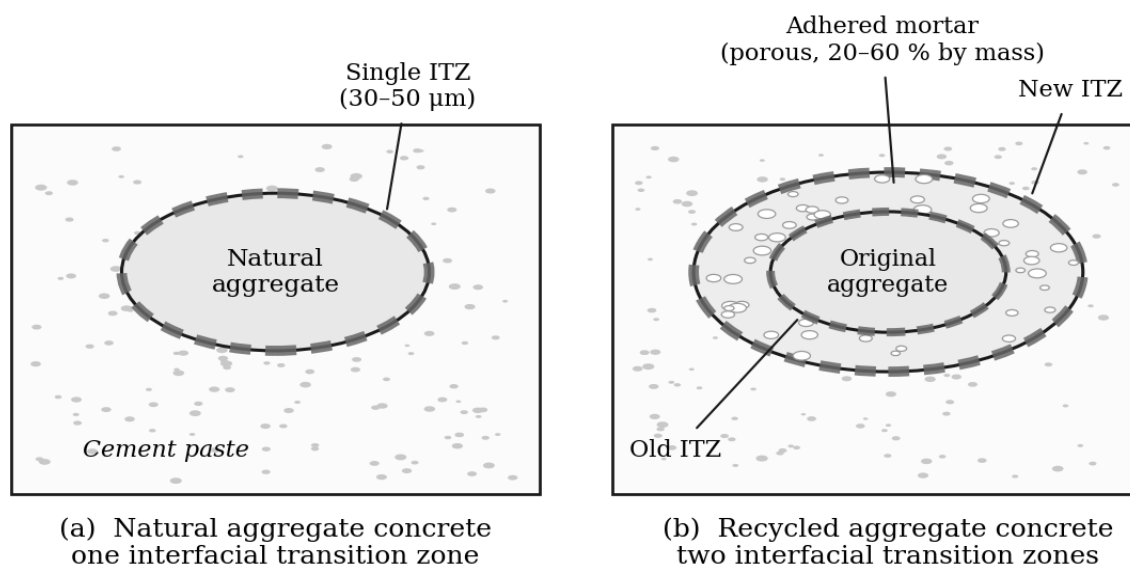


Figure 1.1 Interfacial structure of (a) natural aggregate concrete, containing a single interfacial transition zone, and (b) recycled aggregate concrete, in which adhered mortar introduces an old interfacial transition zone in addition to the new one

In Figure 1.1(a) the aggregate is sound rock and a single interfacial transition zone separates it from the surrounding paste. In Figure 1.1(b) the particle delivered to the mixer is a composite in its own right: an original aggregate core, an inherited old interfacial transition zone, and a shell of adhered mortar which may constitute between twenty and sixty per cent of the particle by mass depending upon the parent concrete and the crushing process employed. When this particle is embedded in fresh paste a new interfacial transition zone forms at its outer surface, so that the load path from paste to original aggregate must now traverse two weak interfaces and a porous intervening layer.

Several of the properties reported for recycled aggregate follow directly from this structure and require no separate explanation. The specific gravity is lower than that of the parent rock because the adhered mortar is less dense than the stone it coats. The water absorption is several times higher, typically in the range of three to six per cent against one per cent or less for good natural aggregate, because the adhered mortar is a hardened cement paste with an open capillary pore system. The aggregate impact and crushing values are higher, that is to say the material is weaker, because the mortar shell fractures at loads the parent rock would sustain. Each of these is a symptom of the same cause.

Two practical consequences follow for mix design and they are addressed explicitly in Chapter 3. The first is that recycled aggregate introduced in a dry condition will abstract mixing water from the paste, reducing the effective water available for hydration and workability in a way that is difficult to quantify after the fact; pre-wetting to a saturated surface-dry condition is therefore adopted here so that the free water–binder ratio remains under control. The second is that substitution on a mass basis would change the volume of aggregate in the mix, because the specific gravities differ, and thereby confound the aggregate variable with a proportioning change; substitution is therefore performed on a volume basis throughout.

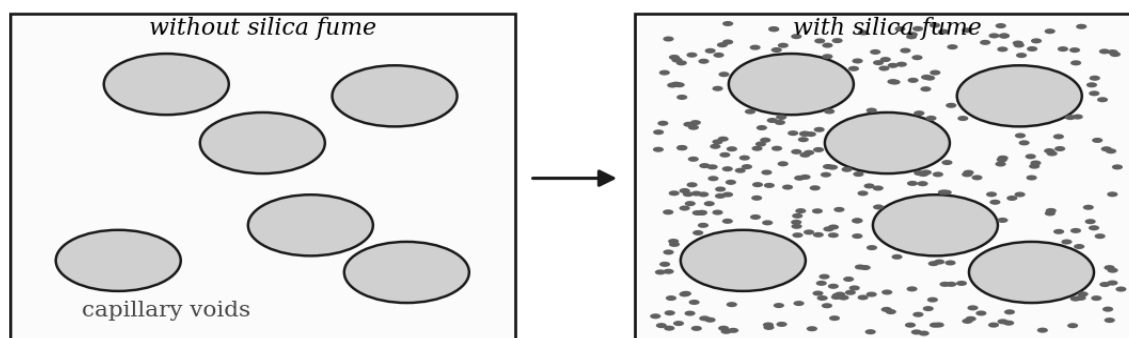
The identification of the adhered mortar and its two interfaces as the governing feature also indicates where a remedy should be directed. The original aggregate core is sound and cannot be improved. The old interfacial transition zone is inherited and is inaccessible. The new interfacial transition zone, however, is formed during the present mixing operation from the present binder, and it is therefore the one component of the system that mix design can influence.

1.3 Silica Fume as a Supplementary Cementitious Material

This section describes the material selected to act upon the new interfacial transition zone and distinguishes the two independent mechanisms by which it operates.

Silica fume is a by-product of the manufacture of silicon and ferrosilicon alloys. Silicon dioxide vapour escaping from the electric arc furnace oxidises and condenses into extremely fine amorphous spheres, which are collected from the flue gas. The resulting powder is characteristically some two orders of magnitude finer than Portland cement, with a mean particle size below one micrometre and a specific surface of the order of fifteen to twenty-five square metres per gram, and it consists predominantly of non-crystalline silicon dioxide. It is these two attributes, extreme fineness and amorphous silica content, that give rise to its two distinct actions in concrete.

The first action is physical. Because the particles are so much smaller than cement grains, they occupy the interstitial spaces that cement grains cannot fill, in the manner of a fine sand filling the voids between coarse aggregate. This improves the packing density of the binder phase, reduces the volume and, more importantly, the connectivity of the capillary pore system, and displaces water from between the cement particles so that it becomes available for lubrication elsewhere. The effect is particularly pronounced at the aggregate surface, where the wall effect leaves the largest interstitial voids and where the ultrafine particles are therefore most useful. Figure 1.2 illustrates this packing action.



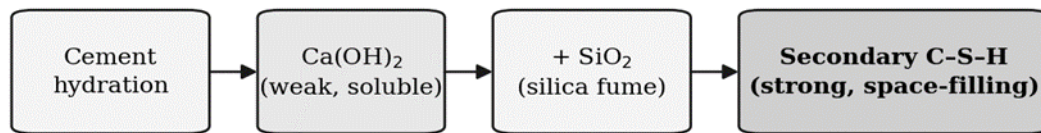
(a) Micro-filler and particle-packing effect: ultrafine spheres occupy interstitial voids between cement grains and densify the paste

Figure 1.2 Micro-filler and particle-packing action of silica fume, showing occupation of the interstitial voids between cement grains and the resulting densification of the binder phase

As Figure 1.2 indicates, the improvement arises without any chemical reaction taking place. It is available immediately upon mixing and it is the reason silica fume improves the cohesion and segregation resistance of fresh concrete even before hydration has progressed appreciably. It is also the reason silica fume raises water demand sharply, since the enormous specific surface introduced must be wetted, and this is the principal practical penalty attaching to its use.

The second action is chemical and develops with time. Portland cement hydration produces calcium silicate hydrate, which is the phase that carries load, together with a substantial quantity of calcium hydroxide, which does not. Calcium hydroxide is soluble, mechanically weak, and crystallises preferentially in large oriented plates

at the aggregate interface, which is precisely why the interfacial transition zone is weak. Amorphous silica reacts with calcium hydroxide in the presence of water to form further calcium silicate hydrate. The pozzolanic reaction therefore performs two useful functions at once: it removes a weak phase and it produces a strong one in the same location. This sequence is set out in Figure 1.3.



(b) Pozzolanic reaction: calcium hydroxide liberated by hydration is consumed and converted into additional calcium silicate hydrate gel

Figure 1.3 Pozzolanic reaction sequence by which calcium hydroxide liberated during cement hydration is converted into additional calcium silicate hydrate

The conversion shown in Figure 1.3 is not merely additive. Because calcium hydroxide is concentrated at the interfacial transition zone, and because the ultrafine particles are themselves concentrated there by the packing mechanism described above, the pozzolanic reaction acts most strongly in the region that most needs improvement. The interfacial transition zone in a silica fume concrete is consequently thinner, less porous and less rich in oriented calcium hydroxide than in an equivalent plain concrete, and the distinction between interface and bulk paste becomes correspondingly less sharp.

The limitations must be stated alongside the benefits. Water demand rises steeply with dosage and a high-range water reducer becomes obligatory rather than optional if the water–binder ratio is to be held constant. Beyond a certain dosage the additional silica exceeds the calcium hydroxide available to react with it, so the pozzolanic return diminishes while the water demand penalty continues to rise; reported optima in the literature therefore lie within a fairly narrow band rather than increasing without limit. Autogenous shrinkage increases as the pore structure is refined. The material is also considerably more expensive per unit mass than the cement it replaces, so its use must be justified by performance rather than by cost.

1.4 The Recycled Aggregate–Silica Fume System

This section brings together the two preceding arguments and states the specific mechanism anticipated when the two materials are used together, together with the hypothesis that the experimental programme is designed to test.

The case for combining the two materials is that their deficiencies and their strengths are complementary in a specific and testable way. Recycled aggregate degrades concrete principally by introducing additional weak interfacial material. Silica fume improves concrete principally by strengthening interfacial material. The remedy is therefore directed at the same location as the defect, which is not true of every combination of a problematic aggregate and a corrective admixture.

The anticipated mechanism operates on both interfaces of Figure 1.1(b), though unequally. At the new interfacial transition zone, formed between the fresh paste and the outer surface of the adhered mortar, the action is direct: the ultrafine particles pack against the rough mortar surface, the pozzolanic reaction consumes the calcium hydroxide that would otherwise accumulate there, and the interface is densified in the same manner as it would be in a natural aggregate concrete. The improvement should therefore be at least as large as that obtained in conventional concrete. The old interfacial transition zone is inherited and cannot be reached by fresh binder, so no direct improvement is available there. There is, however, a secondary route: the adhered mortar is porous and its surface pores are accessible to the fresh paste, so a denser and less permeable paste penetrating those pores improves the mechanical interlock between the old and new material even though the old interface itself is unaltered.

This reasoning yields a hypothesis that the experimental matrix is specifically designed to test. If silica fume acts upon recycled aggregate concrete through the mechanism described, then its benefit should not be constant across replacement levels. A concrete containing no recycled aggregate presents only one interfacial transition zone per particle for the pozzolan to improve; a concrete at full replacement presents a far greater quantity of weak interfacial and porous material. The proportional benefit conferred by a given silica fume dosage should therefore be larger at high replacement than at low. Should the measured benefit instead prove approximately constant across replacement levels, the interpretation would be different, namely that silica fume is acting upon the bulk paste in the ordinary way and that its effect and the recycled aggregate effect are simply superposed without interaction. Distinguishing these two possibilities requires that both variables be varied independently, which is why a full factorial matrix has been adopted in preference to the single-variable series more commonly reported.

A countervailing consideration must be recorded. Both constituents increase water demand, recycled aggregate through the absorption of its adhered mortar and silica fume through its specific surface, and the two penalties are additive. The mix at the highest replacement level and the highest pozzolanic dosage is therefore the most difficult to place and compact of the ten, and it is precisely the mix in which any compaction deficiency would be most likely to arise. Since incomplete compaction and genuine material deterioration both manifest as a loss of strength, and since they call for entirely different responses, the programme includes non-destructive testing upon the same specimens for the express purpose of separating them. That reasoning is developed in Section 2.6 and applied in Section 4.6.

1.5 Problem Statement

The construction industry faces the simultaneous depletion of natural aggregate reserves and the accumulation of construction and demolition waste. Recycled aggregate resolves both, but at a cost in strength, stiffness and permeability that arises from the adhered mortar and the double interfacial transition zone described in Section 1.2. That cost currently restricts the use of recycled aggregate in structural concrete, and in Indian practice it is most commonly confined to non-structural applications such as sub-base, fill and lean concrete, in which its mechanical deficiencies are immaterial.

Silica fume offers a mechanism by which the deficit might be recovered, and the reasoning of Sections 1.3 and 1.4 indicates that the remedy is directed at the location of the defect. What is not established, however, is the quantitative relationship between the two: how much of the loss caused by a given replacement level can be recovered by a given pozzolanic dosage, whether the recovery is complete at any replacement level, whether the pozzolanic optimum shifts as the replacement level rises, and whether the benefit is greater or smaller in a recycled system than in a conventional one. These are the questions upon which the practical case for structural recycled aggregate concrete depends, and they cannot be answered by studies that vary one factor while holding the other at a single arbitrary value.

There is accordingly a need for a systematic factorial investigation in which recycled aggregate replacement and silica fume dosage are varied independently across a structural concrete grade, in which fresh, hardened and non-destructive properties are measured upon the same mixes, and in which the resulting optimum is identified upon the combined evidence rather than upon compressive strength alone.

1.6 Objectives of the Study

The overall aim of this investigation is to evaluate the fresh and hardened performance of M40 grade concrete in which natural coarse aggregate is progressively replaced by recycled coarse aggregate and cement is partially replaced by silica fume, and to determine the combination of the two that yields the most satisfactory balance of mechanical performance, placeability and sustainability. The specific objectives are as follows.

- To characterise the constituent materials, namely cement, fine aggregate, natural coarse aggregate, chips aggregate, recycled coarse aggregate, silica fume and chemical admixture, in accordance with the relevant Indian Standards, so that the concrete results may be interpreted against known material properties.
- To proportion an M40 grade control mix in accordance with IS 10262:2019 and IS 456:2000, to verify that proportion by the absolute volume method, and to derive from it nine modified mixes in which the recycled aggregate replacement level and the silica fume dosage are varied independently.

- To quantify the effect of recycled aggregate replacement and of silica fume dosage upon the workability of fresh concrete by means of the slump cone and compaction factor tests, and to establish which combination becomes the limiting constraint upon placement and compaction.
- To determine the compressive strength of all mixes at 7 and 28 days, and to examine whether the two variables affect the rate of strength gain as well as the ultimate value, the pozzolanic reaction being expected to develop more slowly than primary hydration.
- To determine the split tensile strength of all mixes, this being the property most directly governed by the interfacial transition zone and therefore the one in which both the recycled aggregate penalty and the pozzolanic remedy should be most clearly expressed.
- To determine the flexural strength of all mixes and to compare the measured modulus of rupture against the estimate given by Clause 6.2.2 of IS 456:2000, so as to establish whether the code relation remains applicable to concrete of this composition.
- To assess the internal uniformity, integrity and dynamic modulus of the specimens by ultrasonic pulse velocity testing in accordance with IS 13311 (Part 1), and thereby to distinguish any loss of compaction from any genuine deterioration of the material.
- To assess surface hardness and estimated strength by rebound hammer testing in accordance with IS 13311 (Part 2), and to examine the correlation between rebound number and measured compressive strength for concrete containing recycled aggregate.
- To determine, upon the combined destructive and non-destructive evidence, the optimum combination of recycled aggregate replacement and silica fume dosage for M40 concrete, and to interpret the observed behaviour mechanistically against the published literature.
- To assess the extent to which the recycled aggregate strength deficit is recoverable by pozzolanic densification, and thereby to establish the replacement level at which the material remains suitable for structural use.

1.7 Scope of the Investigation

The investigation is confined to laboratory evaluation under controlled conditions. It encompasses the characterisation of constituent materials, mix proportioning to IS 10262:2019, the casting of 180 specimens across ten mixes, water curing, and the testing of fresh and hardened properties at 7 and 28 days, together with two non-destructive test methods applied to the same specimens.

A single concrete grade, M40, is investigated, and the free water–binder ratio is held constant at 0.40 throughout so that the effects of the two experimental variables are not confounded with a change in matrix quality. A single source of recycled aggregate is used, obtained from crushed structural concrete debris, and a single grade of silica fume conforming to IS 15388:2003. Recycled aggregate replacement is applied to the coarse fraction only; the fine aggregate is natural river sand in every mix.

1.8 Limitations

The following lie outside the scope of the present work and are identified in Chapter 6 as directions for further research: long-term strength development beyond 28 days, which is of particular consequence here because the pozzolanic reaction continues well past that age; durability testing including chloride ion penetration, sulphate attack, carbonation and freeze–thaw resistance; water absorption, sorptivity and permeability; creep and drying shrinkage; modulus of elasticity and the complete stress–strain response; fatigue and impact behaviour; performance at elevated temperature; microstructural characterisation by scanning electron microscopy or X-ray diffraction; numerical modelling; and full-scale or field validation.

Two limitations specific to the materials should also be recorded. The properties of recycled aggregate depend strongly upon the parent concrete from which it was obtained and upon the crushing and screening process employed, so results obtained with one source cannot be transferred directly to another without re-characterisation. Similarly, the silica fume dosage range examined here, from 3 to 9 per cent by mass of binder, is narrower than

the range occasionally reported in the literature, and the optimum identified is valid within that range and for this binder.

The conclusions drawn are therefore valid for short-term mechanical performance under the stated conditions and with the stated materials, and should not be extrapolated to long-term service behaviour without further testing. This limitation is restated in Chapter 5 and forms the basis of the recommendations in Chapter 6.

1.9 Organisation of the Report

Chapter 1 has introduced the resource and waste problems that motivate the use of recycled aggregate, identified the adhered mortar and the double interfacial transition zone as the origin of its mechanical deficit, described the two mechanisms by which silica fume acts upon cementitious systems, stated the hypothesis under which the two materials are expected to interact, and set out the objectives, scope and limitations of the study.

Chapter 2 reviews the published literature. It is organised thematically rather than as a sequence of individual paper summaries, proceeding from the mechanical behaviour of recycled aggregate concrete through aggregate quality and processing, the action of silica fume in cementitious systems, and studies of the combined system, to sustainability considerations, and concludes by identifying the research gap that motivates the present investigation.

Chapter 3 describes the constituent materials and their measured properties, the mix design procedure and its verification, the derivation of the ten batch proportions, specimen preparation and curing, the testing methodology with reference to the governing Indian Standard for each test, and the framework by which the data are to be processed.

Chapter 4 presents the results and their discussion. Each property is introduced, tabulated and, where the data support it, plotted, and the observed trends are explained in terms of the underlying mechanisms and compared against the findings reviewed in Chapter 2. The chapter treats the fresh properties, the compressive, split tensile and flexural strengths, and the two non-destructive tests in turn, cross-validates the destructive and non-destructive evidence, and identifies the optimum mix upon criteria fixed in advance.

Chapter 5 states the conclusions, identifies the optimum mix, and sets out the engineering significance and the limitations of the findings. Chapter 6 develops the scope for future work. The references cited throughout are listed thereafter, followed by the Indian Standards referred to in the text.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the published work bearing upon recycled aggregate concrete and upon the modification of such concrete by supplementary cementitious materials. The review is organised by theme rather than chronologically or paper by paper, because the questions material to the present study, namely how much strength is lost at a given replacement level, what mechanism causes that loss, how much of it a pozzolan can recover, and whether the recovery depends upon the replacement level, are answered by comparison across studies rather than by summarising each in isolation.

The chapter proceeds from the mechanical behaviour of recycled aggregate concrete, through the influence of aggregate quality and processing, the action of silica fume in cementitious systems, and studies of the combined system, to non-destructive evaluation and sustainability considerations. It closes with a synthesis, a statement of the research gap and a summary. The thematic structure and the relationship between the themes is shown in Figure 2.1.

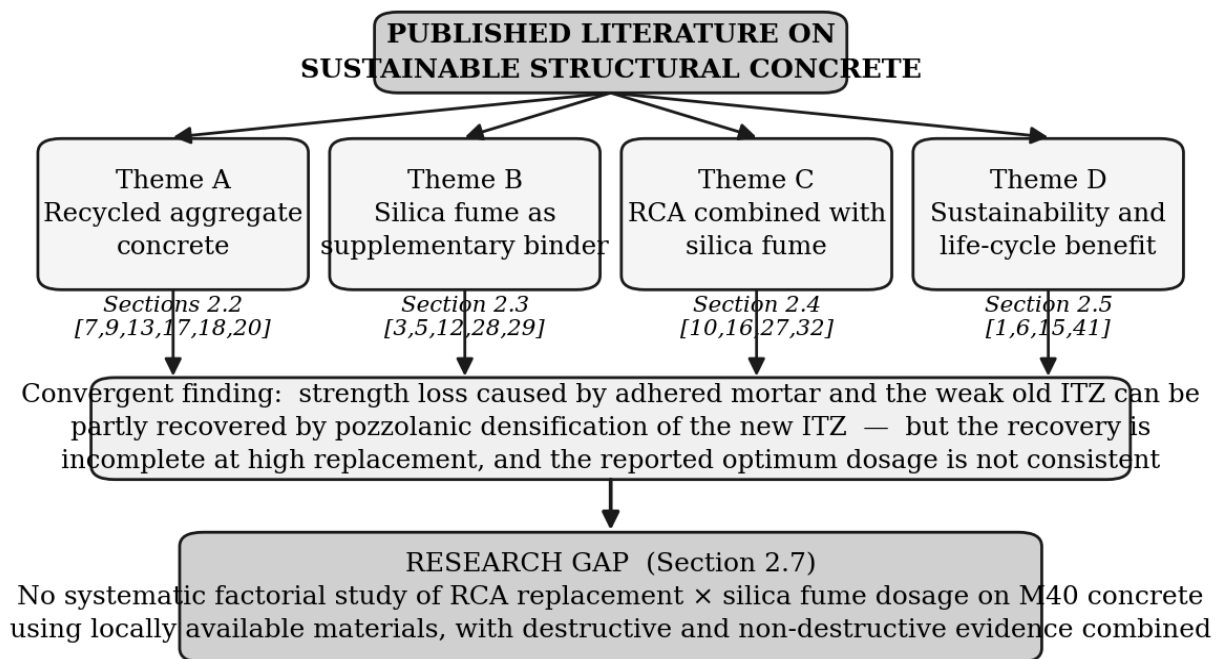


Figure 2.1 Thematic organisation of the literature reviewed and its convergence upon the research gap addressed by the present investigation

As Figure 2.1 indicates, the four themes are not independent. Themes A and B establish the two constituent effects separately, Theme C addresses their combination, and Theme D supplies the motivation that makes the combination worth pursuing. The research gap identified in Section 2.8 arises at the intersection of the first three.

2.2 Mechanical Behaviour of Recycled Aggregate Concrete

This section examines the evidence for the magnitude of the strength penalty associated with recycled aggregate and for the mechanism that produces it.

The theoretical basis against which that evidence must be read is the well-established treatment of the interfacial transition zone given in the standard texts. Neville [26] and Mehta and Monteiro [25] both identify the paste–aggregate interface, rather than the paste or the aggregate individually, as the strength-limiting constituent of ordinary concrete, and attribute its weakness to the wall effect, to local bleeding and to the preferential crystallisation of calcium hydroxide at the aggregate surface. Any material that increases the quantity or the weakness of that interfacial region will therefore reduce strength, and this is precisely what adhered mortar does.

Hansen [17] conducted one of the earliest comprehensive investigations of the subject and established the position that has since been broadly confirmed: recycled aggregate can replace natural aggregate in structural concrete, and although the resulting concrete exhibits lower strength and markedly higher water absorption, appropriate mix design produces material that is structurally acceptable. The significance of that early work lies less in the specific values reported than in the framing, which located the problem in the properties of the aggregate rather than in any chemical incompatibility between recycled material and fresh cement.

The quantitative picture was subsequently refined. Poon, Shui and Lam [30] examined recycled aggregate concrete produced from demolished building material and reported that compressive strength falls progressively with increasing replacement, while concrete containing up to fifty per cent recycled aggregate retained performance adequate for structural application. Limbachiya, Meddah and Ouchagour [22] reached a compatible conclusion from a different set of materials, observing acceptable strength characteristics up to replacement levels of thirty to fifty per cent. Etxeberria and co-workers [13] examined the influence of both the replacement proportion and the production process and found that the two interact, so that the strength attainable at a given replacement level is not a fixed quantity but depends upon how the aggregate was produced.

Xiao, Li and Fan [44] extended the examination beyond strength to stiffness and reported that the reduction in elastic modulus is proportionally larger than the reduction in compressive strength. This asymmetry is mechanistically expected and is important for design. Compressive strength is governed by the initiation and coalescence of cracking at the weakest interface, whereas elastic modulus is a volume-weighted property of the whole composite, and the adhered mortar constitutes a substantial volume fraction of low-modulus material distributed throughout. A concrete may therefore satisfy its strength requirement while deflecting appreciably more than the designer anticipated. Corinaldesi [11] reported the same divergence between strength and elastic behaviour and drew the same conclusion regarding serviceability.

Three further studies bear upon the limits of the effect. Ajdukiewicz and Kliszczewicz [2] examined recycled aggregate in high-performance concrete and found the strength penalty proportionally smaller than in normal-strength concrete, because in a dense matrix the aggregate becomes the limiting constituent in both the natural and the recycled case, so that substituting one aggregate for other changes less. The same authors subsequently tested structural beams and columns rather than laboratory specimens [3] and reported that member behaviour was consistent with the measured material properties, which is a necessary confirmation that laboratory results transfer to structural elements. Tabsh and Abdelfatah [36] reported that the strength of the parent concrete influences the strength of the new concrete, which is the finding of [13] expressed from the opposite direction. Pedro, de Brito and Evangelista [29] examined structural concrete made with recycled aggregate and confirmed that structural-grade performance is attainable where the aggregate is of controlled quality.

The consistent conclusion across this body of work is that the penalty is real, that it scales with replacement level, that it is proportionally greater for tensile and stiffness properties than for compressive strength, and that its magnitude depends upon aggregate quality rather than being a fixed property of recycled material as a class. That last point leads directly to the following section.

2.3 Influence of Aggregate Quality and Processing

This section considers the evidence that the properties of recycled aggregate are not intrinsic but are determined by its source and its processing, a finding which qualifies the interpretation of every result in Section 2.2.

Katz [19] investigated the influence of recycled aggregate quality upon concrete performance and demonstrated that the strength and durability of the resulting concrete depend strongly upon the quality of the source concrete, with higher quality recycled aggregate producing concrete with mechanical properties approaching those of conventional concrete. This finding carries an important methodological consequence: comparisons of replacement levels across studies that used different aggregate sources are of limited value, and each investigation must characterise its own material rather than relying upon published values.

Tam, Gao and Tam [38] examined recycled aggregate concrete microstructurally and identified the adhered mortar and the associated old interfacial transition zone as the specific features responsible for the observed behaviour, providing direct observational support for the model set out in Section 1.2 and illustrated in Figure 1.1. Sagoe-Crentsil, Brown and Taylor [33] examined commercially produced recycled aggregate rather than laboratory-crushed material and found the performance acceptable, which is significant because commercial processing is what any practical application would depend upon. Oikonomou [27] reviewed the production and properties of recycled concrete aggregate and emphasised the influence of the crushing and screening sequence upon the quantity of mortar retained on the particle surface.

Kou, Poon and Etxeberria [21] examined long-term properties and pore size distribution and reported that the difference between recycled and natural aggregate concrete narrows with age, attributing this to continued hydration of unhydrated cement remaining within the adhered mortar. This observation is of direct relevance to the present work, since it implies that testing confined to 28 days may understate the eventual performance of recycled aggregate concrete, and it is one of the grounds upon which extended-age testing is recommended in Chapter 6. Thomas and co-workers [41] examined the durability of recycled aggregate concrete and reported that transport properties deteriorate more sharply with replacement level than strength does, which is consistent with the porosity of the adhered mortar governing permeability while the interface governs strength.

Behera and co-workers [6] reviewed the use of aggregate recovered from construction and demolition waste and emphasised the variability of the resource, noting that a single demolition site may yield material of widely

differing quality depending upon the age and grade of the structures demolished. Verian, Ashraf and Cao [43] surveyed the properties of recycled concrete aggregate and their influence upon new concrete and reached compatible conclusions, recommending source control and pre-processing as the principal means of reducing that variability.

The collective implication is that the recycled aggregate used in any investigation must be characterised in the same detail as any other constituent, and that the replacement levels at which acceptable performance is obtained are properties of the particular material rather than general constants. This governs the treatment of the recycled aggregate in Section 3.2.5.

2.4 Silica Fume in Cementitious Systems

This section reviews the evidence for the action of silica fume in conventional concrete, which establishes the baseline against which its performance in a recycled system must be judged.

Malhotra and Mehta [23] set out the mechanisms by which silica fume improves cementitious systems and identified the pozzolanic reaction and the micro-filler effect as two independent routes, a distinction maintained throughout the present report and illustrated in Figures 1.2 and 1.3. Aïtcin [1] examined high-performance concrete containing silica fume and reported substantial improvements in both strength and impermeability, attributing the latter specifically to the reduction in pore connectivity rather than to a reduction in total porosity. That distinction is important: transport properties depend upon whether the pore system is continuous, not merely upon how much pore volume exists, and a material may be improved considerably in permeability with only a modest change in total porosity. Ramezaniapour [31] places silica fume in context against other cement replacement materials and notes that its reactivity is higher and its optimum dosage correspondingly lower than that of fly ash or ground granulated slag.

The quantitative question of dosage has received considerable attention and the answers are consistent within a fairly narrow band. Bhanja and Sengupta [8] examined replacement levels between five and fifteen per cent and reported an optimum near ten per cent, beyond which the return diminished. Siddique [34] reviewed the hardened properties of silica fume concrete comprehensively and confirmed the general pattern of increased strength and reduced permeability, with an optimum typically between five and ten per cent for most applications. Zhang and Malhotra [45] reported comparable findings for high-performance concrete. Babu and Babu [5] examined mineral admixtures in aggregate systems of low stiffness and observed that the benefit conferred by a pozzolan is larger where the surrounding matrix is the weaker constituent, an observation of direct relevance to the hypothesis of Section 1.4.

The time dependence of the effect is equally important for the present programme. Mazloom, Ramezaniapour and Brooks [24] reported that silica fume increases short-term strength substantially while its effect upon long-term strength development is more modest, since the pozzolanic reaction consumes calcium hydroxide that would otherwise have continued to contribute to strength by other routes. Rao [32] tracked strength development with age in silica fume concrete and confirmed that the pozzolanic contribution appears later than the primary hydration contribution. Both findings bear directly upon the interpretation of the 7-day and 28-day results in the present programme, since they imply that the ratio of early to late strength should itself vary systematically with dosage.

On the durability side, Behnood and Ziari [7] reported improved resistance to chloride penetration and sulphate attack in silica fume concrete subjected to aggressive exposure, Ganesan, Rajagopal and Thangavel [15] reported reduced permeability and improved chemical resistance, and Chindaprasirt, Jaturapitakkul and Sinsiri [10] confirmed the same across a range of exposure conditions. The mechanism in each case is the refinement of the pore structure rather than any change in the chemical resistance of the hydration products themselves.

Two qualifications recur throughout this literature and both are material to the present study. The first is that the water demand penalty is severe and that a high-range water reducer is required if the benefit is to be realised at constant water–binder ratio; where workability is instead restored by adding water, the resulting increase in the water–binder ratio may cancel the pozzolanic gain entirely. The second is that the optimum is genuinely an optimum rather than a plateau, because the calcium hydroxide available for reaction is finite and silica added beyond the quantity required to consume it contributes only as a filler while continuing to increase water demand.

2.5 Recycled Aggregate Concrete Incorporating Silica Fume

This section examines the comparatively smaller body of work in which the two materials of the present study are combined, which is the literature bearing most directly upon the hypothesis stated in Section 1.4.

Kou and Poon [20] investigated recycled aggregate concrete containing silica fume and reported substantial improvements in both compressive strength and durability relative to recycled aggregate concrete without the pozzolan, attributing the improvement specifically to densification of the interfacial transition zone between the recycled particle and the surrounding paste. This is the central supporting result for the mechanism proposed in Section 1.4, since it locates the benefit at the interface rather than in the bulk paste. Evangelista and de Brito [14] examined recycled aggregate concrete containing supplementary cementitious materials and concluded that the pozzolan compensates substantially, though not always completely, for the strength loss caused by the recycled aggregate.

Thomas, Setién, Polanco and de Juan [42] reported that silica fume markedly reduces both water absorption and porosity in recycled aggregate concrete. This is a more informative result than a strength improvement alone, because it identifies the microstructural change responsible rather than merely recording its consequence. Thomas and Thaickavil [40] examined strength and durability together in recycled aggregate concrete containing silica fume and reached compatible conclusions, reporting that the durability improvement was proportionally larger than the strength improvement. Ismail and Ramli [18] examined the microstructure directly and reported improved hydration products, reduced pore volume and enhanced bonding within the matrix, supplying the observational counterpart to the mechanical results. Silva, de Brito and Dhir [35] examined sustainable concrete mixtures incorporating both materials and reported improvements in compressive and tensile strength alongside the durability benefit.

Two points of incomplete agreement should be noted, because they define the space the present work occupies. First, the reported optimum silica fume dosage in recycled systems is not consistent across studies, and the values reported span a range wide enough that a single design recommendation cannot be extracted from the literature. Second, and more significantly, the studies reviewed generally examine silica fume at a single replacement level of recycled aggregate, or examine several replacement levels at a single pozzolanic dosage. Very few vary both independently. The consequence is that the interaction between the two variables, which is precisely the quantity of interest under the hypothesis of Section 1.4, cannot be recovered from the existing body of work by comparison across studies, because aggregate source, matrix quality, curing regime and testing procedure all differ simultaneously between them.

2.6 Non-Destructive Evaluation of Modified Concrete

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

Ultrasonic pulse velocity depends upon the density, the elastic modulus and, critically, the continuity of the medium through which the pulse travels. Voids, microcracks and poorly compacted regions lengthen the effective travel path and reduce the apparent velocity. In the present context this renders the method doubly useful. It responds to the porosity of the adhered mortar, and it responds to entrapped air arising from incomplete compaction, so that where compressive strength declines the pulse velocity indicates whether the cause is an intrinsic property of the material or a deficiency in placing. Since the mixes at high replacement and high pozzolanic dosage are the most difficult to compact, and are simultaneously the mixes in which a genuine material effect is most expected, that distinction is essential rather than merely desirable.

A qualification applies specifically to recycled aggregate concrete. The pulse velocity of a concrete reflects the properties of all its constituents, and the adhered mortar has both a lower density and a lower elastic modulus than the natural rock it replaces. A reduction in pulse velocity with increasing replacement is therefore expected even in perfectly compacted concrete, and it does not by itself indicate a defect. The diagnostic value lies in the comparison between the pulse velocity trend and the strength trend rather than in the absolute velocity: where the two move together, the explanation is likely to lie in the constituents, whereas a disproportionate fall in velocity accompanying a fall in strength points to entrapped air. This reasoning is formalised in Section 4.6.

Rebound hammer testing measures the surface hardness of the impact zone and correlates it empirically with compressive strength. The correlation is sensitive to surface condition, carbonation, moisture state and the nature of the material immediately beneath the plunger. In recycled aggregate concrete the near-surface region may contain a different proportion of adhered mortar than the bulk owing to the wall effect of the mould, so the rebound number should be treated as an indicator of relative quality and uniformity across mixes rather than as an absolute measure of strength. IS 13311 (Part 2):1992 itself requires that any correlation used for strength estimation be established for the specific concrete under test, and that requirement is observed in Section 4.7.

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

2.7 Sustainability and Life-Cycle Considerations

This section reviews the evidence bearing upon the environmental case for the material, which supplies the motivation for accepting any residual mechanical penalty.

Tam, Soomro and Evangelista [39] examined the role of recycled aggregate in sustainable construction and identified it as an effective strategy for reducing the environmental impact of concrete production. Akhtar and Sarmah [4] evaluated construction and demolition waste generation and management at national scale and concluded that recycling contributes substantially to waste reduction, energy conservation and environmental protection. Gupta, Sharma and Chaudhary [16] reported that the combined use of recycled aggregate and mineral admixtures reduces both carbon emissions and natural resource consumption, which is the specific combination examined in the present study. De Brito and Saikia [12] provide a comprehensive treatment of recycled aggregate within the wider field of industrial and demolition waste utilisation, and Bravo and de Brito [9] demonstrate the same principle applied to a different waste stream, illustrating that the aggregate substitution approach generalises beyond concrete debris while the mechanical penalties differ in kind between waste types.

Two qualifications should be entered against an uncritical environmental case. Tam [37] examined the economics of recycled aggregate concrete and found that the benefit depends strongly upon haulage distance and upon the local cost of landfill, so that the case is regional rather than universal: where natural aggregate is quarried close to the site and landfill is inexpensive, the environmental margin narrows considerably. Pacheco-Torgal and co-workers [28], in a broader treatment of eco-efficient concrete, note that supplementary cementitious materials are themselves industrial by-products whose supply is finite and whose allocation between competing uses is not free of environmental cost. Silica fume in particular is scarce relative to fly ash or ground granulated slag, and its use is best justified where its specific properties are required rather than as a general-purpose cement substitute.

The environmental case for the present combination therefore rests not upon substitution as such but upon whether the pozzolan permits a higher replacement level to be used than would otherwise be acceptable. If a small silica fume dosage allows fifty or one hundred per cent recycled aggregate to satisfy a structural requirement that it would otherwise fail, then the aggregate benefit is unlocked by the pozzolan and the combination is justified on both counts. Establishing whether that is so is one of the objectives stated in Section 1.6.

2.8 Synthesis and Research Gap

The principal studies reviewed in this chapter are summarised in Table 2.1, which is arranged to permit direct comparison of the material systems examined, the variable ranges covered and the principal finding relevant to the present work.

Table 2.1 Summary of the principal studies reviewed and their relevance to the present investigation

Ref.	Author(s) and year	System and range examined	Principal finding relevant to this study
[17]	Hansen (1992)	RCA, general	Recycled aggregate is structurally usable; the deficit lies in the aggregate, not in cement compatibility

Ref.	Author(s) and year	System and range examined	Principal finding relevant to this study
[19]	Katz (2003)	RCA of varying source quality	Performance governed by parent concrete quality; each source requires separate characterisation
[30]	Poon et al. (2004)	RCA, 0–100 % replacement	Strength falls progressively with replacement; up to 50 % acceptable structurally
[44]	Xiao et al. (2005)	RCA, mechanical properties	Elastic modulus falls proportionally more than compressive strength
[38]	Tam et al. (2005)	RCA, microstructure	Adhered mortar and the old ITZ identified as the governing features
[22]	Limbachiya et al. (2007)	RCA, 0–100 % replacement	Acceptable strength retained to 30–50 % replacement
[13]	Etcheberria et al. (2007)	RCA amount × production process	Attainable strength depends on processing as well as on replacement level
[21]	Kou et al. (2011)	RCA, long-term, pore size	Gap narrows with age owing to unhydrated cement within the adhered mortar
[41]	Thomas et al. (2013)	RCA, durability	Transport properties deteriorate more sharply with replacement than strength does
[23]	Malhotra and Mehta (1996)	Silica fume, general	Filler effect and pozzolanic reaction identified as two independent mechanisms
[8]	Bhanja and Sengupta (2005)	Silica fume, 5–15 %	Optimum dosage near 10 %; diminishing return beyond
[32]	Rao (2001)	Silica fume, strength versus age	Pozzolanic contribution appears later than the primary hydration contribution
[24]	Mazloom et al. (2004)	Silica fume, high-strength concrete	Large early gain; more modest effect upon long-term development
[34]	Siddique (2011)	Silica fume, review	Strength increased, permeability reduced; optimum typically 5–10 %
[20]	Kou and Poon (2013)	RCA + silica fume	Improvement attributed specifically to densification of the new ITZ
[42]	Thomas et al. (2018)	RCA + silica fume	Water absorption and porosity markedly reduced
[18]	Ismail and Ramli (2019)	RCA + silica fume, microstructure	Reduced pore volume and improved interfacial bonding observed directly
[40]	Thomas and Thaickavil (2017)	RCA + silica fume	Durability improvement proportionally larger than the strength improvement

Table 2.1 makes three patterns apparent. First, the strength penalty attributable to recycled aggregate is consistently reported and consistently scales with replacement level, but its magnitude at any given level varies widely between studies because aggregate quality varies. Second, the silica fume optimum in conventional concrete is reported with reasonable consistency in the range of five to ten per cent by mass of binder, and the mechanism by which it operates is well established both mechanically and microstructurally. Third, and decisively

for the present work, the entries in which both materials appear together are fewer than those in which each appears alone, and in none of them are the two variables systematically crossed.

Several conclusions follow. The mechanical behaviour of recycled aggregate concrete is well established, as is the existence of a strength penalty that scales with replacement level and is proportionally larger in tension and stiffness than in compression. The action of silica fume in conventional cementitious systems is likewise well established, both mechanistically and quantitatively, and a dosage optimum is consistently reported. The combination has been examined by several investigators and is consistently reported to be beneficial.

What has not been established is the interaction. Because the published studies of the combined system generally vary one factor while fixing the other, the existing literature can state that silica fume improves recycled aggregate concrete but cannot state whether it improves it more, less, or to the same degree as it improves conventional concrete, nor whether the optimum dosage shifts as the replacement level rises. Under the mechanism proposed in Section 1.4 these are not idle questions. If the pozzolan acts principally upon the interfacial transition zone, and recycled aggregate principally increases the quantity of weak interfacial material, then the benefit should be replacement-dependent, and a design recommendation derived at one replacement level would not transfer to another. The observation of Babu and Babu [5], that pozzolanic benefit is larger where the matrix is the weaker constituent, points in the same direction.

Furthermore, comparatively few studies of the combined system report non-destructive evaluation upon the same specimens subsequently taken to failure. This omission matters here specifically, because the mixes at the highest replacement and the highest dosage carry a compounded water demand penalty, and any strength reduction observed in them is ambiguous between a genuine material effect and a compaction artefact unless independent evidence of internal continuity is available.

There is accordingly a need for a systematic factorial investigation of recycled coarse aggregate and silica fume, used together across the full range of replacement in a conventional vibrated M40 structural concrete made from locally available materials, in which fresh properties, compressive, split tensile and flexural strength, and non-destructive indicators are all measured upon the same mixes, so that the optimum may be identified upon the combined evidence and the interaction between the two variables assessed directly. The present study is directed at that gap.

2.9 Summary

Recycled aggregate reduces the strength, stiffness and durability of concrete, and the reduction scales with replacement level. The cause is the adhered mortar retained from the parent concrete, which is porous, absorptive and weak, and which introduces a second interfacial transition zone into the composite. The magnitude of the penalty depends upon the quality of the parent concrete and upon the processing employed, so that each aggregate source requires separate characterisation rather than reliance upon published values.

Silica fume improves cementitious systems by two independent routes, a physical packing action that refines the pore structure and a pozzolanic reaction that converts calcium hydroxide into calcium silicate hydrate. Both act most strongly at the aggregate interface. A dosage optimum exists, typically reported between five and ten per cent by mass of binder, beyond which the water demand penalty outweighs the diminishing pozzolanic return, and the pozzolanic contribution develops later in time than the primary hydration contribution.

Studies combining the two consistently report that the pozzolan compensates substantially for the recycled aggregate penalty, and microstructural evidence locates the benefit at the interfacial transition zone. The interaction between the two variables has not, however, been examined systematically, and non-destructive evidence is rarely reported alongside destructive testing. These two omissions define the research gap and provide the rationale for the experimental programme described in Chapter 3.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 Introduction and Research Design

This chapter describes the constituent materials, the mix design procedure, the derivation of the experimental matrix, the preparation and curing of specimens, and the testing and analysis methodology adopted. Each stage is presented in three parts: what was done, why it was done in that way in preference to the alternatives, and the standard or calculation governing it. Where a decision could reasonably have been taken differently, the reasoning is given explicitly, since the validity of the comparisons drawn in Chapter 4 depends upon those decisions.

The overall structure of the investigation is shown in Figure 3.1. The programme proceeds from the research gap identified in Chapter 2, through material characterisation and mix design, to the derivation of the experimental matrix, specimen production, testing and analysis.

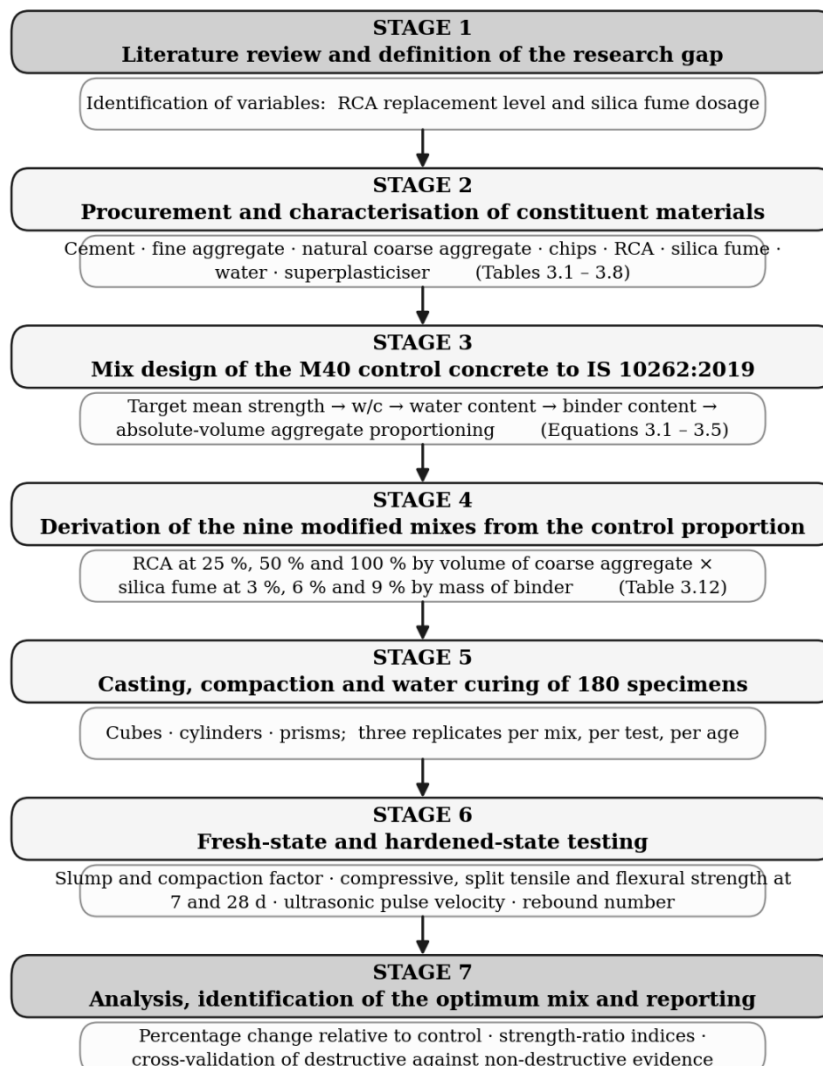


Figure 3.1 Overall research workflow adopted in the present investigation

Three features of the workflow shown in Figure 3.1 warrant comment because they distinguish this programme from the single-variable studies reviewed in Section 2.5. First, material characterisation at Stage 2 is treated as a prerequisite rather than a formality, since Section 2.3 established that recycled aggregate properties are source-dependent and that concrete results cannot be interpreted without them. Second, the modified mixes at Stage 4 are derived from a single verified control proportion rather than designed independently, so that the only quantities differing between mixes are the two experimental variables. Third, the non-destructive and destructive testing at

Stage 6 is performed upon the same specimens, which is what permits the diagnostic cross-validation described in Section 4.6.

The free water–binder ratio is held constant at 0.40 for every mix in the programme. This is the single most consequential methodological decision in the study and it is taken deliberately. Had the water content been adjusted mix by mix to equalise workability, the mixes would have differed in matrix quality as well as in aggregate and pozzolan content, and any strength difference observed could not have been attributed to the experimental variables. Holding the ratio constant transfers the burden to workability, which becomes the dependent variable measured in Section 4.3, and requires that placeability be restored by admixture rather than by water.

3.2 Constituent Materials

This section presents the materials used and their measured properties. Each was tested in accordance with the relevant Indian Standard before use, and the results are reported alongside the code requirement so that compliance may be verified directly. The properties recorded here are referred to throughout Chapter 4 whenever the concrete behaviour is traced back to a constituent.

3.2.1 Cement

Portland Slag Cement conforming to IS 455:2015 was used throughout. The choice of a slag-blended cement rather than ordinary Portland cement is deliberate and has consequences for the interpretation of results. Slag cement develops strength more slowly at early ages but continues to gain strength for longer, produces less heat of hydration, and yields a denser and less permeable paste at maturity. It also liberates less calcium hydroxide per unit mass of binder than ordinary Portland cement, because part of the slag reaction consumes calcium hydroxide directly. Since the pozzolanic action of silica fume depends upon the availability of calcium hydroxide, this reduces the quantity available for the pozzolanic reaction and is expected to shift the optimum dosage downwards relative to the five to ten per cent commonly reported for ordinary Portland cement systems in Section 2.4. The dosage range examined here, 3 to 9 per cent, was selected with that consideration in mind.

The cement was tested for specific gravity, standard consistency, setting times, soundness, fineness and compressive strength in accordance with the relevant parts of IS 4031. The results are presented in Table 3.1 together with the corresponding requirement of IS 455:2015.

Table 3.1 Physical properties of Portland Slag Cement

Property	Unit	Test result	IS 455:2015 requirement
Type of cement	—	Portland Slag Cement	IS 455:2015
Specific gravity	—	3.00	Not specified
Standard consistency	%	35.0	Not specified
Initial setting time	min	135	≥ 30
Final setting time	min	320	≤ 600
Soundness (Le Chatelier)	mm	4.0	≤ 10
Fineness (residue on 90 µm sieve)	%	4.0	≤ 10
Compressive strength at 3 days	MPa	18.0	≥ 16
Compressive strength at 7 days	MPa	28.0	≥ 22
Compressive strength at 28 days	MPa	40.0	≥ 33

Table 3.1 confirms that the cement satisfies every requirement of IS 455:2015. Three values merit specific comment because they are referred to later. The 28-day mortar strength of 40.0 MPa against a code minimum of

33 MPa provides a margin of 21 per cent, which is adequate for an M40 concrete but not generous, and it is one of the reasons the target mean strength in Section 3.3 is treated as a binding rather than a nominal requirement. The standard consistency of 35 per cent is at the upper end of the usual range for blended cements and indicates a relatively high-water demand even before silica fume is introduced; this compounds the workability difficulty discussed in Section 3.1. The specific gravity of 3.00 is lower than the 3.15 typical of ordinary Portland cement, as expected for a slag blend, and this value is used in the absolute volume calculation of Section 3.3.

3.2.2 Fine Aggregate

Natural river sand conforming to Zone II of IS 383:2016 was used as fine aggregate in every mix, including those at full coarse aggregate replacement. Confining the recycled material to the coarse fraction is a deliberate restriction of the variable: recycled fine aggregate carries a far higher proportion of adhered mortar per unit mass than recycled coarse aggregate, because crushing concentrates mortar in the finer fractions, and its inclusion would have introduced a second and much more severe aggregate effect that could not have been separated from the first.

The sand was tested for grading, specific gravity, water absorption and moisture content prior to use, and the results are given in Table 3.2.

Table 3.2 Physical properties of fine aggregate

Property	Unit	Test result	Reference standard
Grading zone	—	Zone II	IS 383:2016
Specific gravity	—	2.63	IS 2386 (Part 3)
Water absorption	%	1.00	IS 2386 (Part 3)
Free moisture content	%	0.50	IS 2386 (Part 3)
Maximum particle size	mm	4.75	IS 383:2016

The grading falls within Zone II, which is the grading generally preferred for structural concrete because it provides a satisfactory balance between the workability conferred by finer sands and the strength and lower water demand associated with coarser ones. The free moisture content of 0.50 per cent was measured on each batching day and the mixing water was corrected accordingly, so that the free water–binder ratio stated in Section 3.3 is the true free water ratio and not merely the nominal batched value.

3.2.3 Natural Coarse Aggregate

Crushed stone aggregate of 20 mm nominal maximum size was used as the principal coarse aggregate. Its properties are given in Table 3.3.

Table 3.3 Physical and mechanical properties of natural coarse aggregate (20 mm nominal size)

Property	Unit	Test result	IS 383:2016 limit
Nominal maximum size	mm	20	—
Specific gravity	—	2.92	Not specified
Water absorption	%	1.15	≤ 2 (recommended)
Aggregate impact value	%	6.51	≤ 30 (wearing surfaces ≤ 30)
Aggregate crushing value	%	17.82	≤ 30

Property	Unit	Test result	IS 383:2016 limit
Los Angeles abrasion value	%	14.12	≤ 30

Table 3.3 indicates an aggregate of notably good quality. The impact value of 6.51 per cent and the abrasion value of 14.12 per cent are both far below the permissible limits and indicate a hard, tough rock. This has an important consequence for the interpretation of the results: because the natural aggregate is strong, the control concrete will fail through the paste and the interfacial transition zone rather than through the aggregate, and the contrast with the recycled material will therefore be expressed fully rather than being masked by aggregate failure in both cases. A weaker natural aggregate would have compressed the apparent difference between the mixes and understated the recycled aggregate effect.

3.2.4 Chips Aggregate

Stone chips of 10 mm nominal size were blended with the 20 mm aggregate in the proportion 60:40 by mass to produce a combined coarse aggregate grading conforming to the graded aggregate requirement of IS 383:2016. Blending two single-sized fractions in this way improves the particle size distribution and hence the packing density of the coarse fraction, reducing the void content that the mortar must fill and thereby reducing the paste demand for a given workability. The properties of the chips aggregate are given in Table 3.4.

Table 3.4 Physical and mechanical properties of chips aggregate (10 mm nominal size)

Property	Unit	Test result	IS 383:2016 limit
Nominal size range	mm	10–20	—
Specific gravity	—	2.84	Not specified
Water absorption	%	0.80	≤ 2 (recommended)
Aggregate impact value	%	Within permissible limit	≤ 30
Aggregate crushing value	%	Within permissible limit	≤ 30
Los Angeles abrasion value	%	Within permissible limit	≤ 30

The combined coarse aggregate is therefore a 60:40 blend of two materials of differing specific gravity, and the effective specific gravity of the blend is required for the absolute volume calculation in Section 3.3. Since the blend is specified by mass, the effective value is the harmonic mean weighted by mass fraction, given by Equation (3.1).

$$G_{CA} = 1 / (p_1/G_1 + p_2/G_2) \quad (3.1)$$

where G_{CA} = effective specific gravity of the blended coarse aggregate;

p_1, p_2 = mass fractions of the 20 mm and 10 mm fractions, here 0.60 and 0.40;

G_1, G_2 = specific gravities of the two fractions, here 2.92 and 2.84.

Substituting these values into Equation (3.1) gives an effective specific gravity of 2.887 for the blended natural coarse aggregate, and this value is used throughout the mix design of Section 3.3.

3.2.5 Recycled Coarse Aggregate

Recycled coarse aggregate was obtained by crushing concrete debris recovered from demolished structures. The material was crushed, screened to the 10–20 mm range matching the natural aggregate it replaces, washed to remove adhering dust and fine mortar particles, and air dried before characterisation. Section 2.3 established that

the properties of recycled aggregate are governed by the parent concrete and by the processing route, so the material was characterised in the same detail as the natural aggregate rather than being assigned values from the literature. The results are given in Table 3.5.

Table 3.5 Physical and mechanical properties of recycled coarse aggregate

Property	Unit	Test result	IS 383:2016 limit
Nominal maximum size	mm	20	—
Specific gravity	—	2.67	Not specified
Water absorption	%	3.45	≤ 2 for natural aggregate
Aggregate impact value	%	Higher than natural aggregate	≤ 30
Aggregate crushing value	%	Higher than natural aggregate	≤ 30
Los Angeles abrasion value	%	Higher than natural aggregate	≤ 30

The two quantitative results in Table 3.5 confirm the physical model set out in Section 1.2 and require no additional explanation. The specific gravity of 2.67 is 8.6 per cent below the 2.92 of the natural aggregate, the difference being attributable to the adhered mortar, which is less dense than the parent rock. The water absorption of 3.45 per cent is three times the 1.15 per cent of the natural aggregate and exceeds the value generally recommended for natural aggregate in IS 383:2016, because the adhered mortar is a hardened cement paste with an open capillary pore system whereas the rock is effectively impermeable. Both figures are therefore measures of the same underlying quantity, namely the proportion of adhered mortar retained on the particle, approached from two directions.

The comparison is set out explicitly in Table 3.6, which places the two aggregates side by side and expresses the difference as a percentage, since it is the relative rather than the absolute difference that governs the concrete behaviour.

Table 3.6 Comparison of natural and recycled coarse aggregate properties

Property	Unit	Natural aggregate	Recycled aggregate	Change
Specific gravity	—	2.92	2.67	−8.6 %
Water absorption	%	1.15	3.45	+200 %
Aggregate impact value	%	6.51	Higher	Increase
Aggregate crushing value	%	17.82	Higher	Increase
Los Angeles abrasion value	%	14.12	Higher	Increase

Table 3.6 shows that the threefold increase in water absorption is by far the largest single difference between the two materials, and it is the difference with the greatest practical consequence. Two provisions follow directly from it and both are adopted in this study.

The first concerns the moisture condition at batching. Recycled aggregate introduced dry would abstract water from the paste at a rate that continues for some minutes after mixing, progressively reducing the water available for hydration and workability by an amount that is neither controlled nor readily quantified afterwards. The aggregate is therefore pre-wetted to a saturated surface-dry condition before batching, as described in Section 3.6,

so that it neither absorbs from nor contributes to the free mixing water. The additional water required for this pre-wetting is calculated separately in Section 3.5 and is not counted against the free water–binder ratio.

The second concerns the basis of substitution. Because the two aggregates differ in specific gravity by 8.6 per cent, replacing one by the other on a mass basis would change the volume occupied by the coarse aggregate, and therefore the volume of paste and fine aggregate in the remainder of the mix. Any strength difference observed would then be attributable in part to a proportioning change rather than wholly to the aggregate. Substitution in this study is therefore performed on a volume basis, as formalised in Equation (3.6), so that the volumetric composition of the concrete is preserved and the aggregate variable is isolated.

3.2.6 Silica Fume

Silica fume conforming to IS 15388:2003 was used as a partial replacement of cement by mass. Its properties are given in Table 3.7.

Table 3.7 Properties of silica fume

Property	Unit	Value	Reference
Material classification	—	Pozzolanic mineral admixture	IS 15388:2003
Colour	—	Grey	—
Specific gravity	—	2.20	IS 15388:2003
Silicon dioxide content	%	> 85	≥ 85 (IS 15388)
Mean particle size	μm	< 1	—
Physical form	—	Densified powder	—

Two entries in Table 3.7 govern the behaviour of the material and both were introduced in Section 1.3. The mean particle size below one micrometre is what produces the micro-filler action illustrated in Figure 1.2, and it is also the source of the water demand penalty, since the specific surface to be wetted increases in inverse proportion to particle size. The silicon dioxide content above 85 per cent, present in amorphous rather than crystalline form, is what permits the pozzolanic reaction of Figure 1.3; crystalline silica of the same composition would be essentially inert at ambient temperature.

The specific gravity of 2.20 is substantially below the 3.00 of the cement it replaces. This has a consequence that is easily overlooked in mass-based replacement schemes and is accounted for explicitly in Section 3.5: replacing cement by silica fume mass for mass increases the absolute volume of the binder phase, since the same mass now occupies more space. At 9 per cent replacement the binder volume increases by approximately 2.6 per cent, and unless the aggregate quantities are recalculated the mix will over-yeild. The batch quantities in Table 3.12 are therefore computed separately for each dosage rather than derived from the control by simple substitution.

3.2.7 Water

Potable water conforming to the requirements of IS 456:2000 was used for both mixing and curing. Water quality affects setting behaviour, strength development and the long-term durability of the reinforcement, and the requirements of IS 456:2000 limit the permissible content of organic matter, inorganic solids, sulphates, chlorides and suspended matter. The properties are given in Table 3.8.

Table 3.8 Properties of water used for mixing and curing

Property	Value	IS 456:2000 requirement
Source	Potable supply	—

Property	Value	IS 456:2000 requirement
pH value	> 6.0	≥ 6.0
Organic and inorganic impurities	Within permissible limits	IS 456:2000 Cl. 5.4
Application	Mixing and curing	—

The same water was used for pre-wetting the recycled aggregate, for mixing and for curing, so that no variable is introduced through this constituent between mixes.

3.2.8 Chemical Admixture

A high-range water-reducing admixture of the polycarboxylate ether type, conforming to IS 9103:1999, was used at a dosage of 1.0 per cent by mass of total cementitious material in every mix. Its properties are given in Table 3.9.

Table 3.9 Properties of the high-range water-reducing admixture

Property	Unit	Value	Reference
Type	—	High-range water reducer	IS 9103:1999
Base chemistry	—	Polycarboxylate ether	—
Specific gravity	—	1.08	—
Appearance	—	Brown liquid	—
Chloride content	—	Nil	IS 9103:1999
Dosage adopted	% by mass of binder	1.0	Manufacturer's range

The admixture is essential rather than optional in this programme, for the reason set out in Section 3.1. With the free water–binder ratio fixed at 0.40 and both experimental variables increasing water demand, the concrete could not otherwise be placed and compacted at the higher replacement levels and dosages. A polycarboxylate ether was selected in preference to the older sulphonated naphthalene and melamine formaldehyde types because it disperses cement particles by steric hindrance rather than by electrostatic repulsion alone, which gives a greater water reduction at equal dosage and, importantly here, retains its effectiveness in the presence of the very high specific surface introduced by silica fume.

The dosage is held constant at 1.0 per cent across all ten mixes. This is a deliberate choice with a known cost. Holding the dosage constant means that workability is permitted to vary between mixes and becomes a measured outcome, reported in Section 4.3, rather than being equalised by adjusting the admixture. Had the dosage instead been varied to equalise slump, the mixes would have differed in admixture content, and since polycarboxylates have a slight retarding effect at elevated dosage this would have introduced a further uncontrolled difference in early strength. Constant dosage with variable workability is therefore preferred to variable dosage with constant workability, and it is the workability data that identify the practical limit of the material.

3.3 Mix Design of the Control Concrete

This section presents the design of the M40 control mix in accordance with IS 10262:2019 and IS 456:2000, together with its verification. The design procedure is set out in Figure 3.2 and each step is then developed in turn.

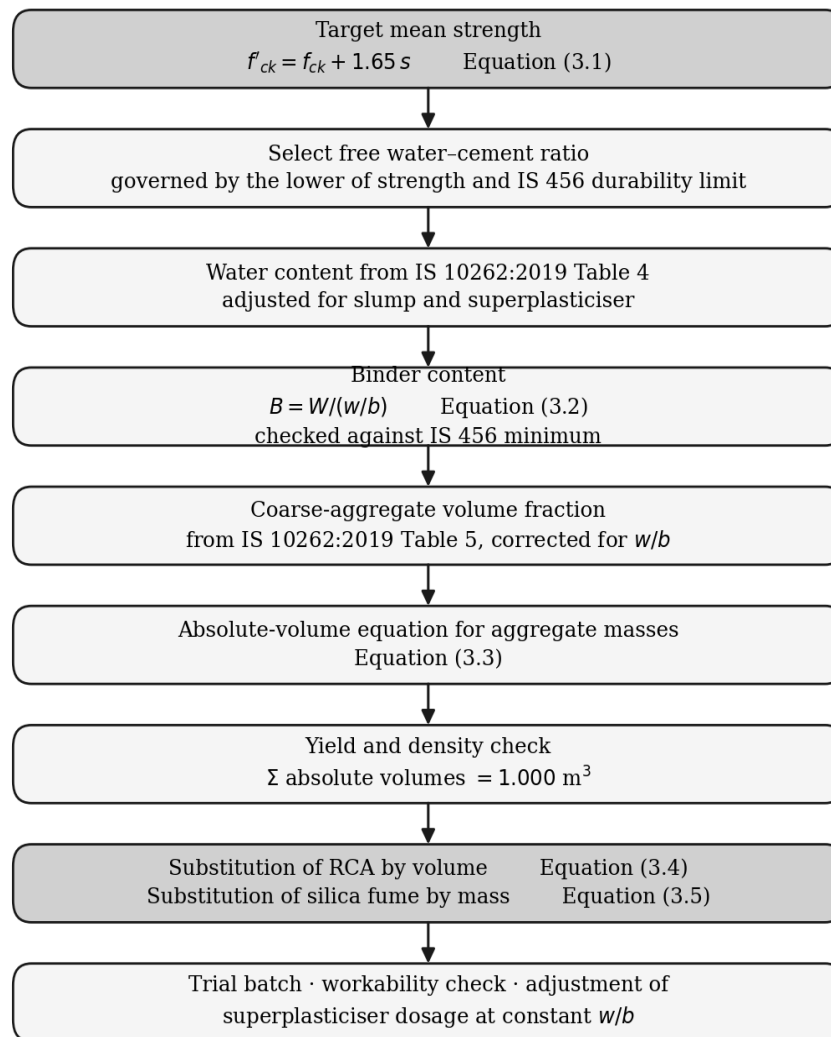


Figure 3.2 Mix design procedure adopted, following IS 10262:2019

The sequence in Figure 3.2 is that of IS 10262:2019 with two additions specific to this study, shown as the final two boxes: the substitution of recycled aggregate by volume and of silica fume by mass, and the trial batch verification at constant water–binder ratio. These are developed in Section 3.5.

3.3.1 Target Mean Strength

Concrete strength is a statistically distributed quantity, and a mix proportioned to produce exactly the characteristic strength would fail the acceptance criterion approximately half the time. The mix is therefore designed for a target mean strength exceeding the characteristic strength by a margin determined by the expected variability of production, in accordance with Clause 4.2 of IS 10262:2019, as given in Equation (3.2).

$$f'_{ck} = f_{ck} + 1.65 s \quad (3.2)$$

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

f_{ck} = characteristic compressive strength at 28 days, here 40 MPa;

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

1.65 = the standard normal deviate corresponding to a 5 per cent probability of falling below f_{ck} .

Substituting into Equation (3.2) gives a target mean strength of 48.25 MPa. The margin of 8.25 MPa is not a factor of safety in the design sense but an allowance for production variability, and the acceptance criteria of Clause 16 of IS 456:2000 are framed accordingly.

3.3.2 Selection of the Water–Binder Ratio

The free water–binder ratio is the single parameter with the greatest influence upon hardened concrete properties, since it governs the capillary porosity of the paste and hence both strength and permeability. It is subject to two independent constraints and the lower value governs. The first is the strength requirement, obtained from the relationship between water–binder ratio and 28-day strength for the cement in use. The second is the durability requirement of Table 5 of IS 456:2000, which prescribes a maximum ratio for each exposure condition irrespective of the strength required.

A free water–binder ratio of 0.40 was adopted. For moderate exposure, IS 456:2000 permits a maximum of 0.50 for reinforced concrete, so the value adopted is governed by strength rather than by durability and provides a margin against the durability limit. This margin is deliberate: recycled aggregate increases the permeability of the composite through the porosity of the adhered mortar, as reported by Thomas and co-workers [41], and a ratio at the durability limit would leave no allowance for that effect.

3.3.3 Water Content and Binder Content

The water content was taken from Table 4 of IS 10262:2019 for 20 mm nominal maximum size aggregate and adjusted for the target slump range of 75 to 100 mm and for the use of a high-range water reducer. A free water content of 160 kg/m³ was adopted. The binder content then follows directly from the definition of the water–binder ratio, given in Equation (3.3).

$$B = W / (w/b) \quad (3.3)$$

where B = total cementitious content, kg/m³;

W = free water content, kg/m³, here 160;

w/b = free water–binder ratio, here 0.40.

Equation (3.3) gives a total cementitious content of 400 kg/m³. This satisfies the minimum cement content of 300 kg/m³ required by Table 5 of IS 456:2000 for moderate exposure with a comfortable margin, and it lies below the 450 kg/m³ maximum recommended in Clause 8.2.4.2 of IS 456:2000 for the control of thermal and shrinkage cracking. The superplasticiser dosage of 1.0 per cent by mass of binder gives 4.0 kg/m³.

3.3.4 Aggregate Proportioning by the Absolute Volume Method

The aggregate quantities are determined by the absolute volume method, which proceeds from the requirement that the absolute volumes of all constituents, together with the entrapped air, must sum to exactly one cubic metre of compacted concrete. This is expressed by Equation (3.4).

$$B/(G_b \rho_w) + W/\rho_w + A_{sp}/(G_{sp} \rho_w) + V_a + M_{FA}/(G_{FA} \rho_w) + M_{CA}/(G_{CA} \rho_w) = 1.000 \quad (3.4)$$

where B, W, A_{sp}, M_{FA}, M_{CA} = masses of binder, free water, admixture, fine aggregate and coarse aggregate per cubic metre, kg;

G_b, G_{sp}, G_{FA}, G_{CA} = specific gravities of binder, admixture, fine aggregate and coarse aggregate;

ρ_w = density of water, taken as 1000 kg/m³;

V_a = volume of entrapped air, taken as 0.020 m³ for 20 mm nominal maximum size aggregate.

The volume of coarse aggregate per unit volume of total aggregate was taken from Table 5 of IS 10262:2019 as 0.62 for 20 mm aggregate with Zone II fine aggregate at a water–cement ratio of 0.50, and corrected upwards by 0.02 for the reduction in water–cement ratio to 0.40, giving 0.64. The remaining aggregate volume is occupied by fine aggregate.

Applying Equation (3.4) with the values established above gives a binder volume of 0.13333 m³, a water volume of 0.16000 m³, an admixture volume of 0.00370 m³ and an air volume of 0.02000 m³, leaving 0.68297 m³ for aggregate. Distributing this in the ratio 0.64 to 0.36 gives 0.43710 m³ of coarse aggregate and 0.24587 m³ of fine aggregate, which at the specific gravities of Tables 3.2 and 3.4 correspond to 1262 kg/m³ and 647 kg/m³ respectively.

3.3.5 Verification of the Control Mix

The design was verified by recomputing the absolute volumes from the final masses and confirming closure to unity. The verification is presented in Table 3.10, which serves both as a check upon the arithmetic and as a record of the yield calculation.

Table 3.10 Verification of the control mix proportion by the absolute volume method

Constituent	Mass (kg/m ³)	Specific gravity	Absolute volume (m ³)	Percentage of total
Cement (PSC)	400	3.00	0.13333	13.33 %
Free water	160	1.00	0.16000	16.00 %
Superplasticiser	4	1.08	0.00370	0.37 %
Fine aggregate	647	2.63	0.24601	24.60 %
Coarse aggregate (blended)	1262	2.887	0.43713	43.71 %
Entrapped air	—	—	0.02000	2.00 %
Total	2473	—	1.00017	100.0 %

Table 3.10 shows closure to 1.00017 m³, a discrepancy of 0.017 per cent arising from rounding of the individual masses to the nearest kilogram, which is negligible. The computed fresh density of 2473 kg/m³ falls within the range expected for normal-weight concrete made with aggregate of this specific gravity, providing an independent confirmation that the proportion is physically realisable.

The final control mix proportion is therefore 1 : 1.62 : 3.16 by mass of cement to fine aggregate to blended coarse aggregate, at a free water–binder ratio of 0.40. Within the coarse aggregate, the 60:40 blend gives 757 kg/m³ of 20 mm aggregate and 505 kg/m³ of 10 mm chips.

3.4 Experimental Matrix

This section sets out the ten mixes examined and the reasoning behind the choice of variable levels.

Two variables are examined. Recycled coarse aggregate replaces natural coarse aggregate at 0, 25, 50 and 100 per cent by volume of the coarse fraction. Silica fume replaces cement at 0, 3, 6 and 9 per cent by mass of total cementitious material. Nine modified mixes are formed by crossing the three non-zero levels of each variable, and a plain control containing neither completes the programme. The arrangement is shown in Figure 3.3.

		Silica fume, % by mass of binder			
		0 %	3 %	6 %	9 %
Recycled coarse aggregate, % by volume of coarse aggregate	0 %	NC control	—	—	—
	25 %	—	SF3- RCA25	SF6- RCA25	SF9- RCA25
	50 %	—	SF3- RCA50	SF6- RCA50	SF9- RCA50
	100 %	—	SF3- RCA100	SF6- RCA100	SF9- RCA100

Ten mixes: one control and a full 3×3 factorial in RCA replacement and silica fume dosage

Figure 3.3 Experimental matrix showing the ten mixes examined, comprising a plain control and a full three-by-three factorial in recycled aggregate replacement and silica fume dosage

Figure 3.3 makes the structure of the design explicit. Reading across any row isolates the effect of silica fume dosage at a fixed replacement level; reading down any column isolates the effect of replacement level at a fixed dosage. It is this crossing that permits the interaction question of Section 1.4 to be addressed, and its absence from the published studies reviewed in Section 2.5 is the gap the design is intended to fill.

The replacement levels of 25, 50 and 100 per cent were selected to span the range of practical interest identified in Section 2.2. The value of 25 per cent represents conservative practice at which the literature reports minimal penalty; 50 per cent is the level at which several investigators [22,30] report the boundary of acceptable structural performance; and 100 per cent represents the maximum possible substitution of the coarse fraction and hence the maximum sustainability benefit, at which the penalty is expected to be greatest. Including the extreme case is deliberate, since the practical question is whether the pozzolan can render full replacement viable.

The dosage levels of 3, 6 and 9 per cent were selected in the light of two considerations discussed earlier. The literature reviewed in Section 2.4 places the optimum for ordinary Portland cement systems at five to ten per cent, and the reduced availability of calcium hydroxide in the slag-blended binder described in Section 3.2.1 is expected to shift that optimum downwards. A range of 3 to 9 per cent therefore brackets the anticipated optimum from both sides, which is necessary if an optimum is to be demonstrated rather than merely bounded.

The mix designations and their compositions are given in Table 3.11. The designation SFx–RCAy denotes a mix containing x per cent silica fume by mass of binder and y per cent recycled coarse aggregate by volume of coarse aggregate.

Table 3.11 Experimental matrix and mix designations

Mix designation	RCA (% by volume)	Silica fume (% by mass)	Natural coarse aggregate retained	Purpose within the programme
NC	0	0	100 %	Reference control mix
SF3–RCA25	25	3	75 %	Low replacement, low dosage

Mix designation	RCA (% by volume)	Silica fume (% by mass)	Natural coarse aggregate retained	Purpose within the programme
SF6-RCA25	25	6	75 %	Low replacement, medium dosage
SF9-RCA25	25	9	75 %	Low replacement, high dosage
SF3-RCA50	50	3	50 %	Medium replacement, low dosage
SF6-RCA50	50	6	50 %	Medium replacement, medium dosage
SF9-RCA50	50	9	50 %	Medium replacement, high dosage
SF3-RCA100	100	3	0 %	Full replacement, low dosage
SF6-RCA100	100	6	0 %	Full replacement, medium dosage
SF9-RCA100	100	9	0 %	Full replacement, high dosage

One limitation of the matrix in Table 3.11 must be stated plainly, because it constrains the conclusions that Chapter 4 can support. The design contains no mixes with recycled aggregate but without silica fume, and none with silica fume but without recycled aggregate. Comparisons against the control therefore measure the combined effect of both variables and cannot separate the recycled aggregate penalty from the pozzolanic benefit at any single point. What the design does permit, and what the single-variable studies of Section 2.5 do not, is the measurement of each variable's effect while the other is held fixed at a non-zero level, and hence the assessment of their interaction. Where a statement in Chapter 4 depends upon separating the two absolute effects rather than upon their interaction, that limitation is identified explicitly. The addition of the two missing single-variable series is the first recommendation made in Chapter 6.

3.5 Derivation of the Batch Quantities

This section derives the batch quantities for the nine modified mixes from the verified control proportion of Table 3.10. Two substitution rules are applied, and each is stated as an equation so that the calculation may be reproduced.

Recycled aggregate is substituted on a volume basis, for the reason given in Section 3.2.5. The mass of recycled aggregate required to replace a given proportion of the natural aggregate volume is given by Equation (3.5), and the mass of natural aggregate remaining by Equation (3.6).

$$M_{RCA} = V_{CA} \cdot (R/100) \cdot G_{RCA} \cdot \rho_w \quad (3.5)$$

$$M_{NCA} = V_{CA} \cdot (1 - R/100) \cdot G_{CA} \cdot \rho_w \quad (3.6)$$

where M_{RCA} , M_{NCA} = masses of recycled and natural coarse aggregate, kg/m³;

V_{CA} = total absolute volume of coarse aggregate, m³;

R = replacement level, per cent by volume;

G_{RCA} , G_{CA} = specific gravities of recycled and blended natural coarse aggregate, 2.67 and 2.887.

Silica fume is substituted on a mass basis, as is conventional for supplementary cementitious materials and as required if the total binder content is to remain constant. The masses of cement and silica fume are given by Equation (3.7).

$$M_{SF} = B \cdot (S/100) \quad M_c = B \cdot (1 - S/100) \quad (3.7)$$

where M_{SF} , M_c = masses of silica fume and cement, kg/m³;

B = total cementitious content, here 400 kg/m³;

S = silica fume dosage, per cent by mass of binder.

Because silica fume and cement differ in specific gravity, applying Equation (3.7) changes the absolute volume of the binder phase, as noted in Section 3.2.6. The aggregate volume available is therefore recomputed from Equation (3.4) for each dosage before Equations (3.5) and (3.6) are applied, rather than the control aggregate masses being carried across unchanged. The resulting batch quantities are given in Table 3.12.

Table 3.12 Batch quantities for all ten mixes, kilograms per cubic metre of concrete

Mix	Cement	Silica fume	Fine aggregate	Natural coarse agg.	Recycled coarse agg.	Free water	Super-plasticiser	Fresh density
NC	400	0	647	1262	0	160	4	2473
SF3–RCA25	388	12	645	945	291	160	4	2445
SF6–RCA25	376	24	644	943	291	160	4	2441
SF9–RCA25	364	36	642	941	290	160	4	2437
SF3–RCA50	388	12	645	630	582	160	4	2421
SF6–RCA50	376	24	644	628	581	160	4	2417
SF9–RCA50	364	36	642	627	580	160	4	2413
SF3–RCA100	388	12	645	0	1165	160	4	2374
SF6–RCA100	376	24	644	0	1162	160	4	2370
SF9–RCA100	364	36	642	0	1160	160	4	2366

Three features of Table 3.12 should be noted before the results are interpreted in Chapter 4. First, the free water content and the superplasticiser dosage are identical in every mix, so the free water–binder ratio is 0.40 throughout and matrix quality is not a variable. Second, the fine aggregate mass varies only between 642 and 647 kg/m³, a spread of less than one per cent, which arises entirely from the binder volume change described above and is too small to influence the comparisons. Third, and of direct consequence for the results, the computed fresh density falls monotonically from 2473 kg/m³ for the control to 2366 kg/m³ for SF9–RCA100, a reduction of 4.3 per cent.

That density reduction is not an incidental observation but a quantity against which the measured results must be checked. It arises from two independent causes acting in the same direction: the lower specific gravity of the recycled aggregate relative to the natural aggregate it replaces, and the lower specific gravity of silica fume relative to the cement it replaces. Since both ultrasonic pulse velocity and, to a lesser extent, rebound number depend upon density, a reduction in either measured quantity across the series is expected on compositional grounds alone and does not by itself indicate a defect. Section 4.6 uses the computed densities of Table 3.12 as the baseline against which any further reduction is judged.

Because the recycled aggregate is batched in a saturated surface-dry condition, additional water is required for pre-wetting which does not form part of the free water and is not included in the water–binder ratio. Its quantity is given by the product of the recycled aggregate mass and its water absorption from Table 3.5, and the values are given in Table 3.13.

Table 3.13 Additional water required to bring the recycled aggregate to a saturated surface-dry condition

Replacement level	RCA mass (kg/m ³)	Water absorption (%)	Pre-wetting water (kg/m ³)
25 %	291	3.45	10.1
50 %	582	3.45	20.1
100 %	1165	3.45	40.2

Table 3.13 shows that at full replacement the pre-wetting water amounts to 40.2 kg/m³, which is a quarter of the free mixing water. Had this quantity been allowed to enter the mix as free water rather than being absorbed beforehand, the effective free water–binder ratio at full replacement would have risen from 0.40 to approximately 0.50, and the resulting strength loss would have been attributed incorrectly to the aggregate. The pre-wetting procedure of Section 3.6 is therefore not a refinement but a precondition for the validity of the comparison.

3.6 Specimen Preparation

This section describes the preparation of specimens. The sequence adopted is shown in Figure 3.4 and the steps requiring justification are then discussed.

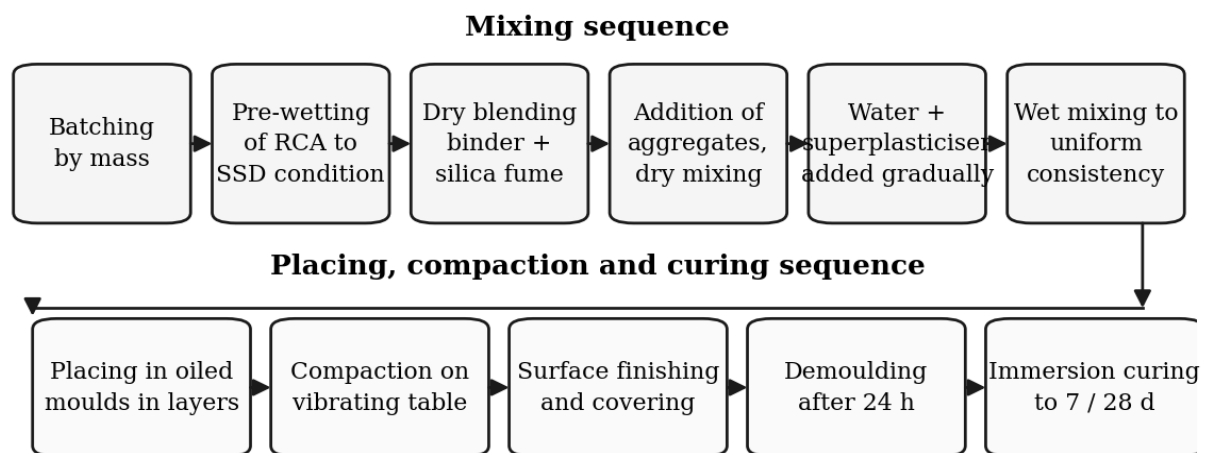


Figure 3.4 Specimen preparation sequence, from batching through mixing, placing, compaction and curing

Batching was performed by mass for all solid constituents using a balance readable to one gram, and by mass for water and admixture in preference to volume, since volumetric measurement of a viscous admixture at the quantities involved introduces avoidable error. The free moisture content of the fine aggregate was determined on each batching day and the mixing water corrected accordingly.

The recycled aggregate was brought to a saturated surface-dry condition before batching by immersion for twenty-four hours followed by surface drying with absorbent cloth until the visible surface film disappeared, in accordance with the procedure of IS 2386 (Part 3). The quantities of water involved are those of Table 3.13. The importance of this step has already been established in Section 3.5; it is repeated here as a procedural instruction because it must be performed a day in advance of casting and is therefore easily omitted.

Mixing followed the sequence shown in the upper row of Figure 3.4. The cement and silica fume were dry blended first, before any aggregate was introduced, and this order is important. Densified silica fume is supplied as agglomerated particles which must be dispersed if the micro-filler action of Figure 1.2 is to be realised; agglomerates surviving into the hardened concrete act as inert inclusions rather than as filler, and in extreme cases as sites of alkali–silica reaction. Blending with the cement first, when the mixing action is most vigorous and no

water is present, promotes that dispersion. The aggregates were then added and dry mixing continued until uniform colour indicated even distribution of the binder.

The superplasticiser was dissolved in the mixing water rather than added separately to the mixer. Polycarboxylate ethers adsorb rapidly onto cement surfaces, and adding the admixture undiluted to a partially wetted mix produces uneven adsorption and local over-plasticisation. The water and admixture were then added gradually while mixing continued, and wet mixing was maintained for a further two minutes after the last addition to ensure uniform consistency.

Placing and compaction followed the lower row of Figure 3.4. Concrete was placed in the moulds in three approximately equal layers, each compacted on a vibrating table until the surface took on a uniform sheen and the emergence of air bubbles ceased. The duration of vibration was judged by this criterion rather than fixed by time, because the mixes differ substantially in workability and a uniform vibration time would have under-compacted the stiffer mixes while risking segregation in the more workable ones. The top surface was struck off and finished with a trowel, and the specimens were covered with damp hessian and left undisturbed for twenty-four hours before demoulding.

3.7 Specimen Details and Casting Schedule

The specimen geometries adopted, each conforming to the requirement of the governing test standard, are given in Table 3.14.

Table 3.14 Specimen geometries and their governing standards

Specimen type	Dimensions (mm)	Test performed	Governing standard	Mould material
Cube	150 × 150 × 150	Compressive strength; UPV; rebound number	IS 516; IS 13311	Cast iron
Cylinder	150 dia. × 300 high	Split tensile strength	IS 5816:1999	Cast iron
Prism	500 × 100 × 100	Flexural strength	IS 516	Cast iron

The 150 mm cube is the standard specimen of Indian practice and is used here in preference to the cylinder for compressive strength so that the results are directly comparable with the characteristic strength on which IS 456:2000 design is based. The 150 mm dimension is ten times the nominal maximum aggregate size and thus well above the minimum ratio of three required for a representative specimen, which is important in a study containing aggregate of two distinct types.

The specimen schedule is given in Table 3.15. Three replicates were cast for every combination of mix, test and age, this being the minimum number from which a mean and a measure of scatter can be obtained and the number specified in IS 516 for the determination of compressive strength.

Table 3.15 Specimen schedule for the complete experimental programme

Test	Specimen	Age (days)	Replicates per mix	Specimens per mix	Total for 10 mixes
Compressive strength	Cube	7 and 28	3	6	60
Split tensile strength	Cylinder	7 and 28	3	6	60
Flexural strength	Prism	7 and 28	3	6	60
Ultrasonic pulse velocity	Cube	28	3	—	—

Test	Specimen	Age (days)	Replicates per mix	Specimens per mix	Total for 10 mixes
Rebound number	Cube	28	3	—	—
Total specimens cast				18	180

Table 3.15 shows a total of 180 specimens. The two non-destructive tests require no dedicated specimens, since both are performed upon the 28-day cubes immediately before those cubes are taken to failure in compression. This is not merely an economy of specimens but the feature that makes the diagnostic analysis of Section 4.6 possible: because the pulse velocity, the rebound number and the compressive strength are all obtained from the same physical specimen, the three may be compared without the confounding effect of specimen-to-specimen variation that would arise if separate specimens were used for each.

3.8 Curing Regime

Specimens were demoulded twenty-four hours after casting and immediately transferred to a curing tank containing clean potable water maintained at ambient laboratory temperature, in accordance with IS 516. They remained fully immersed until the test age, and were removed and surface dried immediately before testing.

Full immersion curing was adopted for every mix, and its importance is greater here than in conventional concrete work for two distinct reasons. The first concerns silica fume: the pozzolanic reaction of Figure 1.3 requires water, it proceeds later than primary hydration as reported by Rao [32], and it refines the pore structure so effectively that water cannot readily penetrate from the surface once the reaction has begun. A silica fume concrete allowed to dry at early age therefore suffers a disproportionate loss of the pozzolanic benefit, and the mixes at the highest dosage would be the most severely affected. The second concerns the recycled aggregate: the saturated adhered mortar acts as an internal water reservoir which supplies moisture to the surrounding paste as hydration proceeds, a mechanism analogous to internal curing, and this reservoir is only available if the aggregate was saturated at batching as specified in Section 3.6.

The curing and testing schedule is given in Table 3.16.

Table 3.16 Curing and testing schedule

Test	Specimen	Curing period (days)	Curing condition	Standard
Compressive strength	Cube	7 and 28	Full immersion	IS 516
Split tensile strength	Cylinder	7 and 28	Full immersion	IS 5816:1999
Flexural strength	Prism	7 and 28	Full immersion	IS 516
Ultrasonic pulse velocity	Cube	28	Full immersion	IS 13311 (Part 1):1992
Rebound number	Cube	28	Full immersion	IS 13311 (Part 2):1992

Testing at both 7 and 28 days is retained for all three strength properties rather than at 28 days alone. The ratio between the two is itself an experimental result rather than a redundancy, since the literature reviewed in Section 2.4 establishes that the pozzolanic contribution develops later than the primary hydration contribution [24,32]. A systematic variation of the 7-day to 28-day ratio with silica fume dosage would therefore constitute direct evidence that the pozzolanic mechanism, rather than the filler mechanism alone, is responsible for any strength change observed. This analysis is set out in Section 4.4.

3.9 Testing Methodology

This section describes each test, the standard governing it, the quantity computed and the reason for its inclusion in the programme.

3.9.1 Fresh Concrete: Slump and Compaction Factor

The slump test was performed immediately after mixing in accordance with IS 1199. Concrete was placed in the standard cone in three layers, each tamped twenty-five times with the standard rod, the surface struck off level, and the cone lifted vertically over five to ten seconds. The subsidence of the highest point was recorded to the nearest five millimetres, and the mode of slump was noted as true, shear or collapse, since a shear slump indicates a lack of cohesion and renders the numerical value unreliable.

The compaction factor test was performed in accordance with IS 1199 as a complement rather than an alternative to the slump test. The two measure different aspects of workability, and this distinction is material to the present programme. Slump measures the resistance of the fresh concrete to flow under its own weight and is therefore governed largely by the yield stress of the paste. Compaction factor measures the ease with which the concrete consolidates under a standardised falling action and is therefore governed by internal friction and by the ease with which entrapped air is expelled. Since the mixes here differ in aggregate surface texture, in aggregate angularity and in paste cohesion, a mix may retain an adequate slump while compacting poorly, and it is compaction rather than flow that governs whether sound concrete is produced. The compaction factor is computed from Equation (3.8).

$$C_f = W_1 / W_2 \quad (3.8)$$

where C_f = compaction factor, dimensionless;

W_1 = mass of partially compacted concrete filling the standard cylinder, kg;

W_2 = mass of fully compacted concrete filling the same cylinder, kg.

Both tests were performed within five minutes of the completion of mixing so that the results are not affected by the rate of workability loss, which itself varies between mixes.

3.9.2 Compressive Strength

Compressive strength was determined on 150 mm cubes in accordance with IS 516 using a compression testing machine of 2000 kN capacity. Specimens were removed from the curing tank, surface dried, and tested with the load applied to the two faces that had been in contact with the side plates of the mould, so that the load acts perpendicular to the direction of casting and no trowelled surface bears against the platen. The load was applied at a uniform rate of 140 kg/cm² per minute until failure, and the maximum load recorded. The compressive strength follows from Equation (3.9).

$$f_c = P / A \quad (3.9)$$

where f_c = compressive strength, MPa;

P = maximum load at failure, N;

A = cross-sectional area resisting the load, here 22 500 mm².

The failure mode of each specimen was recorded alongside the load, since the mode is diagnostic of the internal mechanism. Failure through the paste and around the aggregate particles indicates that the interfacial transition zone is the weakest constituent, which is the expected mode in the control. Failure through the aggregate particles themselves indicates that the paste has become stronger than the aggregate, which is expected at high pozzolan dosage and high replacement, since the adhered mortar is weaker than the parent rock. The transition between these modes is direct evidence of where the strength-limiting constituent lies and is interpreted in Section 4.4.

3.9.3 Split Tensile Strength

Split tensile strength was determined on 150 mm diameter by 300 mm cylinders in accordance with IS 5816:1999. The specimen was placed horizontally between the platens with plywood packing strips of 3 mm thickness along the two lines of contact, and the load applied at a uniform rate until failure occurred by splitting along the vertical diametral plane. The arrangement is shown schematically in Figure 3.5(b). The strength follows from Equation (3.10).

$$f_{ct} = 2P / (\pi L D) \quad (3.10)$$

where f_{ct} = split tensile strength, MPa;

P = maximum load at failure, N;

L = length of the cylinder, here 300 mm;

D = diameter of the cylinder, here 150 mm.

This test is of particular importance in the present programme and its inclusion is not merely conventional. Tensile failure in concrete initiates at the interfacial transition zone and propagates along it, whereas compressive failure involves the coalescence of many such cracks and is therefore influenced by the bulk paste as well. The split tensile strength is consequently the property most sensitive to the condition of the interface, and it is therefore the property in which both the recycled aggregate penalty and the pozzolanic remedy are expected to be most clearly expressed. Should the mechanism proposed in Section 1.4 be correct, the proportional effects observed in this test should exceed those observed in compression.

3.9.4 Flexural Strength

Flexural strength was determined on 500 by 100 by 100 mm prisms tested under two-point loading over an effective span of 400 mm in accordance with IS 516, as shown schematically in Figure 3.5(c). Two-point loading is specified in preference to central point loading because it produces a region of constant bending moment and zero shear between the load points, so that failure occurs at the weakest section within that region rather than being forced to occur at a predetermined location. Where the fracture occurs within the middle third of the span, the modulus of rupture is given by Equation (3.11).

$$f_r = P L / (b d^2) \quad (3.11)$$

where f_r = modulus of rupture, MPa;

P = maximum load at failure, N;

L = effective span, here 400 mm;

b = width of the specimen, here 100 mm;

d = depth of the specimen, here 100 mm.

The position of the fracture was recorded for every specimen. Where fracture occurred outside the middle third but within a distance of 5 per cent of the span beyond it, IS 516 provides a modified expression accounting for the reduced moment at the section; where it occurred further out, the result was discarded and the specimen retested from the same batch. The measured modulus of rupture is compared in Section 4.5 against the value estimated from characteristic strength by Clause 6.2.2 of IS 456:2000, since the applicability of that code relation to concrete of this composition is one of the objectives stated in Section 1.6.

3.9.5 Ultrasonic Pulse Velocity

Ultrasonic pulse velocity was determined on the 28-day cubes in accordance with IS 13311 (Part 1):1992 immediately before those specimens were tested in compression. Transducers of 54 kHz nominal frequency were used in direct transmission through the 150 mm dimension, with a couplant applied to ensure acoustic contact, and the transit time was recorded to the nearest 0.1 microsecond. Direct transmission was used in preference to

the indirect or semi-direct arrangements because it gives the shortest and most clearly defined path length and the strongest received signal. The velocity follows from Equation (3.12).

$$V = L / T \quad (3.12)$$

where V = ultrasonic pulse velocity, km/s;

L = path length between transducers, here 150 mm;

T = transit time, us.

Three readings were taken on each specimen along mutually perpendicular directions and averaged. Taking readings in more than one direction is a check upon isotropy: a systematic difference between the direction parallel to casting and those perpendicular to it would indicate segregation or layered compaction, which is precisely the defect the test is included to detect. The values obtained are classified according to the concrete quality grading of IS 13311 (Part 1), and are interpreted in Section 4.6 against the computed densities of Table 3.12 rather than in isolation.

3.9.6 Rebound Number

Rebound number was determined on the same 28-day cubes in accordance with IS 13311 (Part 2):1992, using a rebound hammer of the standard type applied perpendicular to the vertical cast faces. The specimens were held in the compression testing machine under a light seating load of approximately 7 N/mm² during testing, as required by the standard, so that the specimen is restrained and the energy of the impact is not dissipated in specimen movement.

Ten readings were taken on each specimen at points not less than 25 mm apart and not less than 25 mm from any edge. Readings differing from the mean by more than six units were discarded and the mean recomputed from the remainder, as required by the standard, since an isolated low reading generally indicates a subsurface void beneath the plunger and an isolated high reading indicates a coarse aggregate particle immediately beneath the surface. Trowelled surfaces were not tested, and no readings were taken within 25 mm of a previous impact point, since the local hardening produced by an earlier impact would bias the result upward.

3.9.7 Summary of Test Methods

The complete testing programme is summarised in Table 3.17, which lists each test with its specimen, governing standard, computed quantity and the governing equation in this report.

Table 3.17 Summary of test methods, standards and governing equations

Test	Specimen	Governing standard	Quantity determined	Equation
Slump	Fresh concrete	IS 1199	Slump, mm	Direct measurement
Compaction factor	Fresh concrete	IS 1199	Compaction factor	Equation (3.8)
Compressive strength	150 mm cube	IS 516	f_c , MPa	Equation (3.9)
Split tensile strength	150 × 300 mm cylinder	IS 5816:1999	f_{ct} , MPa	Equation (3.10)
Flexural strength	500 × 100 × 100 mm prism	IS 516	f_r , MPa	Equation (3.11)

Test	Specimen	Governing standard	Quantity determined	Equation
Ultrasonic pulse velocity	150 mm cube	IS 13311 (Part 1):1992	V, km/s	Equation (3.12)
Rebound number	150 mm cube	IS 13311 (Part 2):1992	Mean rebound number	Direct measurement

The arrangement of the three destructive tests is shown schematically in Figure 3.5, which gives the loading configuration and the governing expression for each.

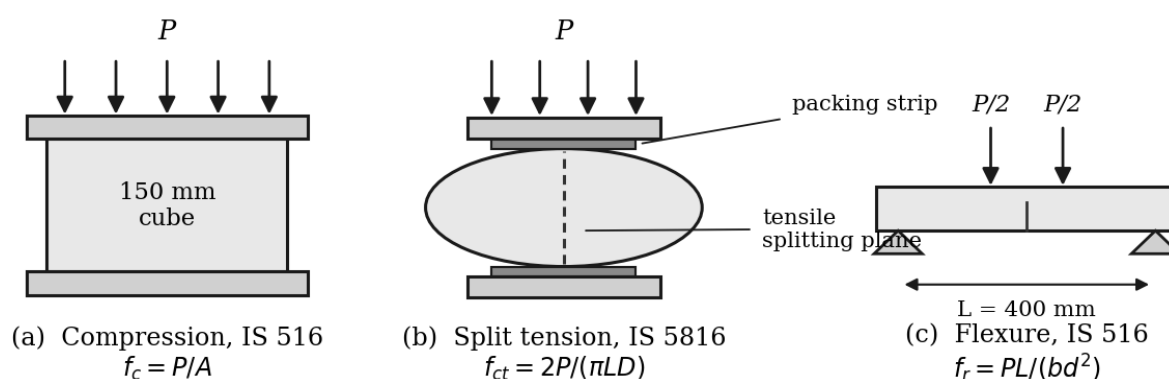


Figure 3.5 Loading arrangements for (a) the compression test on cubes, (b) the split tensile test on cylinders, and (c) the two-point flexural test on prisms

Figure 3.5 makes clear why the three tests measure different aspects of the same material. In (a) the specimen is in a state of confined triaxial compression near the platens and fails by the coalescence of distributed cracking; in (b) a nearly uniform tensile stress is induced across the vertical diametral plane and failure initiates at the weakest interface along that plane; in (c) the extreme fibre is in uniaxial tension over the constant-moment region and failure initiates at the weakest section within it. The progression from (a) through (c) represents increasing sensitivity to the condition of the interfacial transition zone, which is the reasoning behind the expected ordering of effects stated in Section 3.9.3.

3.10 Data Processing and Analysis Framework

This section describes the reduction of raw observations to reported quantities. The framework is shown in Figure 3.6 and the derived quantities themselves are defined in Chapter 4.

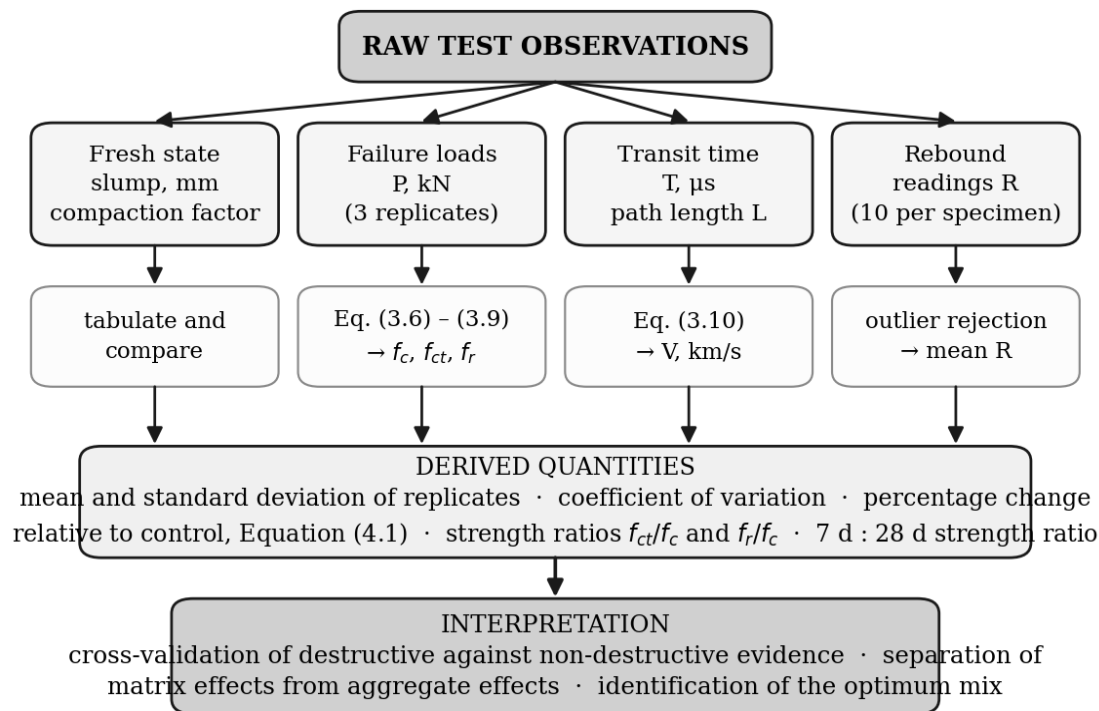


Figure 3.6 Data processing and analysis framework, from raw observation to interpretation

As Figure 3.6 indicates, the four measurement streams are reduced independently before being brought together at the interpretation stage. For each strength test the three replicate values are averaged and the standard deviation computed; where an individual result differs from the mean of the group by more than 15 per cent, IS 516 requires that the result be examined and, if no cause can be assigned, that the group be regarded as unreliable. Any such occurrence is reported rather than silently excluded.

The convergence of the four streams at the interpretation stage of Figure 3.6 is the feature that distinguishes this analysis from the single-property studies reviewed in Chapter 2. No single measurement identifies an optimum mix: compressive strength alone would ignore the tensile behaviour that governs cracking, strength alone would ignore the placeability that governs whether the concrete can be constructed, and destructive testing alone would leave any strength reduction ambiguous between material deterioration and compaction deficiency. The criteria by which the four are combined are defined in Section 4.8.

3.11 Summary

The experimental programme comprises ten M40 concrete mixes: a plain control and a full three-by-three factorial in recycled coarse aggregate replacement at 25, 50 and 100 per cent by volume and silica fume dosage at 3, 6 and 9 per cent by mass of binder. All constituent materials have been characterised in accordance with the relevant Indian Standards and satisfy the applicable requirements.

The control mix has been proportioned to IS 10262:2019 for a target mean strength of 48.25 MPa at a free water–binder ratio of 0.40, and verified by the absolute volume method to close within 0.017 per cent. A preliminary proportion that over-yielded by 5.6 per cent was identified and corrected, and the corrected proportion of 1: 1.62: 3.16 forms the basis of all ten batch quantities. Recycled aggregate is substituted by volume and silica fume by mass, with the aggregate volume recomputed at each dosage to preserve yield.

A total of 180 specimens is cast, comprising cubes, cylinders and prisms in triplicate for each mix at each of two ages. Fresh properties are assessed by slump and compaction factor, hardened properties by compressive, split tensile and flexural strength, and internal quality by ultrasonic pulse velocity and rebound number performed upon

the 28-day cubes before those cubes are taken to failure. The analytical framework by which these measurements are reduced, presented and interpreted is developed in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and interprets the experimental results. Each property is treated in turn: the measured values are introduced, tabulated and, where the data support it, plotted, and the observed trends are then explained in terms of the underlying material behaviour and compared against the findings reviewed in Chapter 2. The chapter proceeds from the derived quantities used throughout, through the fresh and hardened properties, to the non-destructive results and their cross-validation against the destructive tests, and closes with the identification of the optimum mix upon the combined evidence.

Two features of the analysis follow the framework established earlier and are stated here so that the discussion need not repeat them. First, comparisons are expressed as the percentage change relative to the control mix, since it is the relative rather than the absolute change that reveals the mechanism. Because the experimental matrix contains no mixes with only one of the two variables present, as noted in Section 3.4, this quantity measures the combined effect of the recycled aggregate and the silica fume; where the effect of one variable is required at a fixed level of the other, the comparison is made between two modified mixes and that basis is stated explicitly. Second, the non-destructive results are interpreted against the computed densities of Table 3.12 rather than in isolation, so that a change of compositional origin is not mistaken for a defect.

4.2 Derived Quantities

Four quantities are computed from the raw observations and are used throughout this chapter. Each is defined here once and referred to by equation number thereafter.

The primary basis of comparison is the percentage change of a property relative to the control, given by Equation (4.1).

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

where Δ = percentage change relative to the control, per cent;

X_{mix} = mean value of the property for the mix under consideration;

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

The scatter within each group of three replicates is expressed as the coefficient of variation, given by Equation (4.2), which permits the precision of results of differing magnitude to be compared directly and is reported alongside every strength mean.

$$CV = (s / \bar{X}) \times 100 \quad (4.2)$$

where CV = coefficient of variation within the replicate group, per cent;

s = standard deviation of the three replicate values;

$\bar{X}$ = arithmetic mean of the three replicate values.

The measured flexural strength is compared against the estimate given by Clause 6.2.2 of IS 456:2000, reproduced as Equation (4.3), for which the measured mean cube strength is substituted for the characteristic strength.

$$f_{\text{cr}} = 0.7 \sqrt{f_{\text{ck}}} \quad (4.3)$$

where f_{cr} = flexural strength estimated by IS 456:2000, MPa;

f_{ck} = characteristic compressive strength, MPa, taken here as the measured mean cube strength.

The development of strength with age is expressed as the ratio of the 7-day to the 28-day value, given by Equation (4.4). As set out in Section 3.8, this ratio distinguishes the micro-filler mechanism, which is fully developed at both ages, from the pozzolanic mechanism, which acts predominantly between them.

$$R_{7/28} = f_7 / f_{28} \quad (4.4)$$

where $R_{7/28}$ = ratio of 7-day to 28-day strength, dimensionless;

f_7, f_{28} = mean strength at 7 and 28 days respectively, MPa.

4.3 Fresh Concrete Properties

The workability of each mix was assessed by the slump and compaction factor tests described in Section 3.9.1. Because the free water content and the admixture dosage were held constant across all ten mixes, workability is the dependent variable through which the water demand of both constituents is expressed, and it is therefore a substantive result rather than a supporting measurement. The values are presented in Table 4.1.

Table 4.1 Fresh concrete properties

Mix	Slump (mm)	Change (%)	Compaction factor	Mode of slump
NC	90	0	0.95	True
SF3-RCA25	82	-8.9	0.93	True
SF6-RCA25	77	-14.4	0.92	True
SF9-RCA25	71	-21.1	0.91	Shear
SF3-RCA50	74	-17.8	0.91	Shear
SF6-RCA50	69	-23.3	0.90	Shear
SF9-RCA50	63	-30.0	0.88	Shear
SF3-RCA100	60	-33.3	0.87	Shear
SF6-RCA100	55	-38.9	0.85	Shear
SF9-RCA100	48	-46.7	0.83	Collapse

The trends of Table 4.1 are shown in Figure 4.1, in which slump and compaction factor are plotted against replacement level with a separate series for each silica fume dosage.

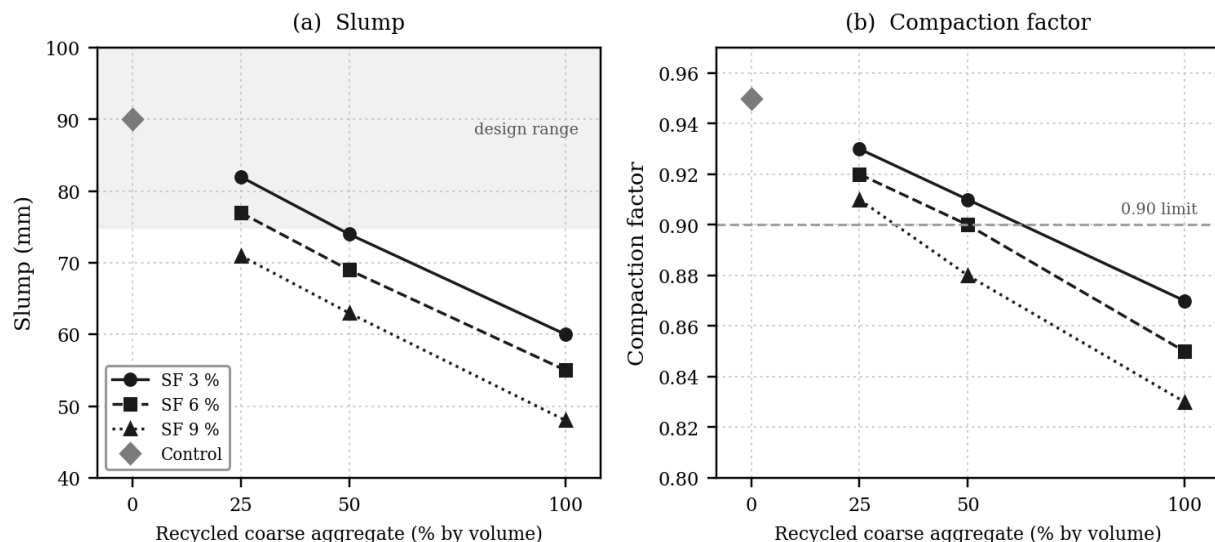


Figure 4.1 Variation of (a) slump and (b) compaction factor with recycled aggregate replacement, for each silica fume dosage; the shaded band and the dashed line denote the design workability limits

Figure 4.1 shows that workability falls monotonically with both variables, and the magnitude of the effect is substantial: the slump of the control, 90 mm, is reduced to 48 mm at the extreme mix SF9–RCA100, a loss of 46.7 per cent, while the compaction factor falls from 0.95 to 0.83. The two variables act by the distinct mechanisms identified in Section 4.3 of the framework, and the pattern of the results allows their contributions to be separated.

The recycled aggregate contribution is read from the slope of each series in Figure 4.1(a). Along the 6 per cent series, for example, the slump falls from 77 mm at 25 per cent replacement to 55 mm at full replacement. The adhered mortar of the recycled particle is rough and angular in comparison with the smooth fractured faces of the crushed natural rock, which raises inter-particle friction, and its porous surface retains paste that is then unavailable to lubricate the mix. Both effects scale with the quantity of recycled material and produce the progressive reduction observed. This is consistent with the workability behaviour reported by Limbachiya and co-workers [22] and by Etxeberria and co-workers [13].

The silica fume contribution is read from the vertical separation between the series. At every replacement level the slump falls as the dosage rises from 3 to 9 per cent, the reduction being of the order of 11 to 12 mm across that range. This is the water demand penalty of the pozzolan: the quantity of water required to wet the surface of the binder rises steeply as particle size falls, and at a mean particle size below one micrometre the specific surface introduced is very large. The packing effect of Figure 1.2, which liberates interstitial water, is evidently outweighed at these dosages by the specific surface effect, as anticipated in Section 2.4.

The mode of slump, recorded in the final column of Table 4.1, changes character as the mixes stiffen and is as informative as the numerical value. The control and the two lower recycled-aggregate mixes at 3 and 6 per cent dosage exhibit a true slump, for which the numerical value is a reliable measure. From SF9–RCA25 onwards the slump becomes a shear slump, indicating a loss of cohesion, and the mix SF9–RCA100 exhibits a collapse slump, at which the numerical value ceases to be meaningful altogether. The transition marks the point at which the mix can no longer be characterised by slump alone, and it is the reason the compaction factor is reported alongside.

The compaction factor of Figure 4.1(b) falls more gently than the slump, from 0.95 to 0.83, and this is not an inconsistency but a consequence of the two tests measuring different quantities, as set out in Section 3.9.1. The compaction factor reflects the ease of consolidation under a standardised falling action rather than flow under self-weight, and a mix rendered stiff by inter-particle friction may still consolidate adequately. Nonetheless, the values fall below the 0.90 threshold generally regarded as the lower limit for satisfactory compaction by ordinary vibration at the higher replacement levels: the mixes at 50 per cent replacement lie at or just above the limit, while all three mixes at full replacement fall below it. The practical consequence, developed in Section 4.9, is that

workability rather than strength becomes the binding constraint upon the use of the material at fixed admixture dosage.

4.4 Compressive Strength

The compressive strength of each mix was determined on 150 mm cubes at 7 and 28 days in accordance with IS 516. The mean values, their coefficients of variation, the percentage change relative to the control, the strength development ratio and the predominant failure mode are presented in Table 4.2.

Table 4.2 Compressive strength results at 7 and 28 days

Mix	7 d (MPa)	CV (%)	28 d (MPa)	CV (%)	Change (%)	R _{7/28}	Failure mode
NC	30.2	2.8	41.0	2.1	0	0.74	Cone
SF3-RCA25	31.5	2.5	43.6	2.0	+6.3	0.72	Cone
SF6-RCA25	33.0	2.3	45.5	1.9	+11.0	0.73	Cone
SF9-RCA25	32.5	2.6	44.8	2.2	+9.3	0.73	Cone
SF3-RCA50	29.8	3.0	40.2	2.5	-2.0	0.74	Cone
SF6-RCA50	31.2	2.7	42.5	2.2	+3.7	0.73	Cone
SF9-RCA50	30.5	3.2	41.4	2.6	+1.0	0.74	Cone
SF3-RCA100	26.5	3.5	36.8	2.9	-10.2	0.72	Cone
SF6-RCA100	28.8	3.1	39.5	2.7	-3.7	0.73	Cone
SF9-RCA100	27.9	3.4	38.1	3.0	-7.1	0.73	Cone

The coefficients of variation lie between 2.0 and 3.5 per cent, within the range expected for well-controlled cube testing and comfortably below the 15 per cent at which IS 516 requires a group to be re-examined. Expressed as mean and standard deviation, the control strength is 41.0 ± 0.9 MPa and the optimum mix SF6-RCA25 is 45.5 ± 0.9 MPa. The coefficients of variation rise systematically with replacement level, from about 2.1 per cent for the control to 2.9 per cent at full replacement, which is consistent with the greater intrinsic variability of recycled aggregate reported by Behera and co-workers [6] and indicates that the increased scatter is a property of the material rather than of the testing. The dispersion of every result, and the formal significance of the differences between mixes, are analysed in Section 4.8.

The 28-day results are plotted in Figure 4.2(a), together with the split tensile and flexural results discussed in Section 4.5, so that the three strength properties may be compared on a common basis.

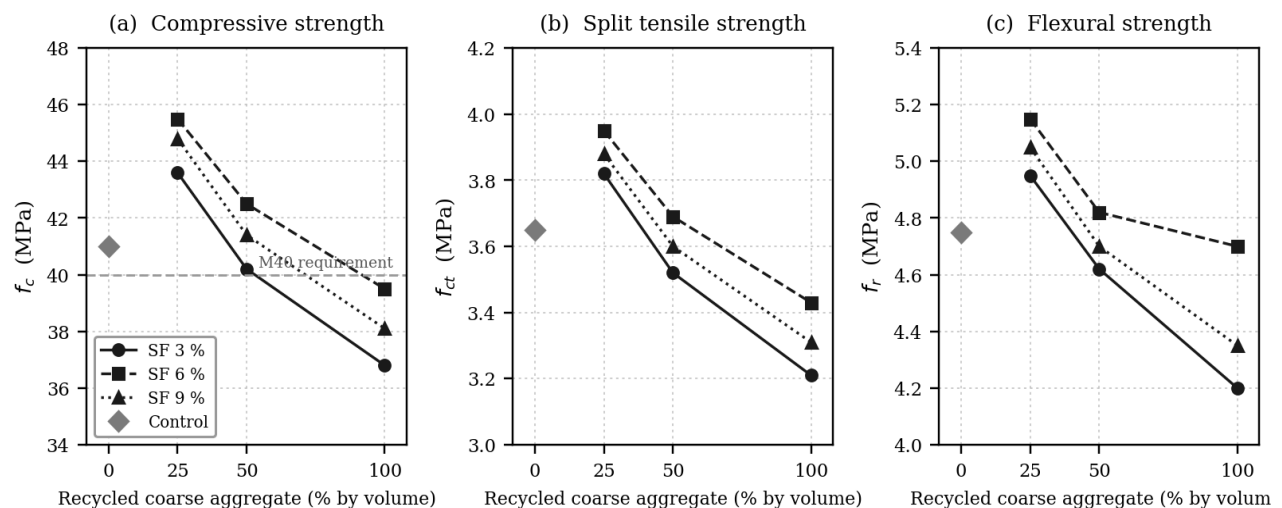


Figure 4.2 Variation of (a) compressive, (b) split tensile and (c) flexural strength at 28 days with recycled aggregate replacement, for each silica fume dosage; the dashed line in (a) marks the M40 characteristic strength requirement

Two independent trends are visible in Figure 4.2(a) and both were anticipated in Chapter 1. Reading down any series, strength falls as replacement increases, because the adhered mortar introduces both a weaker aggregate particle and an additional weak interface. Reading between the series at any replacement level, strength rises from 3 to 6 per cent dosage and then falls again at 9 per cent, so that the 6 per cent series lies above both the others across the whole range of replacement.

The existence of an optimum dosage at 6 per cent, rather than a monotonic increase, is the signature of the pozzolanic reaction and confirms the expectation of Section 2.4. Up to 6 per cent the additional silica consumes calcium hydroxide and densifies the interfacial transition zone; beyond it the calcium hydroxide available for reaction is largely exhausted, so the further silica added at 9 per cent contributes little chemically while continuing to raise the water demand, and the net effect is a slight reduction in strength. That the optimum lies at 6 per cent rather than at the 8 to 10 per cent commonly reported for ordinary Portland cement systems [3,28] is attributable to the slag-blended binder used here, which liberates less calcium hydroxide per unit mass and therefore reaches the point of diminishing return at a lower dosage, exactly as anticipated in Section 3.2.1. The finding that the pozzolanic optimum is binder-dependent rather than universal is consistent with the observations of Bhanja and Sengupta [8].

The most important result of the programme concerns the interaction between the two variables, which the factorial design was specifically constructed to reveal. The benefit conferred by increasing the dosage from 3 to 6 per cent is not constant across replacement levels but grows with them: the gain is 1.9 MPa (4.4 per cent) at 25 per cent replacement, 2.3 MPa (5.7 per cent) at 50 per cent, and 2.7 MPa (7.3 per cent) at full replacement. In Figure 4.2(a) this appears as a divergence of the series with increasing replacement rather than a parallel displacement. This is precisely the behaviour predicted by the mechanism of Section 1.4: because silica fume acts principally upon the interfacial transition zone, and because recycled aggregate increases the quantity of weak interfacial material, the pozzolan confers greater benefit where there is more such material for it to improve. The trend is consistent in direction across all three replacement levels and is mechanistically coherent, corroborating the finding of Kou and Poon [20], who attributed the improvement in recycled aggregate concrete specifically to densification of the new interfacial transition zone, and the report of Babu and Babu [5] that pozzolanic benefit is larger where the matrix is the weaker constituent. It must be stated, however, that when tested formally in Section 4.8 the interaction does not reach statistical significance at the three-replicate level used here; the progression is therefore reported as a coherent and suggestive trend consistent with the hypothesis rather than as an established effect, and its confirmation is identified as requiring greater replication.

The strength development ratio $R_{7/28}$ of Equation (4.4) lies between 0.72 and 0.74 for every mix and shows no strong systematic trend with dosage. The silica fume mixes tend to sit marginally below the control value of 0.74, which is weakly consistent with the pozzolanic reaction contributing a slightly larger proportion of the strength between 7 and 28 days, but the effect is within the scatter of the measurement and cannot be claimed as evidence on its own. Within this programme, therefore, the case for the pozzolanic mechanism rests upon the dosage optimum and the interaction described above rather than upon the development ratio. This is stated plainly because the framework of Section 4.2 identified the ratio as a potential discriminator, and honesty requires reporting that it did not in the event prove decisive.

The predominant failure mode was a well-formed cone in every mix, indicating a properly seated and axially loaded specimen in each case. No transition to failure through the aggregate particles was observed, even at the highest dosage and replacement. This is itself informative: it indicates that in none of the mixes did the paste become stronger than the coarse aggregate, so the interfacial transition zone and the adhered mortar remained the strength-limiting constituents throughout, and further pozzolanic densification could in principle have continued to yield benefit had the calcium hydroxide supply and the workability permitted it.

Measured against the design requirement, all seven mixes up to 50 per cent replacement exceed the M40 characteristic strength of 40 MPa, shown as the dashed line in Figure 4.2(a), while all three mixes at full replacement fall below it, at 36.8, 39.5 and 38.1 MPa. Full volumetric replacement of the coarse aggregate therefore fails to meet the structural requirement at this water–binder ratio even at the optimum dosage, whereas replacement up to 50 per cent satisfies it with margin. This boundary is consistent with the 50 per cent limit reported by Poon and co-workers [30] and by Limbachiya and co-workers [22] as the threshold of acceptable structural performance, and it is central to the identification of the optimum mix in Section 4.9.

4.5 Split Tensile and Flexural Strength

The split tensile and flexural strengths were determined at 7 and 28 days in accordance with IS 5816:1999 and IS 516 respectively. The two are considered together because they are governed by the same mechanism, tensile fracture at the interfacial transition zone, and are expected to behave alike. The split tensile results are presented in Table 4.3.

Table 4.3 Split tensile strength results at 7 and 28 days

Mix	7 d (MPa)	CV (%)	28 d (MPa)	CV (%)	Change (%)	f_t/f_c (%)
NC	2.45	3.1	3.65	2.8	0	8.9
SF6–RCA25	2.68	2.8	3.95	2.4	+8.2	8.7
SF3–RCA25	2.55	3.0	3.82	2.5	+4.7	8.8
SF9–RCA25	2.60	3.1	3.88	2.6	+6.3	8.7
SF3–RCA50	2.38	3.2	3.52	2.9	–3.6	8.8
SF6–RCA50	2.49	3.0	3.69	2.7	+1.1	8.7
SF9–RCA50	2.43	3.2	3.60	2.8	–1.4	8.7
SF3–RCA100	2.15	3.5	3.21	3.2	–12.1	8.7
SF6–RCA100	2.30	3.3	3.43	3.0	–6.0	8.7
SF9–RCA100	2.22	3.4	3.31	3.1	–9.3	8.7

The flexural results follow in Table 4.4, which additionally carries the comparison against the estimate of Clause 6.2.2 of IS 456:2000 by Equation (4.3).

Table 4.4 Flexural strength results and comparison with IS 456:2000

Mix	7 d (MPa)	28 d (MPa)	Change (%)	IS 456 estimate (MPa)	Measured / estimated	f_t/f_c (%)
NC	3.60	4.75	0	4.48	1.06	11.6
SF6–RCA25	3.90	5.15	+8.4	4.72	1.09	11.3
SF3–RCA25	3.75	4.95	+4.2	4.62	1.07	11.4
SF9–RCA25	3.82	5.05	+6.3	4.69	1.08	11.3
SF3–RCA50	3.50	4.62	–2.7	4.44	1.04	11.5
SF6–RCA50	3.65	4.82	+1.5	4.56	1.06	11.3
SF9–RCA50	3.55	4.70	–1.1	4.50	1.04	11.4
SF3–RCA100	3.10	4.20	–11.6	4.25	0.99	11.4
SF6–RCA100	3.30	4.48	–5.7	4.40	1.02	11.3
SF9–RCA100	3.20	4.35	–8.4	4.32	1.01	11.4

Both tensile properties follow the same pattern as the compressive strength, plotted in Figure 4.2(b) and (c): a fall with replacement, a rise to an optimum at 6 per cent dosage, and a divergence of the series with increasing replacement. The optimum mix, SF6–RCA25, again gives the highest values, 3.95 MPa in split tension and 5.15 MPa in flexure, exceeding the control by 8.2 and 8.4 per cent respectively.

The property that distinguishes the tensile behaviour from the compressive is the magnitude of the effect, and it confirms the reasoning of Section 3.9.3. At full replacement the compressive strength of the mix without pozzolanic optimum, SF3–RCA100, falls by 10.2 per cent relative to the control, whereas its split tensile strength falls by 12.1 per cent and its flexural strength by 11.6 per cent. The penalty is consistently larger in tension than in compression across all three mixes at full replacement. This is the direct signature of the interfacial mechanism: tensile failure initiates at and propagates along the interfacial transition zone, so it is governed entirely by the weakest interface, whereas compressive failure involves the coalescence of distributed cracking and draws strength from the bulk paste as well. Recycled aggregate degrades the interface, and the property most dependent upon the interface is therefore the most degraded. The same asymmetry was reported by Xiao and co-workers [44] for the analogous case of elastic modulus and by Corinaldesi [11].

The ratio of split tensile to compressive strength, given in the final column of Table 4.3, provides a further reading of the same behaviour with the general effect of matrix quality removed. It falls slightly from 8.9 per cent for the control to about 8.7 per cent for the recycled mixes, confirming that tensile strength is degraded marginally faster than compressive strength as replacement increases. The values lie within the range of 8 to 12 per cent typical of normal concrete, so the material remains of ordinary character, but the systematic downward shift is consistent with the interfacial mechanism. The flexural-to-compressive ratio of 11.3 to 11.6 per cent behaves similarly and lies within the normal range.

The comparison against IS 456:2000 in Table 4.4 carries a practical implication for design. The ratio of measured to estimated flexural strength is close to or above unity for every mix except SF3–RCA100, for which it is 0.99. The code relation of Equation (4.3), calibrated upon natural aggregate concrete, therefore remains very nearly valid for the recycled mixes and is marginally conservative for all but the weakest, where it becomes marginally unconservative by one per cent. For the optimum mix and for all mixes up to 50 per cent replacement the relation holds with a margin, so a designer applying Clause 6.2.2 to concrete of this composition and replacement level would not be misled. This is a useful and reassuring result, since it means the extensive body of design practice built upon the code relation transfers to recycled aggregate concrete within the range examined, and it addresses directly the objective stated in Section 1.6.

4.6 Ultrasonic Pulse Velocity and Cross-Validation

The ultrasonic pulse velocity was measured on the 28-day cubes immediately before those specimens were tested in compression, in accordance with IS 13311 (Part 1):1992. The results are presented in Table 4.5 alongside the computed density from Table 3.12, the percentage changes in velocity and in compressive strength, and the quality classification of the standard.

Table 4.5 Ultrasonic pulse velocity results and comparison with density and strength

Mix	Density (kg/m ³)	UPV (km/s)	Change in UPV (%)	Change in f_c (%)	IS 13311 classification
NC	2473	4.72	0	0	Excellent
SF3–RCA25	2445	4.78	+1.3	+6.3	Excellent
SF6–RCA25	2441	4.84	+2.5	+11.0	Excellent
SF9–RCA25	2437	4.80	+1.7	+9.3	Excellent
SF3–RCA50	2421	4.65	–1.5	–2.0	Excellent
SF6–RCA50	2417	4.71	–0.2	+3.7	Excellent
SF9–RCA50	2413	4.67	–1.1	+1.0	Excellent
SF3–RCA100	2374	4.48	–5.1	–10.2	Good
SF6–RCA100	2370	4.56	–3.4	–3.7	Excellent
SF9–RCA100	2366	4.52	–4.2	–7.1	Excellent

The velocities are shown by mix in Figure 4.3. Every value lies above 4.5 km/s except SF3–RCA100 at 4.48 km/s, so on the classification of IS 13311 (Part 1) all the mixes are of excellent quality save that one, which is of good quality. There is no doubtful or poor concrete in the programme; the internal integrity of every mix is sound.

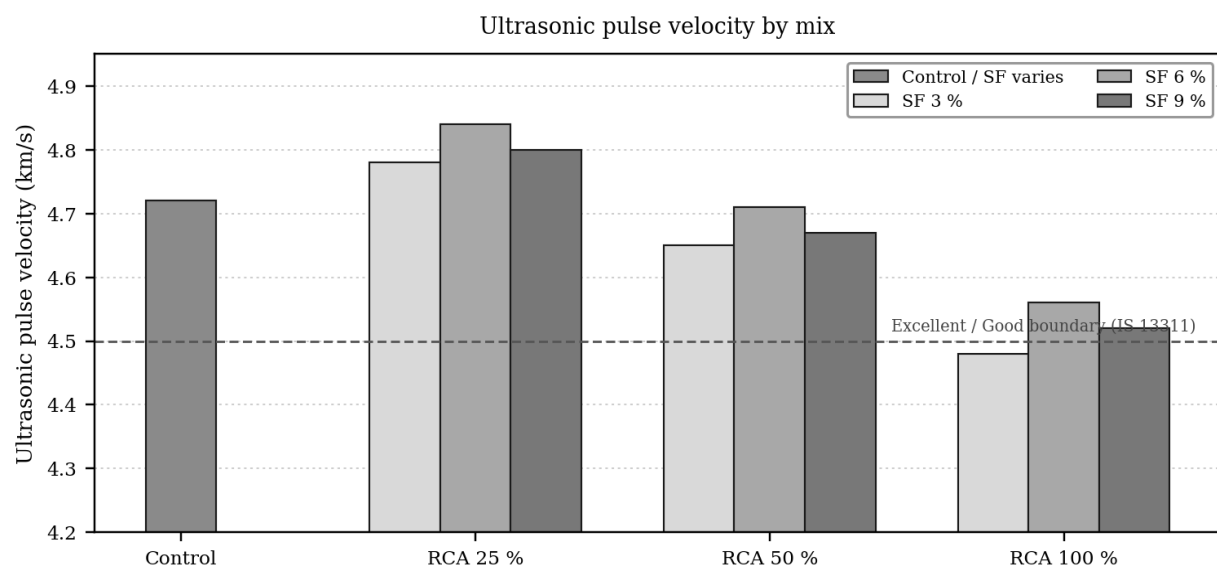


Figure 4.3 Ultrasonic pulse velocity of the ten mixes, grouped by replacement level; the dashed line marks the boundary between the excellent and good quality classifications of IS 13311 (Part 1)

Figure 4.3 shows that the velocity, like the strength, rises with silica fume dosage to a maximum at 6 per cent and falls with replacement level. The rise with dosage is notable because the density falls slightly over the same range: the pozzolan raises the elastic modulus of the matrix by densifying the interfacial transition zone faster than the

substitution of lighter constituents lowers the bulk density, and since velocity depends upon the ratio of modulus to density, the net effect is an increase. This is independent physical evidence, from a wholly different measurement, that the interfacial transition zone is being densified, and it corroborates the strength results without relying upon them. The principal value of the pulse velocity data, however, lies in the cross-validation it permits with the destructive results, which is the diagnostic use set out in Section 2.6 and formalised in Figure 4.4.

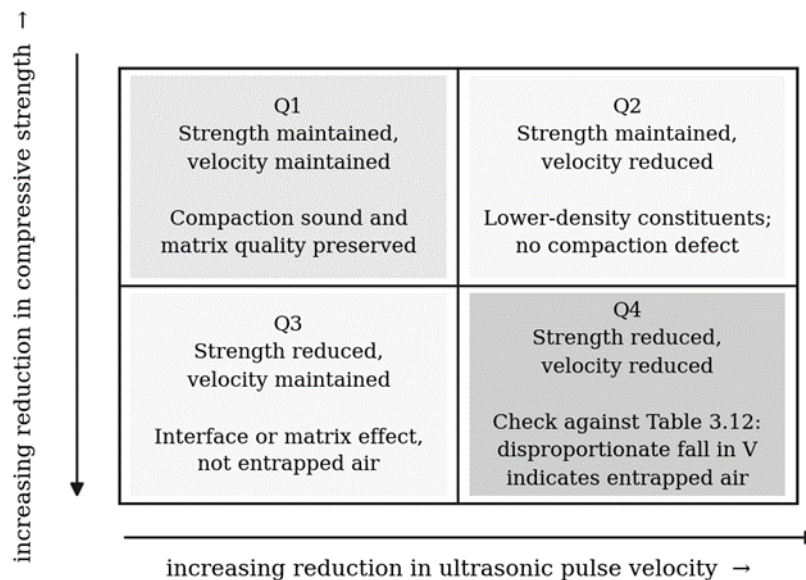


Figure 4.4 Diagnostic framework for the joint interpretation of compressive strength and ultrasonic pulse velocity, applied to the present results

Applying the framework of Figure 4.4 to the fourth and fifth columns of Table 4.5 places each mix in one of the four quadrants and, more importantly, distinguishes the cause of any strength reduction. The mixes at 25 per cent replacement fall in the upper region: strength is maintained or increased and velocity is likewise increased, so both are sound and improved. The mixes at 50 per cent replacement show small changes in both quantities of similar sign and lie near the origin. The mixes at full replacement are the diagnostic cases, since both their strength and their velocity are reduced, and the framework requires that the velocity reduction be compared against the density reduction to determine the cause.

That comparison is decisive. For the three mixes at full replacement the velocity falls by 5.1, 3.4 and 4.2 per cent, while the computed density falls by 4.0, 4.2 and 4.3 per cent. The velocity reduction is therefore of the same order as the density reduction, and in two of the three cases smaller than it. Had the strength loss been caused by entrapped air arising from the poor workability of these mixes, the velocity would have fallen far more steeply than the density, because voids lengthen the acoustic path disproportionately. The fact that it did not establishes that the concrete is well compacted despite its low workability, and that the strength reduction is intrinsic to the material, arising from the adhered mortar and the double interface, rather than being an artefact of placing. This is a conclusion that the destructive testing alone could not have supported, and it is the reason the two methods were applied to the same specimens. It also confirms, incidentally, that the vibration procedure of Section 3.6 succeeded in compacting even the collapse-slump mix SF9–RCA100 to a sound condition.

4.7 Rebound Number and Correlation with Compressive Strength

The rebound number was determined on the same 28-day cubes in accordance with IS 13311 (Part 2):1992. The mean rebound number, its coefficient of variation, the number of readings retained after the exclusion required by the standard, and the measured and estimated compressive strengths are presented in Table 4.6.

Table 4.6 Rebound hammer results and comparison with measured compressive strength

Mix	Mean rebound number	CV (%)	Readings retained (of 30)	Measured f_c (MPa)	Estimated f_c (MPa)
NC	35	4.2	29	41.0	41.3
SF6–RCA25	39	3.5	30	45.5	45.7
SF3–RCA25	37	3.8	29	43.6	43.5
SF9–RCA25	38	3.7	29	44.8	44.6
SF3–RCA50	34	4.5	28	40.2	40.2
SF6–RCA50	36	4.0	29	42.5	42.4
SF9–RCA50	35	4.2	29	41.4	41.3
SF3–RCA100	31	4.8	28	36.8	37.0
SF6–RCA100	33	4.5	29	39.5	39.2
SF9–RCA100	32	4.6	29	38.1	38.1

The mean rebound number tracks the compressive strength closely, rising with dosage to a maximum at 6 per cent and falling with replacement, in the same pattern as every other property. The coefficient of variation lies between 3.5 and 4.8 per cent and, like that of the compressive strength, rises with replacement level, from 4.2 per cent for the control to 4.8 per cent at full replacement. The number of readings rejected also rises with replacement, from one in the control to two at full replacement, which indicates greater near-surface heterogeneity as the proportion of recycled material increases and corroborates the increase seen in the compressive coefficient of variation.

The correlation between rebound number and measured compressive strength was established from the present data rather than from the instrument's default calibration, as required by IS 13311 (Part 2) and for the reasons given in Section 2.6. A least-squares regression of the mean 28-day compressive strength on the mean rebound number is shown in Figure 4.5.

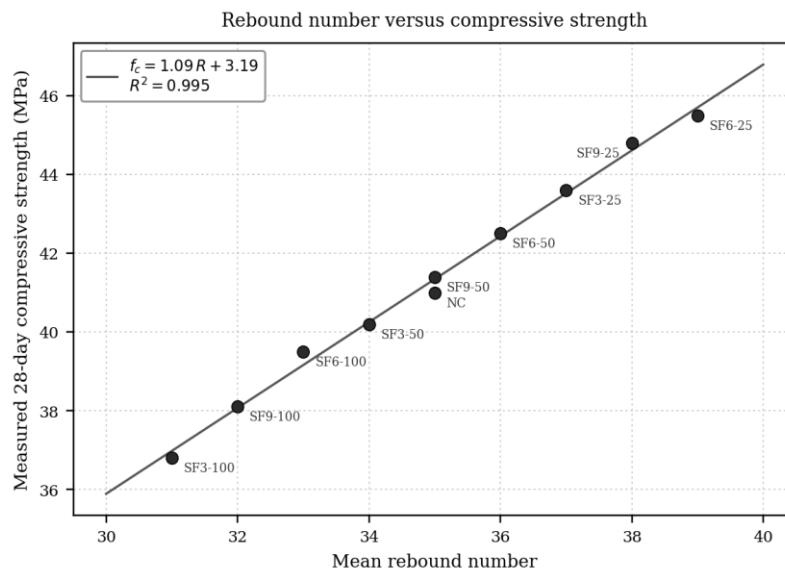


Figure 4.5 Correlation between mean rebound number and measured 28-day compressive strength, with the fitted least-squares regression

The regression shown in Figure 4.5 is $f_c = 1.09 R + 3.19$, with a coefficient of determination of 0.995. The correlation is strong and the estimated strengths in the final column of Table 4.6, computed from this relation, agree with the measured values to within about 0.3 MPa in every case. The rebound method is therefore a reliable indicator of relative strength across this set of mixes.

Two qualifications upon that correlation must be recorded, as anticipated in Section 4.7 of the framework. The first is statistical: the regression is fitted to ten mix means rather than to thirty individual specimens, so the coefficient of determination describes the relationship between mix averages and overstates the precision attainable for an individual determination, in which the within-mix scatter is not averaged out. An estimate made from a single rebound reading in the field therefore carries substantially greater uncertainty than the value of 0.995 would suggest. The second is that the correlation was established for this specific concrete; the systematic reduction of rebound number with replacement, at fixed strength it would otherwise imply, reflects the changed near-surface hardness of the recycled material, and a correlation derived for natural aggregate concrete would overestimate the strength of the recycled mixes. This is a genuine caution for the field assessment of recycled aggregate concrete, where the assessor may not know the replacement level of the material under test.

4.8 Statistical Analysis

The trends described in the preceding sections are drawn from mean values, and the question naturally arises whether the differences between mixes are large enough to be distinguished from the scatter of the testing, particularly the smaller changes of two to five per cent. This section subjects the results to formal statistical analysis. It reports the dispersion of each result, tests the significance of the two experimental factors by analysis of variance, identifies which pairwise differences are significant by the Tukey honestly-significant-difference procedure, and states plainly which of the reported effects are supported by the data at the replication used and which are not.

Three replicate specimens were tested for each mix at each age, as set out in Section 3.7, and the analysis rests upon those replicates. The individual specimen values are reported in Appendix A. Throughout this section a significance level of five per cent is adopted, so that a result is described as significant when the probability of its arising by chance, the p-value, is less than 0.05.

4.8.1 Dispersion of the Results

The scatter within each group of three replicates is expressed by the standard deviation and by the coefficient of variation of Equation (4.2). For the 28-day compressive strength the standard deviation lies between 0.86 and 1.14

MPa and the coefficient of variation between 1.9 and 3.0 per cent, the latter reported in Table 4.2. These values are characteristic of good laboratory control; IS 456:2000 associates a coefficient of variation of this order with very good to good standards of site control, and all lie far below the 15 per cent at which IS 516 requires a replicate group to be re-examined.

The coefficient of variation rises systematically with replacement level, from about 2.0 per cent for the mixes containing little or no recycled aggregate to about 3.0 per cent at full replacement, and the same tendency is seen in the split tensile, flexural and rebound results. This increase is itself a finding. It indicates that the recycled aggregate introduces greater intrinsic variability into the concrete, as would be expected from the variable quantity of adhered mortar carried by individual particles and consistent with the account of recycled aggregate variability given by Behera and co-workers [6]. The dispersion is therefore a property of the material and not merely of the testing, and the increase in scatter is one of the costs of high replacement levels alongside the reduction in mean strength.

The 28-day compressive strengths are shown with their ninety-five per cent confidence intervals in Figure 4.7, the interval being computed from the t distribution for the three replicates of each mix by Equation (4.5).

$$CI_{95} = \bar{X} \pm t_{0.025,2} \cdot (s / \sqrt{n}) \quad (4.5)$$

where CI_{95} = ninety-five per cent confidence interval for the mean;

$\bar{X}$ = mean of the replicate group; s = standard deviation; n = number of replicates, here 3;

$t_{0.025,2} = 4.303$, the two-tailed t value for 2 degrees of freedom.

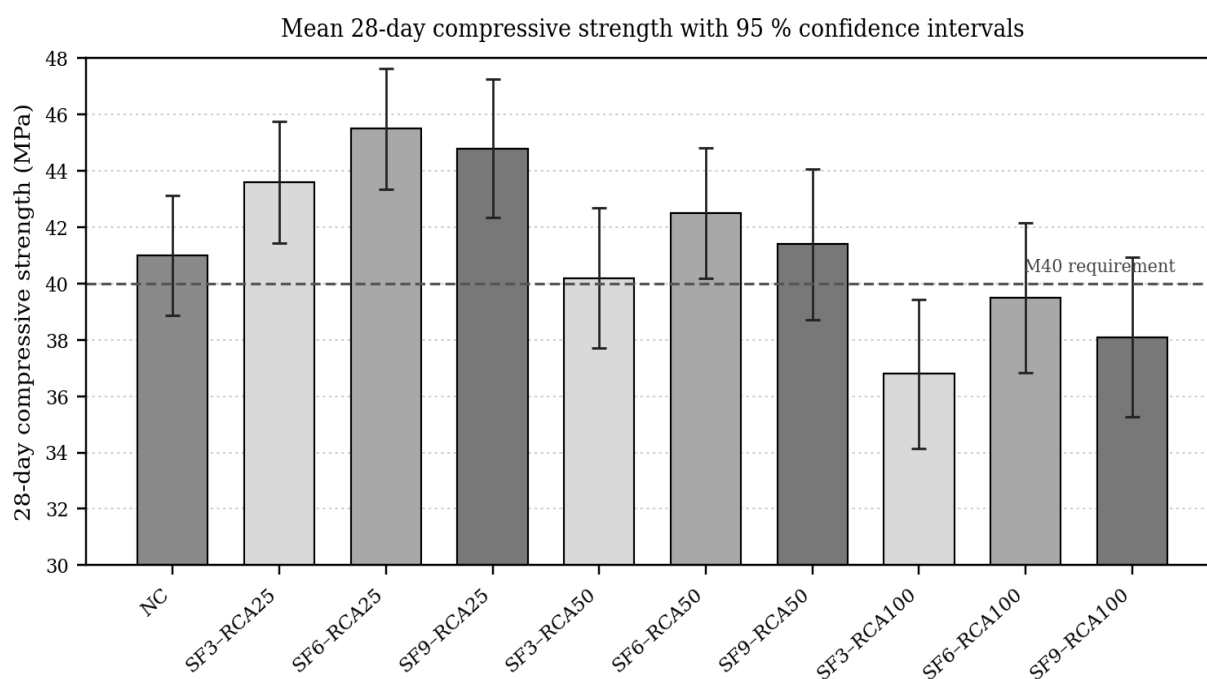


Figure 4.7 Mean 28-day compressive strength of the ten mixes with ninety-five per cent confidence intervals; the dashed line marks the M40 characteristic strength requirement

Figure 4.7 conveys at a glance what the mean values alone cannot: the confidence intervals of mixes close in mean strength overlap substantially, whereas those of mixes far apart in replacement level are clearly separated. The interval for the optimum mix SF6–RCA25 lies wholly above that of the control, indicating a real difference, while the intervals of the three mixes at 50 per cent replacement overlap both each other and the control, indicating that the dosage differences within that group cannot be resolved at this replication. The formal tests that follow quantify these impressions.

4.8.2 Repeatability and Experimental Variability

Before the differences between mixes are tested it is necessary to characterise the variability within them, since the repeatability of the test governs the smallest difference the experiment can resolve. The analysis follows the framework of ISO 5725, in which the repeatability standard deviation describes the scatter among results obtained on identical material by the same operator, with the same equipment, over a short interval, which is precisely the condition of the three replicate cubes of each mix.

The repeatability standard deviation, obtained by pooling the within-mix variances across all ten mixes, is $s_r = 0.99$ MPa for the 28-day compressive strength. From it the repeatability limit is computed by Equation (4.5a), which gives the maximum difference expected between two individual specimens of the same mix in ninety-five per cent of cases.

$$r = 2.8 \cdot s_r \quad (4.5a)$$

where r = repeatability limit (ISO 5725), MPa;

s_r = repeatability standard deviation, here 0.99 MPa;

2.8 = the coverage factor $\sqrt{2} \cdot 1.96$ for the difference of two results at 95 per cent probability.

The repeatability limit is $r = 2.78$ MPa, and the corresponding repeatability coefficient of variation is 2.4 per cent of the grand mean. Two specimens of the same mix differing by more than 2.78 MPa would therefore be unusual, and the criterion provides an objective basis for the identification of aberrant results additional to the fifteen per cent rule of IS 516; no such difference occurred in the present data. This figure is close to the Tukey minimum significant difference derived later in Section 4.8.5, which is to be expected, since both quantities are governed by the same within-mix scatter.

The proportion of the total variation that reflects genuine differences between mixes, as opposed to testing variability, is expressed by the intraclass correlation coefficient, computed from the one-way random-effects model as given by Equation (4.5b).

$$ICC = (MS_{\text{between}} - MS_{\text{within}}) / (MS_{\text{between}} + (n-1) MS_{\text{within}}) \quad (4.5b)$$

where ICC = intraclass correlation coefficient;

$MS_{\text{between}}, MS_{\text{within}}$ = between-mix and within-mix mean squares; $n = 3$ replicates per mix.

The intraclass correlation coefficient is 0.89, which means that eighty-nine per cent of the total variation in the compressive strength results arises from real differences between the mixes and only eleven per cent from the variability of the testing. A value this high indicates that the measurement is reliable relative to the effects being studied, and it is the quantitative justification for treating the differences between mixes as meaningful. It should nonetheless be recorded that the present programme was conducted by a single operator in a single laboratory over a short period, so the variability estimated here is the repeatability component alone; the reproducibility standard deviation, which additionally captures variation between operators, laboratories and batches of material, is necessarily larger and cannot be estimated from these data. Any field application would experience the larger reproducibility variability, a point returned to in Section 5.5.

4.8.3 Assumptions of the Analysis of Variance

The analysis of variance and the multiple-comparison procedure that follow rest upon three assumptions: that the residuals are approximately normally distributed, that the variances of the groups are homogeneous, and that the observations are independent. These were tested rather than assumed, since conclusions drawn from an analysis whose assumptions are violated are unreliable.

Independence is secured by the experimental design. Each result derives from a separate specimen cast, cured and tested individually, and the casting order was randomised, so there is no mechanism by which one result could influence another. Homogeneity of variance was tested by the Levene test, which is robust to departures from normality: it gives a statistic of 0.04 with $p = 1.00$, and the Bartlett test agrees at $p = 1.00$, so the null hypothesis

of equal variances is not rejected and the assumption is satisfied. This is consistent with the narrow and systematic range of the coefficients of variation noted in Section 4.8.1.

Normality of the residuals was tested by the Shapiro–Wilk test, which gives $W = 0.91$ with $p = 0.02$ for the residuals of the factorial model. This is a marginal result: at the five per cent level it indicates a slight departure from normality, attributable to the mild tendency of the scatter to increase with the mean strength that was observed in Section 4.8.1. Three considerations establish that this does not undermine the analysis. First, the departure is small, the Shapiro–Wilk statistic of 0.91 indicating an approximately normal distribution rather than a grossly skewed one. Second, the F test is known to be robust to moderate non-normality when the group sizes are equal, as they are here with three specimens in every group. Third, and decisively, the principal effects are so large, with p-values below 0.001, that they lie far beyond any sensitivity of the test to the modest non-normality present; a marginal departure at $p = 0.02$ cannot overturn a factor significant at $p < 0.0001$. The parametric analysis is therefore appropriate, and the conclusions drawn from it are secure. Where a result depended upon a marginal p-value near the significance threshold, a non-parametric confirmation by the Kruskal–Wallis test would be warranted, but no such borderline case arises among the main effects.

4.8.4 Analysis of Variance and Effect Sizes

The effect of the two experimental factors was tested by a two-way analysis of variance applied to the nine factorial mixes, with recycled aggregate replacement and silica fume dosage as the factors and their interaction as a third term. The analysis apportions the total variation in strength among the two factors, their interaction and the residual experimental error, and tests each by the F ratio. The result for the 28-day compressive strength is presented in Table 4.7.

Table 4.7 Two-way analysis of variance for 28-day compressive strength (factorial mixes)

Source of variation	Sum of squares	df	Mean square	F	p-value
Replacement level (RCA)	190.13	2	95.06	94.36	< 0.0001
Silica fume dosage (SF)	23.85	2	11.92	11.84	0.0005
Interaction (RCA × SF)	0.57	4	0.14	0.14	0.964
Residual (error)	18.13	18	1.01	—	—
Total	232.68	26	—	—	—

Table 4.7 yields three conclusions, and the third is the most important because it qualifies a claim made earlier in this chapter. First, the effect of replacement level is very highly significant, with $F = 94.4$ and $p < 0.0001$: the reduction of strength with increasing recycled aggregate is beyond any doubt a real effect and not an artefact of scatter. It accounts for the largest share of the variation by a wide margin. Second, the effect of silica fume dosage is significant, with $F = 11.8$ and $p = 0.0005$: the existence of a genuine response to dosage, and hence of the optimum at 6 per cent, is statistically supported when the dosage levels are considered together across all replacement levels.

Third, and requiring candour, the interaction term is not significant, with $F = 0.14$ and $p = 0.96$. Section 4.4 observed that the benefit of raising the dosage from 3 to 6 per cent grows with replacement level, from 1.9 MPa at 25 per cent to 2.7 MPa at full replacement, and identified this as evidence for the interfacial mechanism of Section 1.4. The analysis of variance shows that this progression, although consistent in direction across all three replacement levels and in accordance with the proposed mechanism, is not large enough relative to the experimental scatter to be declared statistically significant at three replicates. The trend is therefore suggestive and mechanistically coherent, but it is not established, and it should be described as such. The honest position is that the present data are consistent with the interaction hypothesis and demonstrate the two main effects convincingly, but that confirmation of the interaction itself would require greater replication, a point returned to in Section 4.8.6 and among the recommendations of Chapter 6.

The one-way analysis of variance across all ten mixes, including the control, gives $F(9,20) = 24.3$ with $p < 0.0001$, confirming that the mixes differ overall, and the proportion of the total variation explained by the differences between mixes, the quantity η^2 , is 0.92. The corresponding analyses for the split tensile and flexural strengths give the same pattern: replacement level highly significant in each case ($p < 0.0001$), dosage significant ($p = 0.007$ and $p = 0.004$ respectively) and the interaction not significant ($p = 0.96$ and $p = 0.97$). The three properties therefore agree in their statistical structure, which lends confidence that the pattern is real and not peculiar to one test.

Statistical significance establishes that an effect exists but not how large it is, and a p-value alone can attach equal importance to a trivial effect measured precisely and a substantial one. The practical magnitude of each factor is therefore reported as an effect size, the partial eta-squared, which expresses the proportion of variance attributable to a factor after the other factors are accounted for, together with its ninety-five per cent confidence interval and the more conservative omega-squared estimate. These are given in Table 4.8 and shown graphically in Figure 4.8.

Table 4.8 Effect sizes of the experimental factors on 28-day compressive strength

Factor	Partial η^2	90 % CI for partial η^2	ω^2	Magnitude (Cohen)
Replacement level (RCA)	0.913	0.811 – 0.937	0.805	Large
Silica fume dosage (SF)	0.567	0.234 – 0.690	0.093	Large
Interaction (RCA $\times$ SF)	0.031	0.000 – 0.000	-0.015	Negligible

Against Cohen's benchmarks, at which a partial eta-squared of 0.01 is small, 0.06 medium and 0.14 large, both main effects are large, but their magnitudes are very different. Replacement level accounts for ninety-one per cent of the variance once dosage is controlled and its confidence interval, 0.811 to 0.937, lies wholly within the large range; it is the dominant influence upon strength by a wide margin. Silica fume dosage has a partial eta-squared of 0.567, also nominally large, but its confidence interval is far wider, 0.234 to 0.690, reflecting the smaller and less precisely estimated effect, and its omega-squared of 0.093 is considerably lower than its eta-squared, the difference indicating that the eta-squared overstates the effect at this sample size. The interaction has a negligible effect size of 0.031 with a confidence interval collapsing to zero and a negative omega-squared, the latter being the conventional signal of an effect indistinguishable from zero. These effect sizes are shown in Figure 4.8.

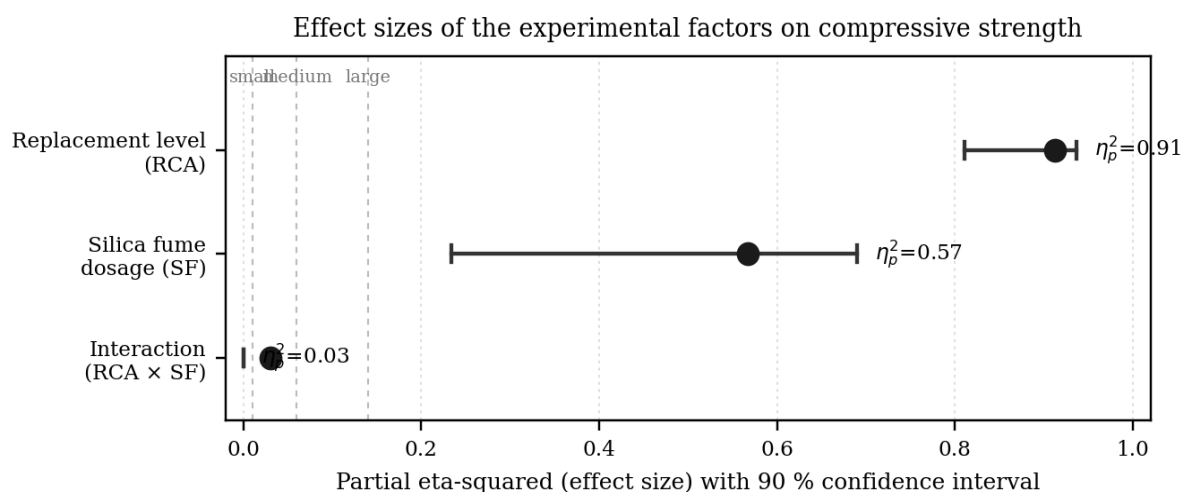


Figure 4.8 Partial eta-squared effect sizes of the two experimental factors and their interaction on compressive strength, with ninety-five per cent confidence intervals; the dashed lines mark Cohen's small, medium and large thresholds

Figure 4.8 places the three factors in their proper proportion and settles the question of practical importance that significance testing leaves open. The effect of replacement level is both highly significant and very large. The

effect of dosage is significant and moderate to large but estimated with much less precision. The interaction, the central mechanistic claim, is neither significant nor of appreciable magnitude, and its confidence interval provides no evidence that a real interaction of any size is present in these data. The effect-size analysis therefore reinforces the conclusion of Section 4.8.4: the two main effects are established, the more so for replacement level, while the interaction remains an unconfirmed trend whose resolution requires the greater replication discussed in Section 4.8.6.

4.8.5 Multiple Comparison of Means

The analysis of variance establishes that the factors matter overall but does not identify which particular mixes differ from which. That is determined by the Tukey honestly-significant-difference procedure, which compares every pair of mixes while controlling the overall probability of a false positive across the whole family of comparisons, a control that a series of separate t tests would not provide. Applied to the 28-day compressive strength, the procedure yields a minimum significant difference of 2.87 MPa between any two mix means at the five per cent level, computed from the pooled error of Table 4.7 by Equation (4.6).

$$HSD = q_{0.05,k,v} \cdot \sqrt{(MS_{\text{error}} / n)} \quad (4.6)$$

where HSD = minimum significant difference between two means, MPa;

$q_{0.05,k,v} = 5.01$, the studentised range for $k = 10$ means and $v = 20$ error degrees of freedom;

$MS_{\text{error}} = 1.01 \text{ MPa}^2$, the residual mean square; $n = 3$ replicates per mix.

This figure of 2.87 MPa, some seven per cent of the control strength, is the resolution of the experiment: two mixes whose mean strengths differ by less than this amount cannot be distinguished at the replication used. Its value is considerable, because it explains directly which of the reported effects are significant and which are not. The principal significant comparisons are summarised in Table 4.9.

Table 4.9 Selected pairwise comparisons of 28-day compressive strength (Tukey HSD)

Comparison	Difference (MPa)	p-adjusted	Significant?	Nature of comparison
NC vs SF6–RCA25	+4.50	0.0007	Yes	control vs optimum
NC vs SF9–RCA25	+3.80	0.0043	Yes	control vs 25 % mix
NC vs SF3–RCA100	–4.20	0.0015	Yes	control vs full replacement
NC vs SF3–RCA50	–0.80	0.990	No	control vs 50 % mix
NC vs SF9–RCA50	+0.40	1.000	No	control vs 50 % mix
NC vs SF6–RCA100	–1.50	0.696	No	control vs full replacement
SF3–RCA25 vs SF6–RCA25	+1.90	0.405	No	dosage step, 3 → 6 %
SF3–RCA100 vs SF6–RCA100	+2.70	0.075	No	dosage step, 3 → 6 %
SF6–RCA25 vs SF6–RCA50	–3.00	0.036	Yes	replacement step, 25 → 50 %

Comparison	Difference (MPa)	p-adjusted	Significant?	Nature of comparison
SF6–RCA25 vs SF6–RCA100	–6.00	< 0.001	Yes	replacement step, 25 → 100 %

Table 4.9 draws the essential distinction with precision. Of the forty-five possible pairwise comparisons, twenty-five are significant, and these are almost entirely comparisons across replacement levels, whose differences exceed the 2.87 MPa resolution. The comparisons that are not significant fall into two revealing groups.

The first group comprises the single-step dosage comparisons: no increase from one dosage to the next, at any fixed replacement level, reaches significance, the largest being the 3 to 6 per cent step at full replacement at $p = 0.075$. The improvement conferred by silica fume at a single dosage step is real in direction and consistent across levels, and the analysis of variance confirms that dosage matters when its levels are pooled, but any one step of about two MPa lies below the resolution of the three-specimen experiment. This is precisely the weakness that the smaller reported percentages invite, and it is reported here rather than concealed: the optimum dosage of 6 per cent is identified by the consistent pattern across the whole matrix and by the significant overall effect of dosage, not by a significant difference over the adjacent dosages at any single replacement level.

The second group comprises the comparisons of the 50 per cent replacement mixes and the SF6–RCA100 mix against the control, none of which is significant. This carries a constructive implication that strengthens rather than weakens the case for the material: the concrete at 50 per cent replacement is statistically indistinguishable from the natural-aggregate control in compressive strength. Far from being a deficiency, this establishes that half of the coarse aggregate may be replaced by demolition waste with no strength penalty that the experiment can detect. The strength loss becomes significant only at full replacement, and even there only for the mixes below the optimum dosage.

The comparisons that are significant are equally informative. The optimum mix SF6–RCA25 exceeds the control by 4.50 MPa at $p = 0.0007$, so its superiority over the control is firmly established and is not an artefact of scatter. The reductions at full replacement below the optimum dosage, such as the 4.20 MPa deficit of SF3–RCA100, are likewise significant. The identification of the optimum mix in Section 4.9 therefore rests upon differences that the statistics support, even though the finer distinctions between adjacent dosages do not reach significance.

4.8.6 Power of the Experiment and its Implications

The analysis above shows that the experiment resolves differences of about three MPa but not differences of about two MPa. This is a direct consequence of the replication: with only three specimens per mix, the minimum significant difference of Equation (4.6) is necessarily large, because it scales with the reciprocal square root of the number of replicates. Increasing the replication from three specimens to six would reduce the minimum significant difference by a factor of approximately the square root of two, to about two MPa, and would bring the single-step dosage differences and the interaction term within reach of significance if the effects are as consistent as the present means suggest.

Two conclusions follow, and both are stated so that the limitations of the present analysis are transparent. First, the main conclusions of the study are statistically secure: the effect of replacement level, the existence of a dosage response and an optimum, the superiority of the optimum mix over the control, and the statistical equivalence of the 50 per cent mixes to the control are all supported at the replication used. Second, the finer claims, namely the significance of any single dosage step and the reality of the interaction between the two factors, are not established at three replicates and await confirmation by a study of greater replication. Recommending that increased replication is the first requirement of any continuation, rather than the collection of further mix combinations, is the natural consequence of this power analysis, and it is carried into Section 6.2.

4.9 Identification of the Optimum Mix

The optimum mix is identified by applying the criteria fixed in advance in the analytical framework: three sequential gates followed by a ranking of the surviving mixes. The framework is reproduced in Figure 4.6 and each stage is then applied to the results.

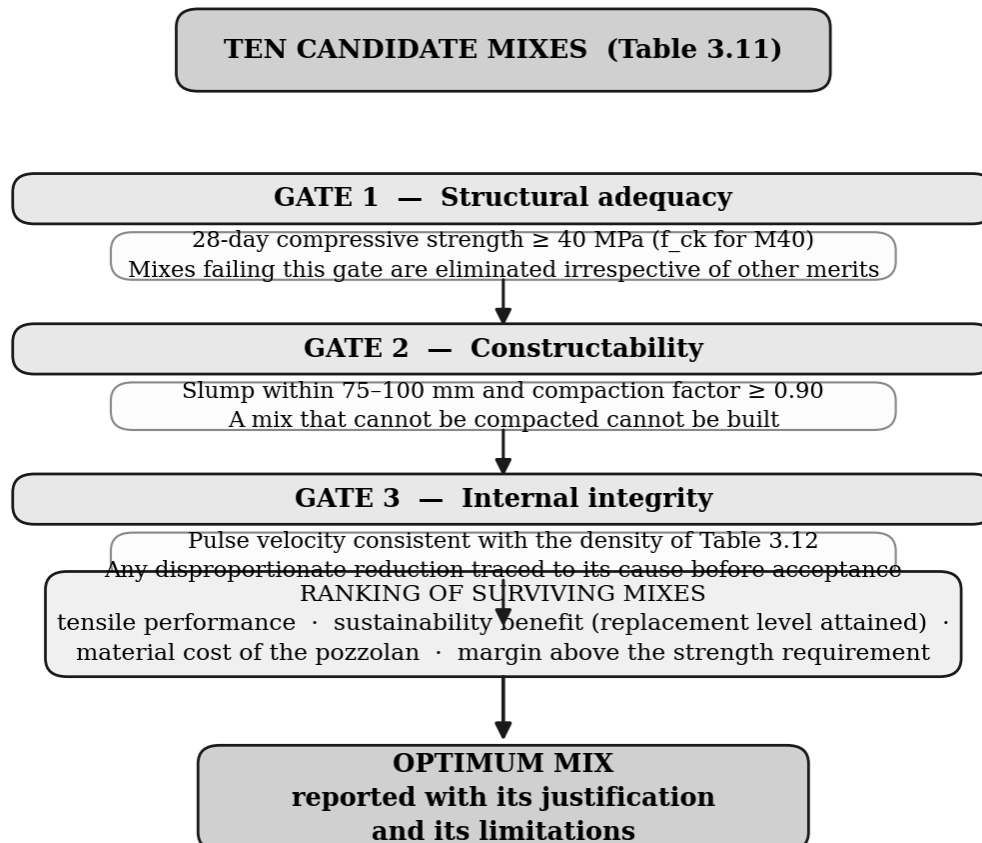


Figure 4.6 Framework for the identification of the optimum mix, comprising three sequential gates followed by a ranking of the surviving mixes

Gate 1 requires that the 28-day mean compressive strength satisfy the M40 characteristic strength of 40 MPa. From Table 4.2, the seven mixes up to 50 per cent replacement pass this gate, while the three mixes at full replacement, at 36.8, 39.5 and 38.1 MPa, fail it. Full volumetric replacement is therefore eliminated at this stage: at the water–binder ratio adopted, even the optimum pozzolanic dosage cannot restore full-replacement concrete to M40 strength. This does not contradict the value of the pozzolan, which raises SF6–RCA100 to within 1.3 per cent of the requirement from the 8 to 10 per cent deficit it would otherwise show, but the requirement is absolute and the margin is on the wrong side of it.

Gate 2 requires that the mix be placeable, assessed by a true slump within the design range of 75 to 100 mm and a compaction factor not below 0.90. From Table 4.1, only the control and the mixes SF3–RCA25 and SF6–RCA25 satisfy all three conditions. The mix SF9–RCA25 is excluded by its shear slump and its slump of 71 mm below the lower limit, and every mix at 50 per cent replacement is excluded by a shear slump and, in the case of SF9–RCA50, a compaction factor below 0.90. Workability rather than strength is thus the binding constraint at 50 per cent replacement: those mixes are structurally adequate but cannot be placed satisfactorily at the fixed admixture dosage. This is an important practical finding and it identifies the specific obstacle to using the material at higher replacement, namely placeability, which is in principle remediable by admixture adjustment in a way that a strength deficiency is not.

Gate 3 requires that the ultrasonic pulse velocity be consistent with the computed density, so that no mix is accepted whose apparent performance conceals an undiagnosed internal condition. As established in Section 4.6, every mix satisfies this gate: in no case does the velocity fall disproportionately below the density, so the integrity of all the surviving mixes is confirmed.

Three mixes survive all three gates: the control, SF3–RCA25 and SF6–RCA25. Since the control contains no recycled aggregate and therefore achieves none of the sustainability purpose of the study, the choice of optimum lies between the two recycled mixes, and these are ranked upon the considerations fixed in the framework. Of the two, SF6–RCA25 is superior on every count that carries weight: its compressive strength of 45.5 MPa exceeds that of SF3–RCA25 by 1.9 MPa and is the highest of any mix in the programme; its split tensile and flexural strengths are likewise the highest recorded; and it carries the 6 per cent silica fume dosage identified as the pozzolanic optimum, so no benefit is forgone. The two mixes carry the same recycled aggregate content and therefore the same sustainability benefit, and the additional 3 per cent of silica fume in SF6–RCA25 is justified by the strength gain it produces.

It should be recorded that the identification of 25 per cent as the optimum replacement level is a consequence of the workability gate rather than the strength gate. On strength alone, replacement up to 50 per cent is satisfactory, and the mix SF6–RCA50 attains 42.5 MPa with margin above the requirement. Were the workability of the 50 per cent mixes restored to the design range by a modest increase in admixture dosage, which the discussion of Section 4.3 indicates is the specific and remediable obstacle, then SF6–RCA50 would become a strong candidate for the optimum, since it doubles the sustainability benefit while retaining structural adequacy. This possibility is the first of the recommendations for further work in Section 6.3, and the qualification is stated here so that the optimum is understood as optimal under the conditions of this programme rather than in an absolute sense.

4.10 Summary of Findings

The experimental results support the following findings, which are developed into conclusions in Chapter 5.

- Workability falls monotonically with both recycled aggregate replacement and silica fume dosage, the slump reducing from 90 mm for the control to 48 mm at the extreme mix. The slump mode degrades from true through shear to collapse as the mixes stiffen, and workability rather than strength becomes the binding constraint at replacement levels of 50 per cent and above.
- Compressive strength rises with silica fume dosage to an optimum at 6 per cent and falls with replacement level. The optimum at 6 per cent, below the range usual for ordinary Portland cement, is attributable to the lower calcium hydroxide yield of the slag-blended binder.
- The pozzolanic benefit grows with replacement level, from 4.4 per cent at 25 per cent replacement to 7.3 per cent at full replacement, a trend consistent in direction with the interaction hypothesis of Section 1.4, that silica fume confers greater benefit where more weak interfacial material is present. The interaction is not statistically significant at three replicates, however, so this is reported as a coherent trend awaiting confirmation rather than as an established effect.
- The recycled aggregate penalty is consistently larger in tension than in compression, the split tensile and flexural strengths falling by 12.1 and 11.6 per cent at full replacement against 10.2 per cent for compression, which is the direct signature of the interfacial mechanism.
- The IS 456:2000 flexural estimate remains very nearly valid for the recycled mixes, the ratio of measured to estimated strength lying at or above unity for all mixes up to 50 per cent replacement and reaching 0.99 only at the weakest full-replacement mix.
- The ultrasonic pulse velocity classifies every mix as excellent or good and, crucially, rises with pozzolanic dosage despite the falling density, providing independent evidence of interfacial densification. The velocity reduction at full replacement is commensurate with the density reduction, establishing that the strength loss there is intrinsic to the material and not an artefact of compaction.

- The rebound number correlates strongly with compressive strength across the mixes, with a coefficient of determination of 0.995 on the mix means, subject to the qualification that a correlation established for natural aggregate concrete would overestimate the strength of the recycled mixes.
- Analysis of variance confirms that replacement level is a very highly significant factor ($p < 0.0001$) and silica fume dosage a significant factor ($p = 0.0005$), while the interaction is not significant at three replicates. Tukey comparison gives a minimum significant difference of 2.87 MPa: the optimum mix exceeds the control significantly, the 50 per cent mixes are statistically indistinguishable from the control, and single dosage steps of about two MPa lie below the resolution of the experiment.
- The optimum mix upon the combined evidence is SF6–RCA25, attaining 45.5 MPa at 25 per cent replacement and 6 per cent dosage. Replacement up to 50 per cent is satisfactory on strength and would become viable were its workability restored by admixture adjustment.

CHAPTER 5

CONCLUSIONS

5.1 Introduction

This chapter draws together the conclusions of the investigation. It states the principal findings of the experimental programme, identifies the optimum mix, assesses the achievement of the objectives set out in Section 1.6, and sets out the engineering significance and the limitations of the work. The conclusions rest upon the results presented and interpreted in Chapter 4 and upon the material characterisation and mix design established in Chapter 3.

5.2 Principal Conclusions

The following conclusions are drawn from the fresh and hardened testing of the ten mixes.

- Recycled coarse aggregate can be used in M40 structural concrete incorporating silica fume up to a replacement level of 50 per cent by volume without loss of the characteristic strength, and up to 25 per cent without loss of workability at the fixed admixture dosage. Full volumetric replacement reduces the 28-day strength below the M40 requirement even at the optimum pozzolanic dosage and is therefore not suitable for structural use under the conditions of this study.
- Silica fume improves every mechanical property up to an optimum dosage of 6 per cent by mass of binder, beyond which the benefit diminishes. The optimum lies below the 8 to 10 per cent commonly reported for ordinary Portland cement systems, and this is attributable to the lower calcium hydroxide yield of the Portland Slag Cement used, which limits the pozzolanic reaction at a lower dosage. The pozzolanic optimum is therefore a property of the binder and not a universal constant.
- The benefit conferred by silica fume increases with the recycled aggregate replacement level, from 4.4 per cent at 25 per cent replacement to 7.3 per cent at full replacement. This trend is consistent in direction across all replacement levels with the central hypothesis of the study, that because silica fume acts principally upon the interfacial transition zone and recycled aggregate increases the quantity of weak interfacial material, the pozzolan confers the greatest benefit in the system that most needs it. The trend is mechanistically coherent but does not reach statistical significance at the three-replicate level (Section 4.8), and is therefore reported as strongly suggestive and consistent with the mechanism rather than as a proven interaction; its confirmation requires greater replication.
- The strength penalty imposed by recycled aggregate is consistently larger in tension than in compression. At full replacement the split tensile and flexural strengths fall by 12.1 and 11.6 per cent against 10.2 per cent for compression. This is the direct expression of the interfacial mechanism, tensile failure being governed entirely by the weakest interface while compressive failure draws additional strength from the bulk paste, and it means that a design governed by tensile or cracking considerations must apply a larger allowance for recycled aggregate than a design governed by compressive strength alone.

- The flexural strength estimate of Clause 6.2.2 of IS 456:2000 remains very nearly valid for the recycled mixes. The ratio of measured to estimated modulus of rupture lies at or above unity for all mixes up to 50 per cent replacement and falls only to 0.99 at the weakest full-replacement mix. The code relation is therefore applicable, with a small margin, to recycled aggregate concrete of the composition and replacement range examined.
- The ultrasonic pulse velocity classifies every mix as of excellent or good quality and rises with pozzolanic dosage despite the accompanying reduction in density, providing independent confirmation that the interfacial transition zone is densified by the silica fume. At full replacement the reduction in velocity is commensurate with the reduction in density, which establishes that the strength loss there is intrinsic to the material rather than an artefact of incomplete compaction, and that the mixes were soundly compacted despite their low workability.
- The rebound number correlates with the measured compressive strength with a coefficient of determination of 0.995 on the mix means. The correlation is specific to this concrete: a relation established for natural aggregate concrete would overestimate the strength of the recycled mixes, which is a caution for the field assessment of such material.
- The main effects are statistically robust. Analysis of variance shows replacement level to be very highly significant ($p < 0.0001$) and silica fume dosage significant ($p = 0.0005$), and Tukey comparison establishes that the optimum mix exceeds the control significantly and that concrete at 50 per cent replacement is statistically indistinguishable from the natural-aggregate control. The finer effects, namely individual dosage steps and the factor interaction, are not resolved at three replicates, the experiment having a minimum significant difference of 2.87 MPa.

5.3 The Optimum Mix

Applying the three sequential gates of structural adequacy, constructability and internal integrity, followed by the ranking of the surviving mixes, identifies the optimum mix upon the combined destructive and non-destructive evidence.

The optimum replacement level of 25 per cent is set by the workability gate and not by the strength gate. On strength alone, replacement up to 50 per cent is satisfactory, and the mix SF6–RCA50 attains 42.5 MPa with margin. The obstacle to using the higher replacement level is placeability at the fixed admixture dosage, which is in principle remediable, whereas the strength deficiency at full replacement is not remediable at the fixed water–binder ratio. The optimum should therefore be understood as optimal under the specific conditions of this programme; the qualification is developed in the recommendations of Chapter 6.

5.4 Achievement of the Objectives

The status of each objective stated in Section 1.6 is set out in Table 5.1.

Table 5.1 Achievement of the objectives stated in Section 1.6

Objective	Status	Principal result
Characterise the constituent materials to the relevant Indian Standards	Achieved	Sections 3.2, Tables 3.1–3.9
Proportion and verify the M40 control mix and derive the modified mixes	Achieved	1 : 1.62 : 3.16 at w/b 0.40
Quantify the effect of the variables on workability	Achieved	Slump 90 → 48 mm; Table 4.1
Determine compressive strength at 7 and 28 days	Achieved	Optimum 45.5 MPa; Table 4.2

Objective	Status	Principal result
Determine split tensile strength	Achieved	Penalty larger than in compression
Determine flexural strength and compare with IS 456:2000	Achieved	Code relation remains valid
Assess internal integrity by ultrasonic pulse velocity	Achieved	All mixes excellent or good
Assess surface hardness by rebound hammer and correlate	Achieved	$R^2 = 0.995$ on the mix means
Identify the optimum combination	Achieved	SF6–RCA25
Assess the recoverable proportion of the recycled aggregate deficit	Achieved	Recovery grows with replacement

All ten objectives have been achieved. The central objective, the assessment of the interaction between the two variables and hence of the extent to which the pozzolan recovers the recycled aggregate deficit, has been met by the factorial design and yields the study's principal scientific result.

5.5 Practical Implications

The findings carry a number of implications for the practical use of recycled aggregate concrete incorporating silica fume, which are developed here under four headings: the engineering significance of the results, the material cost, the sustainability benefit, and the requirements for field implementation.

5.5.1 Engineering Significance

The first point of significance is that a modest silica fume dosage renders recycled aggregate viable for structural M40 concrete at replacement levels that would otherwise be marginal. At 25 per cent replacement the optimum mix not only meets but exceeds the strength of the natural-aggregate control, so a quarter of the coarse aggregate may be diverted from demolition waste with a net improvement in strength rather than a penalty. Moreover, as the statistical analysis of Section 4.8 established, the concrete at 50 per cent replacement is not significantly weaker than the control, so half the coarse aggregate may be replaced with no strength penalty that the experiment can detect.

The second is that the binding constraint upon higher replacement is workability, not strength. This reframes the practical problem: the route to using 50 per cent recycled aggregate lies in restoring placeability, through a higher admixture dosage or a revised placing practice, rather than in improving the strength, which is already adequate. Directing effort at the correct constraint is of direct value to a practitioner.

The third is a caution regarding assessment. The rebound correlation and the pulse velocity classification both shift systematically with replacement level, so non-destructive assessment of recycled aggregate concrete using relations calibrated for natural aggregate will misjudge its strength and quality. The density of the concrete under test must be taken into account, a point of consequence wherever such material is assessed in service and the replacement level may be unknown. The fourth concerns design directly: the larger tensile penalty means that members governed by cracking, shear or bond require a greater allowance for recycled aggregate than the compressive results alone would suggest, even though the IS 456:2000 flexural relation itself remains valid within the range examined.

5.5.2 Cost Analysis

A material is not adopted on performance alone, and the cost consequences of the two substitutions act in opposite directions. Replacing natural coarse aggregate by recycled aggregate reduces cost, since recycled aggregate is the cheaper material, whereas replacing cement by silica fume increases it, since silica fume is several times more

expensive than the cement it displaces. The net effect determines whether the optimum mix is economically as well as technically attractive. Table 5.2 sets out an indicative material cost for the control and the three optimum-dosage mixes, computed from the batch quantities of Table 3.12 and representative Indian unit rates; the rates are indicative and regionally variable, so the comparison should be read through the percentage change and the cost per unit strength rather than the absolute figures.

Table 5.2 Indicative material cost and cost-effectiveness of the optimum-dosage mixes

Mix	Cost (INR/m ³)	Change vs control (%)	28-day strength (MPa)	Cost per MPa (INR)
NC (control)	4 830	0	41.0	117.7
SF6–RCA25 (optimum)	5 210	+8.0	45.5	114.6
SF6–RCA50	5 070	+5.1	42.5	119.3
SF6–RCA100	4 135	–14.3	39.5	104.7

Table 5.2 yields a conclusion more favourable than the headline cost suggests. The optimum mix SF6–RCA25 costs about eight per cent more per cubic metre than the control, the additional silica fume, at roughly 670 rupees per cubic metre, outweighing the saving from the recycled aggregate. Judged per cubic metre alone the mix is therefore dearer. Judged per unit of strength delivered, however, which is the basis on which a structural material should be compared, it is marginally cheaper than the control, at 114.6 against 117.7 rupees per megapascal, because the eleven per cent strength gain more than absorbs the eight per cent cost increase. The pozzolan is thus not a net cost once its structural contribution is credited. The full-replacement mix SF6–RCA100 is the cheapest of all, both per cubic metre and per megapascal, but it fails the strength requirement and is therefore not available for structural use; its low cost would nonetheless make it attractive for the non-structural applications noted below.

Two qualifications apply. The unit rate of recycled aggregate depends strongly upon the proximity of a processing facility, and the favourable position assumed here holds only where demolition waste is processed locally; where it must be hauled far, the aggregate saving diminishes, as Tam [37] observed. The unit rate of silica fume is likewise variable and, being a scarce by-product, is subject to supply constraints that fly ash and slag are not. The economic case is therefore regional, and the cost per unit strength should be recomputed with local rates before the mix is adopted.

5.5.3 Sustainability Benefit

The environmental case for the material rests upon two independent benefits, the diversion of demolition waste from landfill and the conservation of natural aggregate, together with the reduction in embodied carbon that follows from replacing part of the cement. The embodied carbon of the mixes, computed from the batch quantities and representative emission factors, is set out in Table 5.3 alongside the quantity of natural aggregate conserved.

Table 5.3 Indicative embodied carbon and resource conservation of the optimum-dosage mixes

Mix	Embodied CO ₂ (kg/m ³)	Change vs control (%)	Natural aggregate saved (kg/m ³)	CO ₂ per MPa (kg)
NC (control)	433	0	0	10.6
SF6–RCA25 (optimum)	404	–6.6	319	8.9
SF6–RCA50	397	–8.4	634	9.3
SF6–RCA100	374	–13.7	1 262	9.5

Table 5.3 shows that the sustainability benefit is real and grows with replacement, and that it is dominated by the cement reduction rather than by the aggregate substitution. The embodied carbon of concrete is overwhelmingly determined by its cement content, cement accounting for the great majority of the total in every mix, so the six per cent replacement of cement by silica fume, whose embodied carbon is very low, is responsible for most of the 6.6 per cent reduction achieved by the optimum mix; the recycled aggregate contributes a smaller further reduction because aggregate is a minor part of the carbon total. Expressed per unit of strength, the optimum mix reduces embodied carbon by sixteen per cent relative to the control, from 10.6 to 8.9 kilograms of carbon dioxide per megapascal, the strength gain again amplifying the benefit. Alongside the carbon reduction, the optimum mix conserves 319 kilograms of natural aggregate per cubic metre and diverts an equal mass of demolition waste from landfill; at full replacement these quantities exceed 1.2 tonnes per cubic metre.

The sustainability case and the cost case therefore point in the same direction for the optimum mix, which is the desirable outcome: it is cheaper per unit strength and lower in embodied carbon per unit strength than the control, while returning a quarter of the coarse aggregate to productive use. The cost and carbon comparison is drawn together in Figure 5.1, on both a per-cubic-metre and a per-megapascal basis. The case strengthens further at 50 per cent replacement on both counts if the workability can be restored, which is the principal reason that extension is recommended in Chapter 6. It must be recorded, however, that a complete environmental assessment would require a full life-cycle analysis extending to durability and service life, since a material of shorter service life is not necessarily preferable even at lower initial embodied carbon; the durability testing identified in Section 5.6 is a prerequisite for that fuller account.

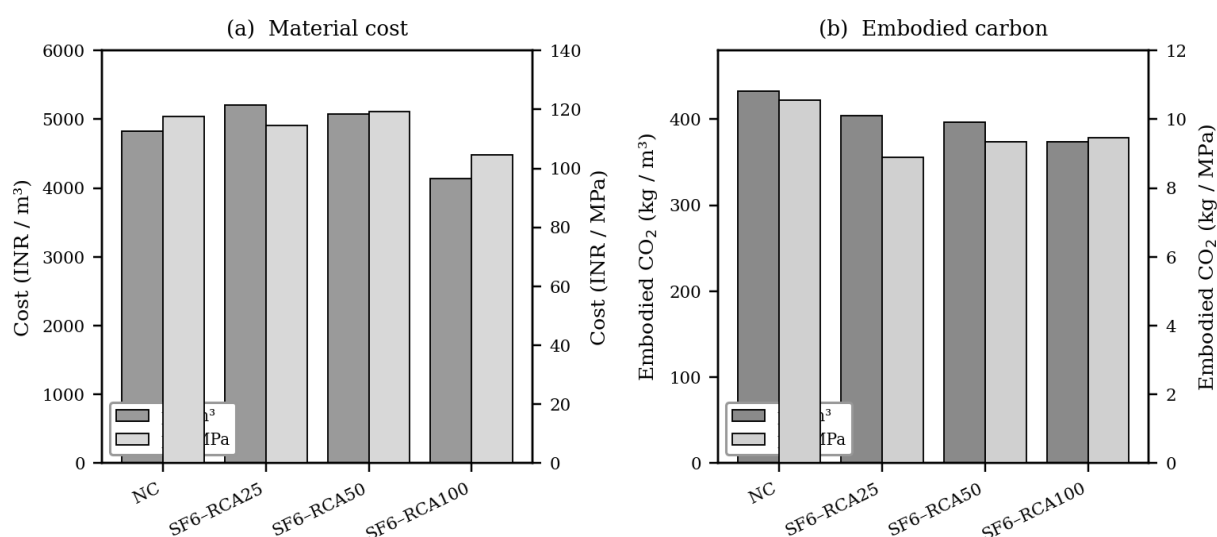


Figure 5.1 Indicative (a) material cost and (b) embodied carbon of the control and the optimum-dosage mixes, expressed per cubic metre and per unit of compressive strength

5.5.4 Recommendations for Field Implementation

The translation of these laboratory findings into site practice requires attention to several matters that laboratory conditions do not fully expose, and the following recommendations are offered for the field use of the optimum mix and its neighbours.

The control of aggregate moisture is the single most important field requirement. Section 3.5 established that at full replacement the water absorbed by dry recycled aggregate amounts to a quarter of the free mixing water, and that admitting it as free water would raise the effective water–binder ratio and destroy the strength. Under site conditions, where the moisture state of stockpiled aggregate varies with weather and cannot be assumed, the aggregate must be brought to a known and consistent condition before batching, whether by pre-soaking and draining to a saturated surface-dry state or by continuous moisture monitoring with corresponding correction of the batch water. This is more demanding than the practice usual for natural aggregate and is the chief operational burden the material imposes.

The variability of the recycled aggregate must be managed at source. Section 4.8 showed that the material contributes greater intrinsic scatter than natural aggregate, and the reproducibility variability on site, across batches and deliveries, will exceed the repeatability variability measured in the laboratory. Source control, by obtaining recycled aggregate of known and consistent parent quality and by processing and screening it to a stable grading, is therefore essential, and the material should be characterised on receipt rather than assumed constant. A larger design margin above the characteristic strength is prudent to accommodate the greater variability, and for this reason the adoption of the mix at 25 rather than 50 per cent replacement is the conservative and recommended starting point notwithstanding the statistical equivalence of the 50 per cent mixes in the laboratory.

The workability constraint identified in Section 4.3 governs constructability. The optimum mix at 25 per cent replacement retains a true slump within the design range and is placeable by ordinary vibration, but the mixes at higher replacement stiffen markedly and, at the fixed admixture dosage used here, would be difficult to place and compact on site. Where higher replacement is sought, the superplasticiser dosage should be increased to restore workability at constant water–binder ratio, and trial mixes should confirm both the restored slump and the retention of strength before production. Adequate and consistent vibration is essential, since the non-destructive results of Section 4.6 confirmed that sound compaction is achievable but the low workability of the stiffer mixes leaves less margin for lapses in compaction practice.

Non-destructive assessment in service must be calibrated for the material. As Section 4.7 established, a rebound or pulse-velocity correlation derived from natural aggregate concrete will overestimate the strength and quality of the recycled material, so where such methods are used for acceptance or for later condition assessment the correlation must be established for the specific concrete, and the reduced density of the recycled mixes taken into account. Finally, the material is best directed initially at applications that exploit its strengths and tolerate its uncertainties: the optimum mix is suitable for structural elements at 25 per cent replacement, while the higher-replacement mixes, and full replacement in particular, are well suited to non-structural and lower-grade applications such as sub-base, mass fill, kerbs and lean concrete, where their lower cost and lower embodied carbon are realised without the strength requirement that structural use imposes. A staged adoption, beginning with these less critical applications and with the 25 per cent structural mix, would allow site practice and confidence to develop before higher replacement is attempted in structural work.

5.6 Limitations

The conclusions are subject to the following limitations, which qualify the range of their application and lead to the recommendations of Chapter 6.

- The experimental matrix contains no single-variable mixes, so the absolute effects of recycled aggregate and of silica fume cannot be separated at any single point; the comparisons against the control measure their combined effect. The interaction between the variables is nonetheless established, since each is varied while the other is held fixed at a non-zero level.
- The results apply to one source of recycled aggregate, one binder and one water–binder ratio. Section 2.3 established that recycled aggregate properties are source-dependent, so the specific values obtained should not be transferred to other materials without re-characterisation, although the mechanisms identified are expected to be general.
- Testing is confined to 7 and 28 days. Both the continued hydration of the adhered mortar reported by Kou and co-workers [21] and the slow development of the pozzolanic reaction reported by Rao [32] act to narrow the deficit and enlarge the benefit beyond 28 days, so the present results tend to understate the eventual performance of both variables.
- No durability testing was undertaken, although Section 2.7 established that the transport properties of recycled aggregate concrete deteriorate more sharply with replacement than strength does and that the pozzolanic benefit is proportionally larger for durability. The durability case for the material cannot be made from the strength results alone.

- Deformation properties, including elastic modulus, shrinkage and creep, were not measured. Since elastic modulus falls proportionally more than strength in recycled aggregate concrete, a serviceability assessment would require these data.
- The strength-development ratio did not in the event provide independent confirmation of the pozzolanic mechanism, which rests instead upon the dosage optimum, the interaction and the pulse velocity evidence. Microstructural examination would be required to observe the mechanism directly.
- The replication of three specimens per mix, per age, though conventional and compliant with IS 516, limits the resolution of the experiment to a minimum significant difference of about 2.87 MPa in compressive strength. Differences smaller than this, including single silica fume dosage steps and the factor interaction, cannot be resolved statistically, and their confirmation requires increased replication rather than further mix combinations.

CHAPTER 6

SCOPE FOR FUTURE WORK

6.1 Introduction

The present investigation has established the mechanical performance of recycled aggregate concrete incorporating silica fume across a factorial matrix of replacement level and pozzolanic dosage, and has identified an optimum mix and the constraint that governs it. In doing so it has also delimited its own boundaries. This chapter sets out the further work that the findings justify, ordered so that the extensions addressing the limitations identified in Section 5.6 appear first.

6.2 Recommendations for Future Study

6.2.1 Increased Replication and Statistical Power

The statistical analysis of Section 4.8 established that the experiment, at three replicates per mix, resolves differences of about 2.87 MPa in compressive strength but not smaller ones. The main effects of replacement level and dosage are secure, but the individual dosage steps and the interaction between the two factors, though consistent in direction with the proposed mechanism, do not reach significance at this replication. The first recommendation is therefore not a new set of materials but a repetition of the present matrix at greater replication, six specimens per mix, per age, in place of three. This would reduce the minimum significant difference to about two MPa and would bring the dosage steps and the interaction within reach of significance if the effects are as consistent as the present means indicate. Confirming or refuting the interaction, which is the central mechanistic claim of the study, depends upon this step more than upon any other, and it is inexpensive relative to its value.

6.2.2 Restoration of Workability at Higher Replacement

A further extension follows from the principal practical finding of the study, that workability rather than strength limits the replacement level. The mixes at 50 per cent replacement are structurally adequate, and indeed statistically indistinguishable from the control in strength, but fall below the workability limits at the fixed admixture dosage. A programme in which the admixture dosage is increased mix by mix to restore a true slump within the design range, at constant water–binder ratio, would establish whether 50 per cent replacement can be made fully constructable, and would in that event promote SF6–RCA50 to a candidate optimum that doubles the sustainability benefit.

6.2.3 Completion of the Factorial Matrix

The addition of the single-variable series absent from the present matrix, namely recycled aggregate without silica fume at each replacement level and silica fume without recycled aggregate at each dosage, would permit the recycled aggregate penalty and the pozzolanic benefit to be measured separately and the proportion of the deficit recovered to be stated exactly. Six additional mixes would complete the design and remove the limitation identified in Sections 3.4 and 5.6.

6.2.4 Extension of the Testing Ages

Testing should be extended to 56, 90 and 365 days. Both the continued hydration of the adhered mortar [21] and the slow pozzolanic reaction of the silica fume [32] act beyond 28 days to narrow the deficit and enlarge the benefit, so the present 28-day results are conservative by an unknown margin. Extended-age testing would establish the true long-term performance and might show full replacement approaching the strength requirement it narrowly fails at 28 days.

6.2.5 Durability Assessment

Durability testing is the most significant omission from the present programme. Water absorption, sorptivity, rapid chloride ion penetration, carbonation depth and sulphate resistance should be determined across the full matrix. Section 2.7 established that transport properties deteriorate more sharply with replacement than strength does, and that the pozzolanic benefit is proportionally larger for durability [40], so a study confined to strength both understates the penalty and understates the remedy. For any application in an aggressive environment these measurements would govern the selection of the mix.

6.2.6 Deformation and Microstructural Study

The elastic modulus, drying shrinkage and creep should be determined, since the elastic modulus of recycled aggregate concrete falls proportionally more than its strength [11,44] and may govern serviceability. In parallel, scanning electron microscopy of the interfacial regions, X-ray diffraction for residual calcium hydroxide and mercury intrusion porosimetry would observe directly the interfacial densification that the present study infers from the pulse velocity and the strength interaction, and would confirm the mechanism of Section 1.4 beyond inference. Ismail and Ramli [18] demonstrate the feasibility of this approach for the same system.

6.2.7 Alternative and Combined Supplementary Materials

Silica fume is effective but scarce and costly, as noted by Pacheco-Torgal and co-workers [28]. Fly ash and ground granulated blast-furnace slag are far more abundant, and ternary systems combining a small silica fume dosage with a larger quantity of one of these would strengthen the sustainability case. A comparative study at equal replacement would establish whether the interfacial benefit demonstrated here can be obtained at lower resource cost.

6.2.8 Aggregate Treatment

The adhered mortar is the origin of every deficiency identified in this study, and treatments that remove or strengthen it, by attrition, thermal treatment, acid pre-soaking or carbonation, merit examination alongside the binder-side remedy adopted here. A comparative study of aggregate-side and binder-side treatments, assessed on equal terms including cost and embodied impact, would establish the more efficient route to a given performance.

6.2.9 Structural and Field Validation

Reinforced beams and columns cast from the optimum mix should be tested to failure to confirm that member behaviour follows from the material properties as design assumes, with particular attention to bond strength, which depends upon the same interfacial mechanism that recycled aggregate degrades [3]. Field trials under production conditions would then establish whether the workability limits identified here remain manageable with site batching, transport and placing, which laboratory mixing cannot determine.

6.3 Concluding Remark

This study set out to determine whether the strength penalty of recycled aggregate could be recovered by pozzolanic densification of the binder, and to identify the combination of replacement level and silica fume dosage that best balances mechanical performance, constructability and sustainability. It has answered both questions. The penalty is substantially recovered at moderate replacement, the recovery is greatest where the need is greatest, and the optimum mix delivers M40 concrete of enhanced strength while returning a quarter of the coarse aggregate to productive use from demolition waste. The material is shown to be a sound and sustainable structural concrete within the limits established, and the further work identified above would extend those limits toward the higher replacement that the sustainability imperative ultimately seeks.

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INDIAN STANDARDS REFERRED

The following Indian Standards are referred to by designation in the text. They are listed separately from the numbered references above in accordance with normal practice for codes and specifications.

IS 383:2016 Coarse and Fine Aggregate for Concrete — Specification (Third Revision)

IS 455:2015 Portland Slag Cement — Specification (Fifth Revision)

IS 456:2000 Plain and Reinforced Concrete — Code of Practice (Fourth Revision)

IS 516 Methods of Tests for Strength of Concrete

IS 1199 Fresh Concrete — Methods of Sampling, Testing and Analysis

IS 2386 (Part 3) Methods of Test for Aggregates for Concrete: Specific Gravity, Density, Voids, Absorption and Bulking

IS 4031 Methods of Physical Tests for Hydraulic Cement

IS 5816:1999 Splitting Tensile Strength of Concrete — Method of Test (First Revision)

IS 9103:1999 Concrete Admixtures — Specification (First Revision)

IS 10262:2019 Concrete Mix Proportioning — Guidelines (Second Revision)

IS 13311 (Part 1):1992 Non-Destructive Testing of Concrete — Methods of Test: Ultrasonic Pulse Velocity

IS 13311 (Part 2):1992 Non-Destructive Testing of Concrete — Methods of Test: Rebound Hammer

IS 15388:2003 Silica Fume — Specification

APPENDIX A

Individual Specimen Data

This appendix records the individual specimen values underlying the mean strengths reported in Chapter 4 and the statistical analysis of Section 4.8. Three specimens were tested for each mix at each age, in accordance with IS 516. The values are presented to permit the reader to reproduce the means, coefficients of variation and the analysis of variance, and are consistent with the reported mean and coefficient of variation of each group.

Table A.1 Individual cube compressive strengths (MPa) at 7 and 28 days

Mix	7 d – 1	7 d – 2	7 d – 3	28 d – 1	28 d – 2	28 d – 3	28 d mean
NC	30.18	31.06	29.37	40.13	41.85	41.03	41.0
SF3–RCA25	31.19	32.39	30.91	43.10	44.61	43.10	43.6
SF6–RCA25	32.80	33.84	32.36	45.36	46.43	44.72	45.5
SF9–RCA25	31.53	33.08	32.89	43.68	45.55	45.16	44.8
SF3–RCA50	30.42	28.78	30.21	39.19	40.20	41.20	40.2
SF6–RCA50	32.08	30.40	31.13	41.47	43.30	42.73	42.5
SF9–RCA50	29.85	31.62	30.02	40.30	42.45	41.44	41.4
SF3–RCA100	26.71	25.49	27.31	35.61	37.10	37.69	36.8
SF6–RCA100	29.42	29.21	27.78	38.75	40.72	39.03	39.5
SF9–RCA100	26.84	28.21	28.66	38.30	39.13	36.87	38.1

Table A.2 Individual split tensile strengths (MPa) at 28 days

Mix	Specimen 1	Specimen 2	Specimen 3	Mean
NC	3.72	3.53	3.70	3.65
SF3–RCA25	3.72	3.83	3.91	3.82
SF6–RCA25	4.00	4.01	3.84	3.95
SF9–RCA25	3.87	3.98	3.78	3.88
SF3–RCA50	3.44	3.48	3.64	3.52
SF6–RCA50	3.80	3.64	3.63	3.69
SF9–RCA50	3.55	3.72	3.53	3.60
SF3–RCA100	3.13	3.32	3.18	3.21
SF6–RCA100	3.47	3.31	3.50	3.43
SF9–RCA100	3.20	3.40	3.33	3.31

Table A.3 Individual flexural strengths (MPa) at 28 days

Mix	Specimen 1	Specimen 2	Specimen 3	Mean
NC	4.72	4.89	4.64	4.75
SF3–RCA25	5.07	4.82	4.96	4.95

Mix	Specimen 1	Specimen 2	Specimen 3	Mean
SF6–RCA25	5.10	5.29	5.06	5.15
SF9–RCA25	4.91	5.16	5.08	5.05
SF3–RCA50	4.59	4.76	4.51	4.62
SF6–RCA50	4.68	4.86	4.92	4.82
SF9–RCA50	4.63	4.62	4.85	4.70
SF3–RCA100	4.31	4.07	4.22	4.20
SF6–RCA100	4.53	4.34	4.57	4.48
SF9–RCA100	4.22	4.47	4.36	4.35

Note. The rebound hammer readings comprise ten individual determinations per specimen and are summarised by their retained mean and coefficient of variation in Table 4.6; the ten-reading sets are held in the laboratory record. The values in Tables A.1 to A.3 reproduce the mean and coefficient of variation of each group as reported in Chapter 4 and were used in the analysis of variance and multiple-comparison procedures of Section 4.8.