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Article

Flexural Performance–Driven Optimization of Steel Slag as a Partial Cement Substitute in Paving-Grade Concrete for Sustainable Rigid Pavements

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Abstract: Rigid pavement thickness design is governed by flexural strength, yet studies of steel slag as a cement replacement have overwhelmingly reported compressive strength alone. Paving-grade concrete in which ordinary Portland cement was replaced by ground steel slag at 0, 20, 30, 40, and 50% by mass was tested for slump and for cube compressive and third-point flexural strength at 7 and 28 days. The response was not a smooth optimum but a plateau terminated by an abrupt threshold. Up to 30% replacement, 28-day compressive (54.11–54.35 MPa) and flexural (6.52–6.61 MPa) strengths were indistinguishable from the control. Between 30 and 40%, compressive strength fell by 23.6% and flexural strength by 22.5%, taking both below the 48.25 and 5.16 MPa target mean strengths required for acceptance. The flexural-to-compressive ratio, constant at 0.891 MPa up to 30%, fell to 0.760 at 50%, indicating a disproportionate loss of tensile capacity. The 30% mix satisfied all acceptance criteria, cut cement demand by 89 kg/m³ (22.8%) and materials cost by 1.7%, but required double the admixture dosage.
Keywords: Steel slag; Pavement quality concrete; Rigid pavement; Supplementary cementitious material; Flexural strength; Cement replacement; Sustainable pavement materials

1. Introduction

Rigid pavements constructed in pavement quality concrete (PQC) are increasingly preferred over flexible pavements on heavily trafficked and climatically severe corridors because of their higher load-distributing capacity, longer fatigue life, and substantially lower routine maintenance demand. These advantages are purchased at the cost of a binder-intensive material. A paving mix typically carries a cement content of the order of 390 kg/m³ and is placed at slab thicknesses of 250–300 mm, so that a single kilometer of a 10 m wide, 0.28 m thick carriageway consumes of the order of 1,100 t of cement. Cement is simultaneously the most expensive and the most carbon-intensive constituent of that mix. Any fractional reduction in cement content therefore propagates into large absolute savings across a road network, and the technical question is not whether cement should be reduced but how far it can be reduced before the properties that govern pavement performance are compromised.

Steel slag is a natural candidate for that reduction. Between 150 and 200 kg of slag is generated for every ton of steel produced, and it has historically been landfilled at a direct disposal cost to the producer. It is a calcium-silicate-bearing material, dominated by CaO and SiO_2 with significant iron and manganese oxides, and possesses both latent hydraulic and pozzolanic character, which allows it to participate in the binder system rather than act purely as a filler. Tightening environmental regulation and the rising cost and scarcity of landfill capacity have converted slag disposal from a routine cost into a strategic liability for steel producers, while the same period has seen cement prices rise sharply. The economic and environmental incentives for its use in pavement construction are consequently aligned.

The published record on steel slag as a cement replacement is, however, unusually inconsistent in the one number that practitioners need: the maximum replacement level that can be adopted without penalty. Reported optima span a threefold range. Rajaram et al., Sawant et al., and Mohan and Srinivas each identify 20% as the optimum; Dondi adopted 30% for road applications; Shariq Prasad reports 40% as optimum for long-term strength; and Mat Dom et al. report that replacements between 40 and 60% exceeded their control at 28 days and beyond. Nair and Johny report satisfactory performance at 50%, but in mixes where slag also replaced half of the coarse aggregate, which is a different material system altogether. This spread cannot be explained by concrete grade alone. It reflects differences in slag source and fineness, in curing regime, in the strength of the control mixture against which improvement is measured, and most consequentially in the property chosen as the criterion of success.

That last point defines the gap addressed here. Slab thickness in rigid pavement design is governed by the flexural strength of the concrete and by its fatigue behavior under repeated flexural stress, not by its compressive strength. Yet the large majority of replacement studies evaluate compressive strength only, and where flexural strength is reported it is usually reported as a secondary observation rather than as the governing acceptance criterion. A replacement level validated on cube strength cannot be transferred into pavement practice without independent flexural verification, because there is no a priori guarantee that the two properties degrade at the same rate. A second and related omission concerns the acceptance criterion itself. Paving mixes are accepted against a target mean strength the characteristic strength augmented by a statistical margin rather than against the design value used in thickness computation. A mix may exceed the design flexural strength comfortably and still fail acceptance. Studies that report only whether a mix "met the grade" do not distinguish these two thresholds. Finally, the workability penalty that accompanies replacement, and the admixture demand required to offset it, is rarely costed, even though it can consume a substantial fraction of the cement saving.

This paper reports a laboratory program on paving-grade concrete in which ordinary Portland cement was replaced by ground steel slag at 0, 20, 30, 40, and 50% by mass. Compressive and flexural strength were measured at 7 and 28 days and evaluated against both the target mean and the design criteria applicable to PQC; workability was measured, together with the admixture dosage required to sustain it; and a materials cost account was constructed for the optimum mix. The objectives were (1) to establish the conformity of the constituent materials; (2) to determine the effect of replacement level on fresh-state behavior; (3) to determine the effect of replacement level on compressive and flexural strength at 7 and 28 days; (4) to identify the maximum replacement level satisfying both target mean criteria; and (5) to quantify the resulting change in materials cost and cement demand.

1.1 Research Significance

Four contributions are claimed. First, compressive and flexural strength are assessed simultaneously against the target mean acceptance criteria applicable to paving-grade concrete across a full 0–50% replacement series, rather than against a generic grade requirement. Second, the response is shown to be a plateau terminated by an abrupt threshold rather than a smooth optimum, with the threshold located between 30 and 40% replacement; this reframes the practical question from "what replacement maximizes strength" to "what replacement preserves it." Third, the normalized flexural-to-compressive ratio is shown to be constant up to the threshold and to fall sharply beyond it, demonstrating that tensile capacity degrades disproportionately once the threshold is crossed. Because agencies commonly infer flexural performance from cube strength, this result identifies a specific and non-obvious route by which compressive-strength-based quality control could pass an inadequate paving mix. Fourth, the cost account is decomposed to show how much of the gross cement saving actually survives once slag purchase and increased admixture demand are charged against it.

2. Materials and Methods

2.1 Constituent Materials

Ordinary Portland cement from a single consignment was used throughout. Crushed coarse aggregate and natural fine aggregate were obtained locally, and potable water and a proprietary chemical admixture completed the mix. All constituents were characterized in accordance with the relevant Indian Standards before mixing; the measured properties and the limits against which they were assessed are given in Table 2. Coarse aggregate was tested for aggregate crushing value and aggregate impact value in accordance with IS 2386 (Part IV), for flakiness and elongation index in accordance with IS 2386 (Part I), and for specific gravity and water absorption in accordance with IS 2386 (Part III). Fine aggregate was tested for specific gravity and water absorption to the same standard. Cement was tested for fineness by dry sieving on the 90 µm sieve (IS 4031 Part 1), normal consistency (IS 4031 Part 4), soundness by the Le Chatelier method (IS 4031 Part 3), initial and final setting time (IS 4031 Part 5), and 3-day mortar cube compressive strength on 70.6 mm cubes at a cement-to-standard-sand ratio of 1:3 (IS 4031 Part 6).

2.2 Steel Slag

The steel slag was supplied in ground powder form and is shown as received in Fig. 1. It presented as a uniformly fine, light grey powder with a small proportion of weakly bonded agglomerates that broke down under light pressure, consistent with a material that has been ground and stored rather than freshly processed. Indicative compositional ranges for steel slag are given in Table 1. It must be stated explicitly that the chemical and mineralogical composition of the specific slag used in this programme was not determined; Table 1 is compiled from the literature and is presented as context, not as a measurement. This is a material limitation of the study and constrains the mechanistic interpretation offered in the discussion, since the free lime and periclase contents the constituents that control both late pozzolanic reactivity and the risk of delayed expansion are precisely the quantities not measured.

Fig. 1. Ground steel slag as received, showing the fine grey powder

2.3 Mix Proportions and Specimen Preparation

A paving-grade mix was proportioned to a 28-day target mean compressive strength of 48.25 MPa and a 28-day target mean flexural strength of 5.16 MPa, the design flexural strength adopted for slab thickness computation being 4.00 MPa. Steel slag replaced cement by mass at five levels: 0 (control), 20, 30, 40, and 50%. Mix proportions are given in Table 3 for the control and for the 30% mix; proportions for the intermediate and higher replacement levels were not recorded in the source program and are not reconstructed here. Admixture dosage was adjusted between mixes to hold slump within the specified band, and this adjustment is itself a result rather than a fixed input: the dosage required at 30% replacement was more than double that of the control.

Materials were batched by mass to within 0.1% of batch weight. Dry cement, slag, and fine aggregate were blended to uniform color before the coarse aggregate was introduced, and water and admixture were added last. Cubes of 150 mm side were cast for compression and beams of 150 × 150 × 700 mm for flexure, each compacted in layers with a standard tamping rod. Specimens were held in the moulds for 24 ± 0.5 h in moist air of at least 90% relative humidity at 27 ± 2 °C, then demoulded and water-cured until testing. Two specimens were tested for each combination of replacement level, property, and age, giving 20 cubes and 20 beams and a total of 40 specimens.

2.4 Test Methods

Workability was measured by the slump cone (300 mm high, 200 mm bottom diameter, 100 mm top diameter) filled in four tamped layers, the specified consistency for the paving mix being 25 ± 15 mm. Compressive strength was determined in accordance with IS 516 at a loading rate of approximately 140 kg/cm² per minute (about 13.7 MPa/min), with strength computed as maximum load divided by nominal cross-sectional area. Flexural strength was determined by third-point loading on a 700 mm span in accordance with IS 516, the load being applied without shock at a rate producing an extreme-fibre stress increase of approximately 7 kg/cm² per minute, equivalent to 400 kg/min for the 150 mm specimens. The loading arrangement is shown in Fig. 2. Beams were tested in the saturated condition immediately on removal from curing, since even brief surface drying depresses the measured modulus of rupture. For readers accustomed to North American practice, the compressive, flexural, and slump procedures are broadly equivalent to ASTM C39, ASTM C78, and ASTM C143 respectively, with the important qualification that all compressive strengths reported here are 150 mm cube values and are not directly interchangeable with cylinder strengths.

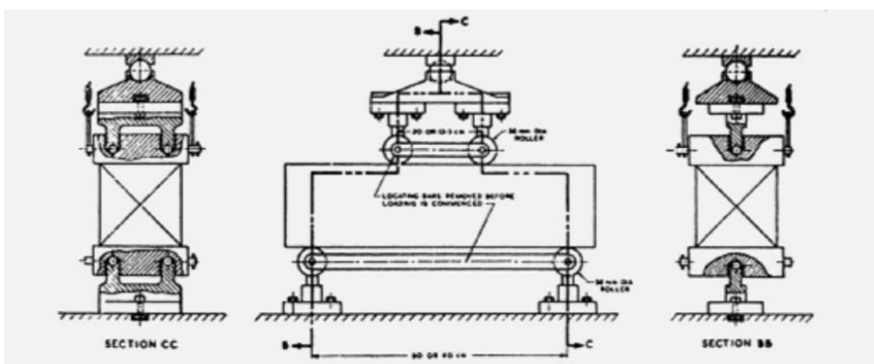

Fig. 2. Third-point loading arrangement used for determination of flexural strength.

Table 1. Indicative chemical composition of steel slag.

Constituent	**Composition (%)**
CaO	40–52
SiO_2	10–19
FeO	10–40 (70–80% FeO, 20–30% Fe_2O_3)
MnO	5–8
MgO	5–10

Al_2O_3	1–3
P_2O_5	0.5–1
S	< 0.1
Metallic Fe	0.5–10

Table 2. Physical properties of constituent materials and conformity with specified limits.

Material	**Property**	**Standard**	**Measured**
Coarse aggregate	Aggregate crushing value (%)	IS 2386 (IV)	24.30
	Aggregate impact value (%)	IS 2386 (IV)	22.66
	Flakiness index (%)	IS 2386 (I)	5.32
	Elongation index (%)	IS 2386 (I)	10.82
	Combined flakiness and elongation index (%)	IS 2386 (I)	16.14
	Specific gravity	IS 2386 (III)	2.76
	Water absorption (%)	IS 2386 (III)	0.60
Fine aggregate	Specific gravity	IS 2386 (III)	2.68
	Water absorption (%)	IS 2386 (III)	1.48
Cement	Fineness, residue on 90 µm sieve (%)	IS 4031 (1)	0.55
	Normal consistency (%)	IS 4031 (4)	30
	Soundness, Le Chatelier expansion (mm)	IS 4031 (3)	2.29
	Initial setting time (min)	IS 4031 (5)	74
	Final setting time (min)	IS 4031 (5)	250
	Compressive strength at 3 d (MPa)	IS 4031 (6)	27.28

Table 3. Mix proportions (kg/m³).

Constituent	**Control (0% slag)**	**30% slag**
Cement	390	301
Steel slag	0	129
Fine aggregate	774	770
Coarse aggregate	1,184	1,180
Chemical admixture	1.20	2.58

3. Results and Discussion

3.1 Conformity of Constituent Materials

All constituents satisfied the limits adopted, in most cases with considerable margin (Table 2). The aggregate crushing value of 24.30% and impact value of 22.66% lie roughly a fifth below the 30% ceiling applicable to concrete for roads and pavements, and the combined flakiness and elongation index of 16.14% is less than half the 35% limit. This matters for the interpretation of everything that follows: the aggregate skeleton was demonstrably not the strength-limiting phase in any of the five mixes, and the differences observed between mixes can therefore be attributed to the binder system rather than to aggregate quality or particle shape. Water absorption was low for both fractions (0.60 and 1.48%), so free-water corrections were small and consistent across mixes. The cement satisfied all requirements, with a Le Chatelier expansion of 2.29 mm against a 10 mm limit. That soundness result, however, applies to the cement alone. No soundness or volumetric-expansion test was performed on the slag or on slag-bearing pastes, which is a significant omission given that delayed hydration of free lime and periclase is the principal recognized durability hazard associated with steel slag; the point is returned to under Limitations.

3.2 Fresh-State Behaviour

Slump varied from 30 mm for the control to 35 mm at 20% replacement, 31 mm at 30%, 26 mm at 40%, and 20 mm at 50% (Fig. 5). Every mix remained inside the specified 25 ± 15 mm band, so on a slump criterion alone all five would be placeable. That conclusion is misleading in isolation. The admixture dosage required to achieve 31 mm at 30% replacement was 2.58 kg/m³ against 1.20 kg/m³ for the control (Table 3), an increase of 115%. Workability neutrality at 30% was therefore purchased, not obtained; the underlying water demand of the slag-bearing system is higher than that of the control, and the slump figures conceal rather than reveal that fact. Beyond 30% the admixture adjustment evidently could not keep pace, and slump fell by 13% at 40% replacement and by 33% at 50%.

The modest rise in slump at 20% replacement, if real, would be consistent with a lower water demand arising from particle morphology, but the admixture dosage for that mix was not recorded and the observation cannot be resolved. The practical implication for paving is nonetheless clear. Slipform paving depends on consistent, closely controlled consistency; a mix whose slump falls by a third relative to the control, and which requires progressively larger admixture dosages to hold consistency, imposes a batching-control burden that is disproportionate to any strength benefit. The economic consequence is quantified later: the additional admixture at 30% replacement costs rupees77.35/m³, which absorbs a meaningful fraction of the cement saving.

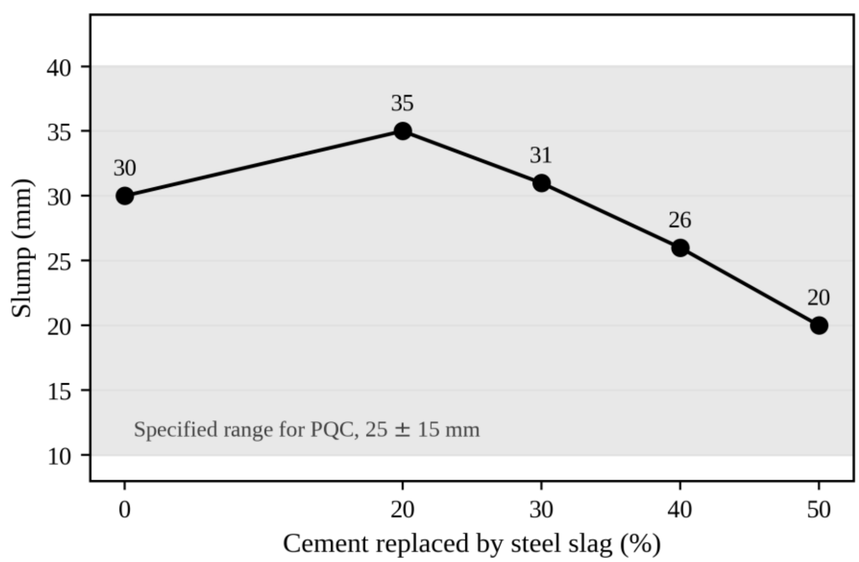

Fig. 5. Slump against cement replacement level. All mixes fall within the specified band

3.3 Compressive Strength

Cube compressive strengths are given in Table 4 and plotted in Fig. 3. At 28 days the control developed 54.11 MPa, and the 20 and 30% mixes developed 54.31 and 54.35 MPa, increases of 0.37 and 0.44% respectively. These differences must not be reported as strength enhancement. The difference between the control and the 30% mix is 0.24 MPa, which is smaller than the 0.50 MPa spread between the two duplicate specimens of the 30% mix itself. On the resolution criterion adopted here that a difference between mixes is regarded as real only if it exceeds the larger of the two duplicate ranges being compared the 0, 20, and 30% mixes are mutually unresolved at 28 days. The correct statement of the result is that replacement of up to 30% of the cement by steel slag left 28-day compressive strength unchanged. This distinction is not pedantic: several published studies report percentage gains of this order as evidence of a beneficial pozzolanic contribution, and gains of that magnitude are not distinguishable from specimen-to-specimen scatter.

At 7 days the picture differs, and here the effect is real. The control developed 42.36 MPa against 42.97 MPa at 20% and 43.94 MPa at 30%, gains of 1.4 and 3.7%. The 30% versus control difference of 1.58 MPa comfortably exceeds both duplicate ranges (0.16 and 0.32 MPa) and is resolved. Steel slag at 20–30% therefore accelerated early strength development while conferring no net benefit at 28 days. The most plausible explanation is a physical one: fine slag particles provide additional nucleation sites for calcium silicate hydrate and accelerate the hydration of the remaining cement, an effect that manifests early and is progressively offset by the dilution of cement as hydration proceeds. Confirmation would require isothermal calorimetry and thermogravimetric analysis of portlandite consumption, neither of which was performed.

The behaviour between 30 and 40% replacement is the central result. Compressive strength fell from 54.35 to 41.32 MPa, a loss of 23.6%, taking the mix from 12.6% above the 48.25 MPa target mean to 14.4% below it. The abruptness is the informative feature. A simple dilution model does not predict it: moving from 30 to 40% replacement removes a further 14% of the cement remaining in the 30% mix, which cannot by itself account for a 24% strength loss. The response is better described as the crossing of a threshold than as the continuation of a trend. A consistent interpretation is that below approximately 30% replacement the portlandite liberated by cement hydration is sufficient to activate the slag, which then contributes to the binding phase, whereas above that level the available calcium hydroxide is exhausted, the additional slag behaves as an inert filler, and the effective water-to-reactive-binder ratio rises sharply. This interpretation is a hypothesis consistent with the data, not a demonstrated mechanism, and it is testable by portlandite quantification across the replacement series.

The 40 and 50% mixes are indistinguishable from one another at 28 days: 41.32 and 41.26 MPa, a difference of 0.06 MPa against duplicate ranges of 2.02 and 1.84 MPa. Strength has floored. This is consistent with the threshold interpretation, in that slag added beyond the level the system can activate contributes nothing further, and inconsistent with a progressive dilution model, which would predict continued decline. At 7 days the 50% mix recorded 35.27 MPa against 31.28 MPa at 40%, an apparent reversal; the 50% mix also produced the highest scatter in the programme, with a coefficient of variation of 5.69% against 0.09% at 40%, and no interpretation is placed on this inversion.

One feature of the experimental design deserves comment because it conditions the generality of the findings. The control mix was itself 12.1% above its target mean strength. A conservatively proportioned control leaves headroom that a replacement series will consume before any deficiency becomes visible; a leaner control, proportioned closer to its target, would have failed acceptance at a lower replacement level. The 30% ceiling identified here should therefore be read as specific to a mix of this richness and not transferred uncritically to leaner paving mixes.

Table 4. Cube compressive strength at 7 and 28 days.

Slag (%)	7 d individual (MPa)	7 d mean (MPa)	28 d individual (MPa)	28 d mean (MPa)	CV at 28 d (%)	28 d mean / 48.25
0	42.44, 42.28	42.36	54.06, 54.16	54.11	0.13	1.12
20	43.20, 42.74	42.97	54.50, 54.12	54.31	0.49	1.13

30	44.10, 43.78	43.94	54.60, 54.10	54.35	0.65	1.13
40	31.26, 31.30	31.28	42.33, 40.31	41.32	3.46	0.86
50	36.69, 33.85	35.27	40.34, 42.18	41.26	3.15	0.86

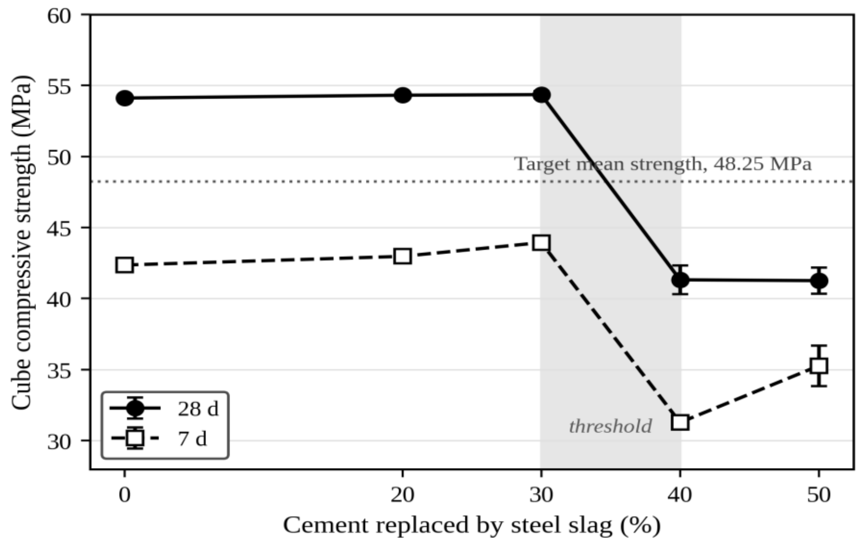

Fig. 3. Cube compressive strength against cement replacement level

3.4 Flexural Strength

Flexural strengths are given in Table 5 and plotted in Fig. 4. At 28 days the control reached 6.61 MPa, with 6.52 MPa at 20% and 6.56 MPa at 30% changes of −1.4 and −0.8%. Applying the same resolution criterion, all three are unresolved: the largest difference among them, 0.09 MPa between the control and the 20% mix, is smaller than the control's own duplicate range of 0.10 MPa. Flexural strength was therefore preserved, not improved, up to 30% replacement. It is worth stating plainly that no replacement level produced a flexural gain at 28 days, in contrast to reports in parts of the literature of simultaneous compressive and flexural enhancement. At 7 days, by contrast, the 20 and 30% mixes both reached 5.47 MPa against 5.25 MPa for the control, a gain of 4.2% that exceeds the duplicate ranges and is resolved mirroring the early-age acceleration seen in compression.

Across the threshold, flexural strength fell from 6.56 MPa at 30% to 5.12 MPa at 40%, a loss of 22.5%, closely matching the 23.6% compressive loss over the same interval. The 40% mix landed 0.8% below the 5.16 MPa target mean flexural strength. This is a marginal failure, and its interpretation requires care. The same mix exceeded the 4.00 MPa design flexural strength used for slab thickness computation by 28%. In other words, a mix that would be rejected at acceptance would nonetheless, on its mean strength, satisfy the flexural value on which the pavement's thickness was based. The two thresholds answer different questions: the design value asks whether the slab is thick enough, while the target mean asks whether the production process delivers the characteristic strength with adequate statistical confidence. With only two specimens per condition, no confidence statement can be attached to the 40% mix, and it cannot be recommended. The observation nonetheless identifies where the practical boundary actually sits at the acceptance criterion, not at structural adequacy and implies that in a jurisdiction adopting a lower design flexural strength, or accepting a smaller margin, the viable replacement ceiling would shift. At 50% replacement, flexural strength of 4.88 MPa fell 5.4% below the target mean while remaining 22% above the design value.

Table 5. Flexural strength at 7 and 28 days.

Slag (%)	7 d individual (MPa)	7 d mean (MPa)	28 d individual (MPa)	28 d mean (MPa)	CV at 28 d (%)	28 d mean / 5.16
0	5.31, 5.19	5.25	6.66, 6.56	6.61	1.07	1.28
20	5.44, 5.50	5.47	6.54, 6.50	6.52	0.43	1.26
30	5.51, 5.43	5.47	6.61, 6.51	6.56	1.08	1.27
40	4.96, 4.84	4.90	5.18, 5.06	5.12	1.66	0.99
50	4.86, 4.94	4.90	4.77, 4.99	4.88	3.19	0.95

Note: Target mean flexural strength = 5.16 MPa; design flexural strength = 4.00 MPa. Third-point loading, 700 mm span.

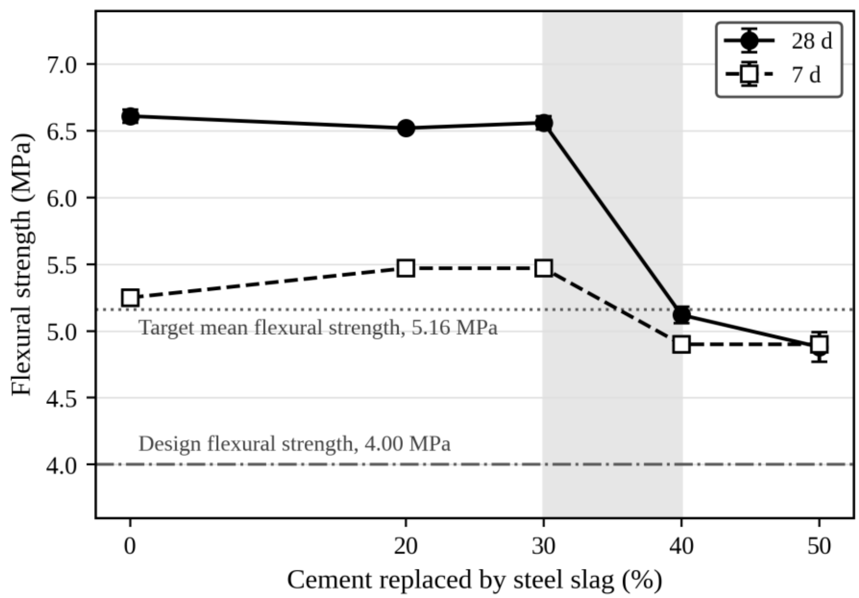

Fig. 4. Flexural strength against cement replacement level, shown against both the target mean strength governing acceptance and the design flexural strength governing slab thickness.

3.5 Strength Development and the Flexural–Compressive Relationship

The ratio of 7-day to 28-day strength (Table 6) exposes a change in the character of hydration that the strength values alone do not. In compression the ratio is broadly stable, between 75.7 and 85.5%. In flexure it is not. The control gained 25.9% in flexural strength between 7 and 28 days; the 20 and 30% mixes gained 19.2 and 19.9%; the 40% mix gained only 4.5%; and the 50% mix gained nothing at all, its 7-day and 28-day means being 4.90 and 4.88 MPa. This is the reverse of what a pozzolanic mechanism would predict. Supplementary cementitious materials characteristically shift strength development later, because the pozzolanic reaction is slow and follows the liberation of portlandite by cement hydration. Observing the opposite a complete loss of late-age flexural gain at high replacement is strong evidence that beyond the threshold the slag is not reacting pozzolanically to any useful extent in this system, and that the reduced quantity of cement present has substantially completed its hydration by 7 days. It also reinforces the earlier conclusion that the 40 and 50% mixes are limited by the same mechanism. Testing at 56 and 90 days would settle the question directly and is the single most informative extension of this program.

Table 6. Derived performance indices.

Slag (%)	Slump (mm)	Admixture (kg/m³)	7 d / 28 d compressive (%)	7 d / 28 d flexural (%)	*fr / fc*	*fr* / √*fc*
0	30	1.20	78.3	79.4	0.122	0.899
20	35	not recorded	79.1	83.9	0.120	0.885
30	31	2.58	80.8	83.4	0.121	0.890
40	26	not recorded	75.7	95.7	0.124	0.797
50	20	not recorded	85.5	100.4	0.118	0.760

The relationship between flexural and compressive strength is examined in Fig. 6 through the ratio of flexural strength to the square root of cube compressive strength, the form in which code correlations are conventionally expressed. For the control and the 20 and 30% mixes this ratio is 0.899, 0.885, and 0.890 MPa, a mean of 0.891 with a coefficient of variation of 0.8% remarkably constant. At 40 and 50% replacement it falls to 0.797 and 0.760, reductions of 10.5 and 14.7%. The simple ratio of flexural to compressive strength, by contrast, remains between 0.118 and 0.124 throughout and would have concealed the effect entirely, because it is not dimensionally consistent with the square-root scaling that the two properties actually follow.

The engineering consequence is direct and, in the authors' view, the most important practical finding of the study. Up to 30% replacement, the standard compressive-to-flexural correlation remains valid for slag-modified paving concrete, so existing design correlations and the quality-control practices built on them can be applied unchanged. Beyond 30%, the same correlation over-predicts flexural strength by 12 to 17%. An agency that specifies compressive-strength acceptance for PQC and infers flexural adequacy from it a common and otherwise defensible practice, since cube testing is faster and cheaper than beam testing would be systematically unconservative at high replacement levels, and would be so precisely in the region where flexural performance governs pavement life. The failure mode is silent: cube results would show a shortfall of one magnitude while the flexural shortfall was materially larger.

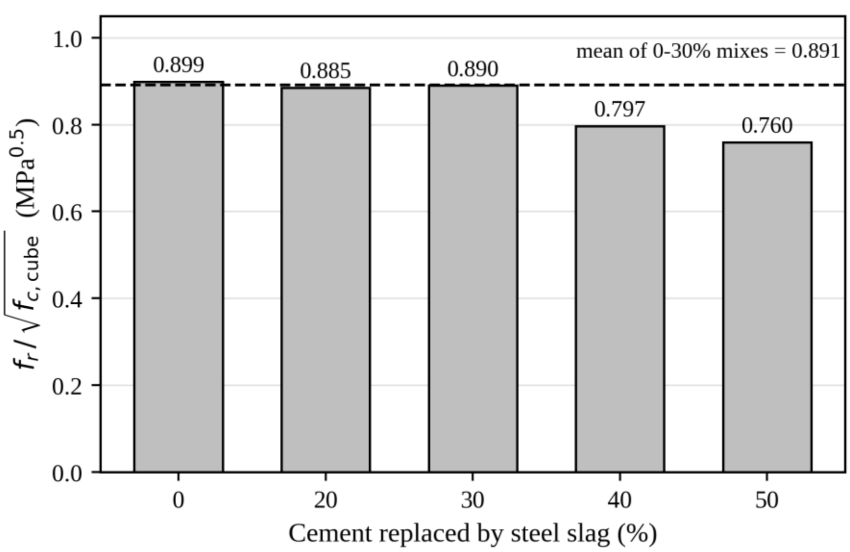

Fig. 6. Normalized flexural capacity against cement replacement level.

3.6 Repeatability and Statistical Treatment

Two specimens were tested for each combination of replacement level, property, and age. Coefficients of variation between duplicates ranged from 0.13 to 3.46% for 28-day compressive strength, 0.09 to 5.69% for 7-day compressive strength, and 0.43 to 3.19% for 28-day flexural strength. Variability was consistently low for the mixes at and below 30% replacement and rose at 40 and 50%, which is itself consistent with a less homogeneous binder phase at high replacement.

No inferential statistics are claimed, and none should be. With two specimens per condition the degrees of freedom are insufficient to support analysis of variance or t-testing, and reporting p-values from such a design would convey a false precision. The interpretation above instead applies an explicit and conservative resolution criterion: a difference in mean strength between two mixes is regarded as real only where it exceeds the larger of the two duplicate ranges being compared. Under this rule the following differences are resolved: the 7-day compressive and flexural gains at 20 and 30% replacement relative to the control; the losses in both properties between 30 and 40% replacement; and, marginally, the flexural difference between the 40 and 50% mixes. The following are not resolved: all 28-day differences among the 0, 20, and 30% mixes in both properties, and the 28-day compressive difference between the 40 and 50% mixes. Any confirmatory program should adopt a minimum of three specimens per condition per age, with replicate batches, so that batch-to-batch variability can be separated from within-batch variability and formal hypothesis testing becomes defensible.

3.7 Comparison with Published Studies

Table 7 places the present optimum alongside those reported previously. The 30% ceiling identified here sits centrally within a distribution that spans 20 to 60% and coincides with the level adopted by Dondi for road applications. The dispersion in the literature becomes more intelligible once the strength of the control mixture is taken into account. Mat Dom et al., who report benefits at 40 and 60% replacement, worked with control mixtures developing only 15 to 20 MPa; against so weak a reference, a slag-bearing mix has substantial room to show relative improvement. The present control developed 54.11 MPa. In a paving mix of this richness there is no headroom for slag to add strength, and the realistic and useful objective is strength neutrality at reduced cement content which is precisely what was achieved up to 30%. Studies reporting optima of 20%, including Rajaram et al., Sawant et al., and Mohan and Srinivas, evaluated compressive strength principally and in general grades rather than paving grades. Nair and Johny's 50% figure derives from mixes in which slag also replaced half of the coarse aggregate, a materially different system in which the slag contributes as a dense angular aggregate as well as a binder, and it is not directly comparable. Girish et al. examined the fatigue performance of paving-grade concrete containing steel slag and are the closest antecedent to the present work in application; fatigue was not measured here, and the comparison cannot be extended.

Table 7. Reported optimum cement replacement levels in previous studies.

Study	Grade	Replacement levels examined (%)	Reported optimum (%)
Rajaram et al.	Not stated	0, 5, 20, 35, 50	20
Sawant et al.	M30	10, 20, 30	20
Mohan and Srinivas	M40	20, 35, 50	20
Dondi	Not stated	30 (single level)	30
Shariq Prasad	Not stated	20, 40, 60	40
Mat Dom et al.	Not stated	up to 60	40–60
Nair and Johny	M30 / M35	20, 30, 40, 50, 60	20 (M35); 50 (M30, with slag aggregate)
Present study	Paving grade	0, 20, 30, 40, 50	30

4. Implications for Rigid Pavement Design and Construction

Because slab thickness in rigid pavement design is derived from flexural strength and from fatigue under repeated flexural stress, the governing question is not whether slag-modified concrete is strong in compression but whether its modulus of rupture is preserved. At 30% replacement it is: 6.56 MPa against 6.61 MPa for the control, a difference that is not resolvable against specimen scatter, and 64% above the 4.00 MPa design flexural strength. The practical consequence is that a slab thickness derived for the control mix can be retained without modification when 30% of the cement is replaced by steel slag. The substitution is design-neutral. This is a stronger and more useful statement than a claim of strength improvement would be, because it can be acted upon directly by a designer without recomputation and without any residual doubt about whether a marginal reported gain is real.

At 40 and 50% replacement the position changes in a way that quality-control practice may not detect. Mean flexural strength of 5.12 and 4.88 MPa still exceeds the 4.00 MPa design value, so a designer reviewing mean results alone might conclude that the pavement remains adequate. But the acceptance margin has been consumed entirely, and as Fig. 6 shows the correlation between cube strength and flexural strength has itself shifted. An agency accepting PQC on cube strength and inferring flexural performance would over-estimate the modulus of rupture by 12 to 17% at these replacement levels. Two specification recommendations follow. First, where steel slag is permitted as a cement replacement in PQC, acceptance should be based on beam testing rather than on cube strength with an assumed correlation, at least until the correlation has been re-established for the specific slag and replacement level in use. Second, pending durability and fatigue verification, the replacement ceiling should be set at 30%.

The early-age results carry operational value that the 28-day figures do not express. At 20 and 30% replacement, 7-day flexural strength was 4.2% higher than that of the control and 7-day compressive strength up to 3.7% higher, both resolved differences. Early strength governs the timing of joint sawing in jointed plain concrete pavement and the earliest permissible opening to construction and public traffic. A modest but real early-age gain widens the sawing window and can shorten the critical path on a paving contract, benefits that accrue at no cost in 28-day performance and, at 30% replacement, alongside a reduction in cement content.

One significant caution attaches to any field application. The dominant durability hazard associated with steel slag is delayed hydration of free lime and periclase, which produces volumetric expansion long after placement; established practice for slag used as aggregate requires extended outdoor weathering, in some cases up to 18 months, so that the expansive oxides hydrate before the material is incorporated. The hazard for a finely ground slag used as a binder replacement is different in character the particles are small, well dispersed, and hydrate faster but it has not been shown to be absent, and it was not evaluated in this program. Autoclave expansion testing and accelerated ageing of the specific slag, together with confirmation of its free lime content, should be regarded as prerequisites to field trial rather than as refinements to be undertaken afterwards.

5. Cost and Sustainability Implications

A materials cost comparison for the control and the 30% mix is given in Table 8. Total materials cost fell from rupees 4,777.70/m³ to rupees 4,696.61/m³, a reduction of rupees 81.09/m³ or 1.70%. The headline figure is modest, and the decomposition explains why. Replacing 89 kg of cement saved rupees 640.80/m³, but purchasing 129 kg of slag cost rupees 490.20/m³ and the additional admixture cost a further rupees 77.35/m³, with minor aggregate adjustments returning rupees 7.84/m³. Only 12.7% of the gross cement saving therefore survived as a net saving.

This result deserves emphasis because steel slag is routinely described as a waste material whose use is self-evidently economic. At the rate assumed here, rupees 3.80/kg, slag costs 53% as much as cement per unit mass while replacing it at a 1:1 mass ratio, so more than three-quarters of the gross saving is returned to the supplier. The economics are consequently dominated by the slag purchase price rather than by the cement displaced, and they are highly sensitive to it. Holding all else constant, halving the slag price to rupees 1.90/kg would raise the net saving to rupees 326/m³, or 6.8%; slag supplied at zero cost, as might be negotiated where the producer's alternative is landfill with its own disposal charge, would yield rupees 571/m³, or 12.0%. The commercial case for slag-modified PQC is therefore made or lost in the supply agreement, not in the laboratory. Procurement strategies that treat slag as a purchased commodity at prevailing market rates will find the margin thin; those that capture part of the producer's avoided disposal cost will not. The cost account is materials-only, is based on rates from a single supply region at a single point in time, and excludes grinding, transport, plant modification, and any change in quality-control cost arising from the additional beam testing recommended above.

The environmental case rests on firmer ground than the economic one. At 30% replacement the mix consumes 89 kg/m³ less cement, a reduction of 22.8%, and diverts 129 kg/m³ of slag from disposal. For the 1,000 m × 10 m × 0.28 m carriageway considered, corresponding to 2,800 m³ of PQC, this amounts to approximately 249 t of cement avoided and 361 t of slag consumed per kilometer. Set against a generation rate of 150 to 200 kg of slag per ton of steel produced, a single kilometer of pavement absorbs the slag arising from roughly 1,800 to 2,400 t of steel production. No carbon accounting is offered here, and the omission is deliberate. A defensible cradle-to-gate figure requires emission factors for the specific cement, the energy consumed in drying and grinding the slag, and the haulage distance from steel plant to batching plant, none of which was determined. Grinding energy and transport distance can be material to the balance, and slag transported several hundred kilometers to a site may deliver a considerably smaller net benefit than the cement-mass reduction implies. The cement mass avoided is therefore reported as the primary sustainability metric, and any life-cycle claim should follow a full assessment rather than precede it.

Table 8. Materials cost comparison per cubic meter of PQC.

Material	Rate (rupees/kg)	Control qty (kg)	Control cost (rupees)	30% qty (kg)	30% cost (rupees)	Difference (rupees)
Cement	7.20	390	2,808.00	301	2,167.20	−640.80
Steel slag	3.80	0	0.00	129	490.20	+490.20
Fine aggregate	1.02	774	789.48	770	785.40	−4.08
Coarse aggregate	0.94	1,184	1,112.96	1,180	1,109.20	−3.76
Admixture	56.05	1.20	67.26	2.58	144.61	+77.35
Total			**4,777.70**		**4,696.61**	**−81.09**
Reduction					1.70%	

6. Limitations

The findings are bounded by the following, each of which defines a specific requirement for further work before field adoption.

1. Sample size. Two specimens were tested per condition per age, which permits an assessment of repeatability but not formal hypothesis testing. Differences reported as unresolved may be real but small.
2. Slag characterization. The chemical and mineralogical composition of the slag used was not determined. Free lime, periclase, fineness, and specific gravity are unmeasured, and the mechanistic interpretations offered in the discussion are consequently hypotheses rather than demonstrated mechanisms.
3. Volumetric stability. No autoclave expansion, accelerated ageing, or long-term soundness testing was performed on slag-bearing pastes or concrete. This is the principal recognized durability risk for steel slag and the most urgent gap.
4. Durability. No permeability, water absorption, abrasion, chloride ingress, sulfate resistance, freeze–thaw, or alkali–aggregate reactivity testing was undertaken. Claims of improved durability cannot be supported from this dataset.
5. Fatigue. Rigid pavement design depends on fatigue behaviour under repeated flexural stress. Fatigue was not measured, and static flexural strength is not a substitute.

6. Age. Testing ceased at 28 days. Given the loss of late-age flexural gain observed at high replacement, testing at 56 and 90 days is essential to establish whether the threshold shifts with age.
7. Mix proportions. Full proportions were recorded only for the control and the 30% mix; water content, water-to-binder ratio, and admixture dosage for the 20, 40, and 50% mixes are not available, which limits normalization of the results.
8. Field validation. All results are from laboratory-cast and laboratory-cured specimens. No trial section was constructed, and no field performance data are reported or implied.
9. Cost. The economic analysis is materials-only, single-region, and single-period, and excludes processing, transport, and quality-control costs.
10. Generality of the control. The control mix exceeded its target mean compressive strength by 12.1%. The 30% ceiling identified here applies to a mix of this richness and should be re-established for leaner paving mixes.

7. Conclusions

Paving-grade concrete in which ordinary Portland cement was replaced by ground steel slag at 0, 20, 30, 40, and 50% by mass was evaluated for workability and for compressive and flexural strength at 7 and 28 days, against both the target mean strengths governing acceptance and the design flexural strength governing slab thickness. The following conclusions are drawn.

1. Replacement of up to 30% of the cement by steel slag left 28-day strength unchanged rather than improved. Compressive strength was 54.11, 54.31, and 54.35 MPa and flexural strength 6.61, 6.52, and 6.56 MPa at 0, 20, and 30% replacement; all differences were smaller than the scatter between duplicate specimens and are not resolvable. Reports of strength enhancement of this magnitude elsewhere in the literature should be interpreted with the same caution.
2. A real early-age benefit was observed. At 7 days the 30% mix exceeded the control by 3.7% in compression and the 20 and 30% mixes exceeded it by 4.2% in flexure, differences that exceed specimen scatter and are resolved. This is consistent with a physical nucleation effect that is offset by cement dilution by 28 days.
3. The response to replacement is a plateau terminated by an abrupt threshold between 30 and 40%, not a smooth optimum. Across this interval compressive strength fell by 23.6% and flexural strength by 22.5%, taking both below the 48.25 and 5.16 MPa target mean strengths. The 40 and 50% mixes were indistinguishable from one another in compression at 28 days, indicating that slag added beyond the threshold contributes nothing further.
4. Late-age flexural strength gain disappeared above the threshold. Between 7 and 28 days the control gained 25.9% in flexural strength, the 40% mix gained 4.5%, and the 50% mix gained nothing. This is the opposite of the behaviour expected of a pozzolanic material and indicates that the slag is not reacting usefully at high replacement levels.
5. The ratio of flexural strength to the square root of cube compressive strength was constant at 0.891 MPa to within 0.8% up to 30% replacement, and fell to 0.797 and 0.760 at 40 and 50%. Standard compressive-to-flexural correlations therefore remain valid up to 30% but over-predict flexural strength by 12 to 17% beyond it, so compressive-strength-based acceptance would be unconservative at high replacement levels.
6. Workability was maintained within the specified 25 ± 15 mm band at all replacement levels, but at 30% replacement this required an admixture dosage of 2.58 kg/m³ against 1.20 kg/m³ for the control, an increase of 115%. Slump fell by 33% at 50% replacement.
7. Thirty percent replacement is the maximum level satisfying both acceptance criteria, exceeding the target mean compressive strength by 12.6% and the target mean flexural strength by 27.1%. Because flexural strength at this level is statistically identical to that of the control, slab thickness derived for the control mix may be retained without modification; the substitution is design-neutral.
8. At 30% replacement, cement demand fell by 89 kg/m³ (22.8%) and 129 kg/m³ of slag was diverted from disposal, corresponding to approximately 249 t of cement avoided and 361 t of slag consumed per kilometer

of the carriageway considered. Materials cost fell by 1.70%, but only 12.7% of the gross cement saving survived after the slag purchase and the additional admixture were charged against it; the economic case is dominated by the slag supply price.

Data Availability Statement

All data generated during the study appear in the published article. Raw specimen records are available from the corresponding author upon reasonable request.

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