

Comprehensive Investigation of Aggregate Gradation, Mechanical Performance, Durability, and Life Cycle Assessment of Multi-Recycled Aggregate Concrete for Sustainable Infrastructure Applications

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Abstract - Multi-recycled aggregate concrete offers a route for conserving virgin aggregate and closing material loops, but successive recycling can increase adhered mortar, porosity and water absorption and thereby alter packing and concrete performance. This study integrates aggregate gradation, particle packing, concrete proportioning, mechanical performance and life-cycle assessment for natural aggregate concrete and first-, second- and third-generation recycled aggregate concrete. Concrete was designed for 30 and 50 MPa strength levels using IS 10262:2019 and the Compressible Packing Model (CPM). Workability, compressive strength, split tensile strength and flexural strength were evaluated at 7 and 28 days. CPM proportioning generally produced higher 28-day strength and lower binder intensity than corresponding code-based mixtures. For 30 MPa concrete, CPM compressive strengths were 37.01, 34.53, 35.65 and 33.28 MPa for NCR, CR1, CR2 and CR3, respectively; corresponding 50 MPa values were 56.14, 54.76, 55.27 and 53.23 MPa. Life-cycle assessment indicated reductions in carbon footprint, energy demand and major impact categories through recycling and optimized packing. The results demonstrate that particle-packing-based proportioning can partially compensate for performance losses associated with repeated recycling while improving material efficiency.

Key Words: recycled aggregate concrete, multi-recycled aggregate, particle packing, Compressible Packing Model, life cycle assessment, sustainable infrastructure.

1. INTRODUCTION

Concrete construction depends heavily on virgin aggregate and cementitious materials, while construction and demolition activities generate large quantities of concrete waste. Recycling concrete into aggregate can reduce virgin-resource demand, but repeated recycling

modifies aggregate density, absorption, surface texture and adhered mortar content. These changes influence the aggregate skeleton, water demand, paste requirement and interfacial transition zones [1], [2], [12], [16], [29].

Multi-recycled aggregate concrete therefore requires more than simple substitution of natural aggregate. Aggregate gradation and particle packing can be used to control voids and improve the stability of the granular skeleton. Particle-packing approaches such as the Modified Toufar Method (MTM), J. D. Dewar Method (JDD) and Compressible Packing Model (CPM) provide analytical means of optimizing size-class proportions [10], [15], [20], [23], [31], [33], [36].

Mechanical performance must be assessed through complementary properties. Compressive strength represents the principal load-bearing response, while split tensile and flexural strengths provide information on cracking resistance and tension-zone behaviour. Life-cycle assessment (LCA) is also needed because a material can be mechanically adequate but environmentally inefficient if binder use, transportation or processing burdens remain high [8], [9], [21], [27], [32].

The objective is to link aggregate generation, particle packing, mechanical performance and environmental indicators within a common concrete proportioning framework. Natural aggregate concrete (NCR) and three recycled generations (CR1, CR2 and CR3) were compared at 30 and 50 MPa strength levels using conventional IS 10262:2019 and CPM-based proportioning.

2. LITERATURE REVIEW AND RESEARCH GAP

Recent studies show that repeated recycling progressively changes recycled aggregate quality. Multi-generation aggregates generally exhibit lower density

and higher absorption because adhered mortar and microcracking accumulate with each recycling cycle [2], [6], [12], [16], [29]. Nevertheless, treatment, moisture conditioning and optimized mixture proportioning can recover part of the lost performance. Studies also report non-monotonic responses in some second-generation systems because aggregate morphology and failure paths vary between recycling cycles [6], [18].

Particle packing has emerged as an effective strategy for reducing voids and binder demand. CPM and related frameworks account for interaction effects between particle classes and can provide denser granular skeletons than simple codal grading alone [10], [15], [23], [31], [33], [36]. Low-binder and high-performance concrete investigations further indicate that packing optimization can maintain strength while reducing cement intensity [13], [20], [26].

Sustainability research consistently identifies cement production and transportation as dominant environmental contributors. Recycled aggregate can reduce extraction and processing of virgin aggregate, while supplementary cementitious materials and optimized binder contents can further lower global warming potential and energy demand [4], [5], [8], [19], [21], [22], [27], [32], [34], [39].

The research gap is the limited integration of repeated recycling, particle packing, structural material properties and life-cycle indicators within one controlled comparison. The present investigation addresses this gap by comparing NCR, CR1, CR2 and CR3, using both IS 10262:2019 and CPM proportioning, and evaluating fresh-state behaviour, three hardened strength properties, binder intensity and LCA indicators.

3. MATERIALS AND METHODOLOGY

3.1 Experimental Framework

The investigation followed four linked stages: characterization and gradation of natural and multi-recycled aggregates; particle-packing analysis; proportioning of 30 and 50 MPa concrete using IS 10262:2019 and CPM; and evaluation of workability, compressive, split tensile and flexural strength. A cradle-to-cradle LCA with a functional unit of 1 m³ of concrete was used to assess environmental performance.

3.2 Materials and Aggregate Characteristics

The concrete system contains cement, fly ash, natural coarse aggregate, recycled coarse aggregates representing CR1, CR2 and CR3 generations, fine aggregate, water and chemical admixture. Successive recycling generations are associated with increasing adhered mortar and water absorption, which must be

accounted for during batching and moisture conditioning.

Table 1: Physical properties of natural and multi-recycled coarse aggregate

Size range (mm)	NA Bulk density	CR1 Bulk density	CR2 Bulk density	CR3 Bulk density	NA G G	CR1 G	CR2 G	CR3 G	NA GWA %	CR1 GWA %	CR2 GWA %	CR3 GWA %
20 – 16	1414	1285	1278	1250	2.64	2.68	2.54	2.48	1.12	1.75	2.12	3.42
16 – 12.5	1376	1270	1265	1242	2.62	2.64	2.50	2.48	1.20	1.62	1.95	3.10
12.5 – 10	1392	1290	1270	1248	2.60	2.60	2.56	2.50	1.20	1.45	1.87	2.85
10 – 4.75	1360	1210	1250	1230	2.45	2.52	2.48	2.40	1.06	1.37	1.72	2.55

Table 2: Reported improvement in packing density using particle-packing methods

Packing method	Increase in packing density over IS 383:2016 (%)
Modified Toufar Method (MTM)	23.07
J. D. Dewar Method (JDD)	26.83
Compressible Packing Model (CPM)	14.28

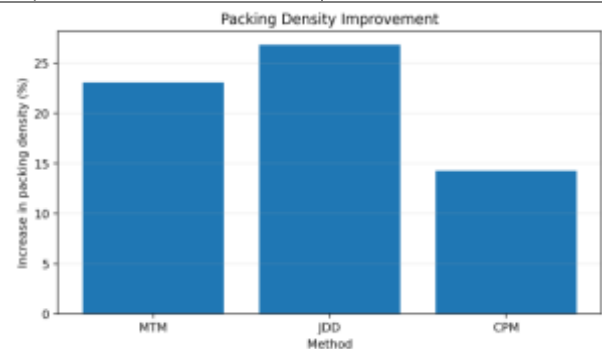


Fig. 1: Relative improvement in packing density reported for particle-packing approaches

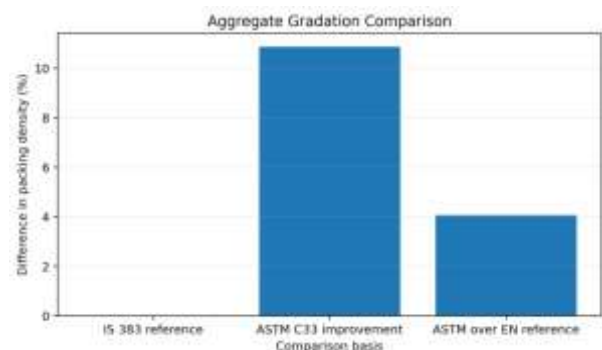


Fig. 2: Packing-density improvement relative to IS 383:2016

3.3 Particle Packing and Mix Design

The Modified Toufar, J. D. Dewar and Compressible Packing Model approaches were used to evaluate packing behaviour. For a binary particle system, packing density is obtained by considering the virtual packing

density of each class and interaction terms. CPM additionally accounts for wall and loosening effects and compaction. The optimized aggregate skeleton was then used to establish concrete proportions.

Table 3: Mix proportions of natural and multi-recycled concrete – 30 MPa strength

Constituent (kg/m ³)	NC R-IS	CR1 -IS	CR2 -IS	CR3 -IS	NC R-CP M	CR 1-CP M	CR 2-CP M	CR 3-CP M
Cement	300.03	300.03	300.03	300.03	278.02	282.43	288.50	291.18
Fly ash	75.01	75.01	75.01	75.01	69.50	70.61	72.12	72.80
Coarse aggregate	1185.25	1166.41	1108.25	1088.84	vari ous size clas ses	vari ous size clas ses	vari ous size clas ses	vari ous size clas ses
Fine aggregate	721.25	700.12	695.14	684.25	vari ous size clas ses	vari ous size clas ses	vari ous size clas ses	vari ous size clas ses
Superplasticizer	1.88	2.63	3.00	3.75	2.78	2.82	2.88	2.91
Water	166.06	166.06	166.06	166.06	153.91	156.34	159.67	161.15
Water/cementitious material	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44

Table 4: Mix proportions of natural and multi-recycled concrete – 50 MPa strength

Constituent (kg/m ³)	NC R-IS	CR1 -IS	CR2 -IS	CR3 -IS	NC R-CP M	CR 1-CP M	CR 2-CP M	CR 3-CP M
Cement	381.05	381.05	381.05	381.05	342.08	357.57	366.74	376.98
Fly ash	68.58	68.58	68.58	68.58	61.57	64.36	66.01	67.86
Coarse aggregate	1195.50	1200.65	1187.50	1161.15	vari ous size clas ses	vari ous size clas ses	vari ous size clas ses	vari ous size clas ses
Fine aggregate	676.58	650.15	625.42	610.14	vari ous size clas ses	vari ous size clas ses	vari ous size clas ses	vari ous size clas ses
Superplasticizer	2.24	3.14	3.59	4.48	3.42	3.58	3.67	3.77
Water	175.54	175.54	175.54	175.54	155.86	162.23	166.01	170.23
Water/cementitious material	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39

Table 5: Binder Intensity Index of natural and multi-recycled concrete

Strength	Generation	IS 10262:2019	CPM	Decrease (%)
30 MPa	NCR	10.72	9.42	12.13
30 MPa	CR1	11.36	10.23	9.95
30 MPa	CR2	11.02	10.13	8.08
30 MPa	CR3	12.36	10.95	11.41
50 MPa	NCR	8.27	7.23	12.58
50 MPa	CR1	8.46	7.69	9.10
50 MPa	CR2	8.29	7.82	5.67
50 MPa	CR3	8.63	8.34	3.36

Table 7: Comparison of aggregate gradation and packing performance

Gradation basis	Reported comparison	Engineering interpretation
IS 383:2016	Reference	Conventional grading basis

Gradation basis	Reported comparison	Engineering interpretation
ASTM C33/C33M	10.87% higher packing density than IS 383	Higher packing efficiency reported
EN 12620	4.07% lower than ASTM C33 grading	Intermediate packing performance
Particle packing methods	Higher density than IS 383 reference	Optimization of size-class proportions

3.4 Experimental Programme and Test Methods

Fresh-state workability was assessed immediately after mixing. Hardened specimens were cast using 150 × 150 × 150 mm cubes for compression, 150 mm diameter × 300 mm cylinders for split tension and 150 × 150 × 700 mm beams for flexure. Testing was conducted at 7 and 28 days under a common curing framework.

Table 6: Experimental programme

Test	Specimen	Curing ages	Primary output
Workability	Fresh concrete	Fresh state	Slump/workability observation
Compressive strength	150 × 150 × 150 mm cube	7 and 28 days	Compressive strength (MPa)
Split tensile strength	150 mm dia. × 300 mm cylinder	7 and 28 days	Split tensile strength (MPa)
Flexural strength	150 × 150 × 700 mm beam	7 and 28 days	Flexural strength (MPa)

Table 8: Key mix-design parameters used for batching

Design item	30 MPa	50 MPa
Water/cementitious material ratio	0.44	0.39
Fly ash in IS mixes (kg/m ³)	75.01	68.58
Fly ash in CPM NCR mix (kg/m ³)	69.50	61.57
Cement in IS NCR mix (kg/m ³)	300.03	381.05
Cement in CPM NCR mix (kg/m ³)	278.02	342.08

Table 9: Specimen and curing control parameters

Property	Specification
Cube size	150 × 150 × 150 mm
Cylinder size	150 mm diameter × 300 mm
Beam size	150 × 150 × 700 mm
Testing ages	7 days and 28 days
Mix generations	NCR, CR1, CR2, CR3
Mix-design methods	IS 10262:2019 and CPM

Compressive strength was calculated from the maximum load divided by the loaded cross-sectional area:

$$f_c = P / A$$

Split tensile strength was obtained from the diametral loading relation:

$$f_t = 2P / (\pi LD)$$

Flexural strength was evaluated using the applicable IS 516 procedure for the stated beam geometry and loading arrangement.

3.5 Life-Cycle Assessment

LCA was performed using openLCA with ecoinvent 3.10 inventory data for the Indian context. The functional unit was 1 m³ of concrete and the boundary

was cradle-to-cradle, including material production, transportation, concrete production, use, disposal and recycling. The CML 2016 baseline method was used for impact categories and Cumulative Energy Demand for embodied energy.

4. RESULTS AND DISCUSSION

4.1 Aggregate Packing

Table 10: Improvement in aggregate packing density

Packing method	Increase in packing density over IS 383:2016 (%)
Modified Toufar Method (MTM)	23.07
J. D. Dewar Method (JDD)	26.83
Compressible Packing Model (CPM)	14.28

Particle-packing methods increased aggregate packing density relative to the IS 383:2016 reference. The reported improvements were 23.07% for MTM, 26.83% for JDD and 14.28% for CPM. Higher packing density reduces voids in the granular skeleton and provides a basis for reducing binder demand while maintaining required strength and workability.

4.2 Fresh-State Workability

Table 11: Workability trend of natural and multi-recycled concrete

Generation	Workability trend	Engineering observation
NCR	Higher	Reference conventional concrete
CR1	Reduced	Moderate reduction due to recycled aggregate characteristics
CR2	Further reduced	Higher adhered mortar and absorption influence consistency
CR3	Lowest trend	Highest influence of successive recycling on fresh-state behaviour

Workability decreased progressively from NCR to CR3. The reduction is attributed to higher surface roughness, adhered mortar and water absorption with increasing recycling generation. CPM mixtures also tend to have lower workability because the denser aggregate skeleton reduces paste volume. Saturated-surface-dry conditioning and controlled admixture dosage are therefore important for reproducible production.

4.3 Compressive Strength

Table 12: Compressive strength – 30 MPa concrete

Mix	7-day IS	28-day IS	7-day CPM	28-day CPM
NCR	24.30	35.02	27.40	37.01
CR1	23.60	33.07	24.40	34.53
CR2	25.60	34.10	27.32	35.65
CR3	20.10	30.34	22.21	33.28

For 30 MPa concrete, CPM increased the 28-day compressive strength of NCR from 35.02 to 37.01 MPa and produced 34.53, 35.65 and 33.28 MPa for CR1, CR2 and CR3. The corresponding IS

values were 33.07, 34.10 and 30.34 MPa. Thus, CPM provided a positive strength increment for every recycling generation.

Table 13: Compressive strength – 50 MPa concrete

Mix	7-day IS	28-day IS	7-day CPM	28-day CPM
NCR	33.50	54.22	35.50	56.14
CR1	30.80	53.02	38.20	54.76
CR2	31.40	54.09	36.22	55.27
CR3	25.21	52.00	32.24	53.23

For 50 MPa concrete, the 28-day CPM strengths were 56.14, 54.76, 55.27 and 53.23 MPa for NCR, CR1, CR2 and CR3, respectively, compared with 54.22, 53.02, 54.09 and 52.00 MPa for IS 10262:2019. Improved packing can therefore partly compensate for the quality reduction associated with repeated recycling.

4.4 Split Tensile Strength

Table 14: Split tensile strength – 30 MPa concrete

Mix	7-day IS	28-day IS	7-day CPM	28-day CPM
NCR	2.30	3.60	2.60	4.00
CR1	2.20	3.40	2.30	3.80
CR2	2.40	3.50	2.60	3.91
CR3	2.01	3.02	2.23	3.42

Table 15: Split tensile strength – 50 MPa concrete

Mix	7-day IS	28-day IS	7-day CPM	28-day CPM
NCR	3.20	4.90	3.48	5.18
CR1	2.90	4.40	3.67	4.91
CR2	2.90	4.70	3.80	5.08
CR3	2.81	4.01	3.21	4.62

Split tensile strength followed the general compressive-strength trend. At 28 days, CPM increased the 30 MPa values from 3.60, 3.40, 3.50 and 3.02 MPa to 4.00, 3.80, 3.91 and 3.42 MPa for NCR through CR3. For 50 MPa concrete, the corresponding CPM values were 5.18, 4.91, 5.08 and 4.62 MPa. The results indicate that packing optimization influences both the load-bearing matrix and aggregate–paste interaction.

4.5 Flexural Strength

Table 16: Flexural strength – 30 MPa concrete

Mix	7-day IS	28-day IS	7-day CPM	28-day CPM
NCR	3.45	4.20	3.67	4.40
CR1	2.90	3.81	2.80	4.01
CR2	2.78	3.90	2.81	4.10
CR3	2.13	2.91	2.18	3.12

Table 17: Flexural strength – 50 MPa concrete

Mix	7-day IS	28-day IS	7-day CPM	28-day CPM
NCR	4.10	4.90	4.10	5.10
CR1	3.30	4.40	3.70	4.70
CR2	3.10	4.60	3.20	4.91
CR3	2.65	4.01	2.83	4.20

Flexural strength also improved with CPM proportioning. For 30 MPa concrete, the 28-day values increased to 4.40, 4.01, 4.10 and 3.12 MPa for NCR, CR1, CR2 and CR3. For 50 MPa concrete, the corresponding CPM values were 5.10, 4.70, 4.91 and 4.20 MPa. The reduction toward CR3 reflects the cumulative effect of adhered mortar and weaker aggregate-related interfaces.

4.6 Relationships Among Mechanical Properties

Table 18: Relationship between mechanical strength parameters

Property	Reported relationship with compressive strength
Split tensile strength	Approximately 8–10% of compressive strength
Flexural strength	Approximately 5–7% of compressive strength
Correlation range (R^2)	0.91–0.96

The reported relationships indicate that split tensile strength is approximately 8–10% of compressive strength and flexural strength is approximately 5–7%. Coefficients of determination between the mechanical properties range from about 0.91 to 0.96, demonstrating strong correlation. Compressive strength can therefore serve as a primary performance indicator, while tensile and flexural measures provide complementary evidence of cracking and bending behaviour.

4.7 Binder Intensity and Strength Efficiency

Table 19: Binder Intensity Index comparison

Strength	Generation	IS 10262:2019	CPM	Decrease (%)
30 MPa	NCR	10.72	9.42	12.13
30 MPa	CR1	11.36	10.23	9.95
30 MPa	CR2	11.02	10.13	8.08
30 MPa	CR3	12.36	10.95	11.41
50 MPa	NCR	8.27	7.23	12.58
50 MPa	CR1	8.46	7.69	9.10
50 MPa	CR2	8.29	7.82	5.67
50 MPa	CR3	8.63	8.34	3.36

CPM reduced binder intensity across all reported generations. For 30 MPa concrete, the reduction ranged from 8.08% to 12.13%, while for 50 MPa concrete it ranged from 3.36% to 12.58%. The overall reported reductions were approximately 10.4% for 30 MPa concrete and 7.67% for 50 MPa concrete. Lower binder intensity indicates more efficient use of cementitious material for the achieved strength.

4.8 Life-Cycle Assessment and Environmental Performance

Table 20: Reported life-cycle performance improvements

Indicator	Reported reduction / contribution
Carbon footprint – recycled concrete	3–10% lower than conventional concrete
Carbon footprint – CPM	4–12% lower than IS 10262:2019
Energy requirement – recycled concrete	6–8% lower than conventional concrete
Embodied energy – CPM	6–14% lower than IS 10262:2019
Environmental impact indicators – CPM	6–30% lower than IS 10262:2019
Impact indicators – recycled concrete	20–40% lower than conventional concrete

The LCA results indicate that recycled concrete can reduce carbon footprint by approximately 3–10% and energy requirements by approximately 6–8% relative to conventional concrete. CPM proportioning provides

additional reductions of approximately 4–12% in carbon footprint and 6–14% in embodied energy compared with IS 10262:2019.

Table 21: Major contributors to life-cycle impact indicators

Environmental parameter	Reported contribution (%)
Cement – carbon dioxide equivalent emissions	70–75
Transportation – carbon footprint	25–30
Cement – Acidification Potential	69
Cement – Eutrophication Potential	66.6
Cement – Global Warming Potential	72.4
Transportation – ADP	77.5
Transportation – ODP	72.8
Transportation – Human Toxicity	69.6
Transportation – POF	56.6

Cement is the dominant contributor to several environmental indicators, accounting for approximately 70–75% of carbon dioxide equivalent emissions. Transportation contributes approximately 25–30% of the carbon footprint. For other impact categories, cement and transportation remain the principal contributors, demonstrating the importance of reducing binder intensity and optimizing logistics.

Table 22: Life-cycle impact-category interpretation

Impact category	Reported reduction using CPM/recycling
Global Warming Potential (GWP)	Reduced; approximately 20–30% depending on comparison
Eutrophication Potential (EP)	Reduced; approximately 20–30% depending on comparison
Acidification Potential (AP)	Reduced; approximately 20–30% depending on comparison
Abiotic Depletion Potential (ADP)	Reduced; approximately 40% in reported CPM comparison
Ozone Depletion Potential (ODP)	Reduced; approximately 40% in reported CPM comparison

4.9 Integrated Engineering Assessment

The results demonstrate a balance between aggregate quality and packing efficiency. Successive recycling reduces aggregate quality and fresh workability, but optimized particle packing produces a more stable granular skeleton and permits lower binder intensity. The 28-day results show that NCR generally provides the highest strength, while CR3 exhibits the greatest reduction; CR2 often performs better than CR1 for individual parameters, confirming that the response is not strictly monotonic with recycling generation.

From a sustainability perspective, the value of multi-recycled aggregate concrete is not limited to aggregate substitution. Recycling reduces demand for virgin aggregate extraction and processing, while CPM reduces binder demand. The combined approach therefore provides environmental benefits without requiring the concrete to maximize compressive strength alone.

4.10 Comparative Strength Variation

Table 23: Percentage variation in 28-day compressive strength

Mix	CPM vs IS – 30 MPa (%)	CPM vs IS – 50 MPa (%)	CR generation vs NCR – 30 MPa (%)	CR generation vs NCR – 50 MPa (%)
NCR	5.68	3.54	0	0
CR1	4.41	3.28	-5.57	-2.21
CR2	4.55	2.18	-2.63	-0.24
CR3	9.69	2.37	-13.36	-4.09

Table 24: Percentage variation in split tensile and flexural strength due to CPM

Mix	Split tensile – 30 MPa CPM vs IS (%)	Split tensile – 50 MPa CPM vs IS (%)	Flexural – 30 MPa CPM vs IS (%)	Flexural – 50 MPa CPM vs IS (%)
NCR	11.11	5.71	4.76	4.08
CR1	11.76	11.59	5.25	6.82
CR2	11.71	8.09	5.13	6.74
CR3	13.25	15.21	7.22	4.74

The percentage comparisons confirm that CPM improves compressive, split tensile and flexural strength relative to the corresponding IS 10262:2019 mixtures. The magnitude of improvement varies with recycling generation because aggregate quality and interfacial characteristics change.

4.11 Early-Age to 28-Day Strength Development

Table 25: Percentage strength development from 7 to 28 days

Mix	Compressive gain 30 MPa IS (%)	Compressive gain 30 MPa CPM (%)	Compressive gain 50 MPa IS (%)	Compressive gain 50 MPa CPM (%)
NCR	44.12	35.07	61.85	58.14
CR1	40.13	41.52	72.14	43.35
CR2	33.2	30.49	72.26	52.6
CR3	50.95	49.84	106.27	65.11

All mixtures developed strength between 7 and 28 days. The increase from 7 to 28 days demonstrates continued strength development for all concrete generations and both mix-design methods. The 28-day values provide the principal basis for comparing mature mechanical performance, while the 7-day results demonstrate the rate of early-age development.

4.12 Consolidated Experimental and Analytical Figures

The following figures reproduce the complete set of quantitative visualizations associated with the aggregate-packing, fresh-state, mechanical-strength, binder-efficiency and sustainability analyses. Their numerical trends correspond to the tabulated results and reported impact ranges.

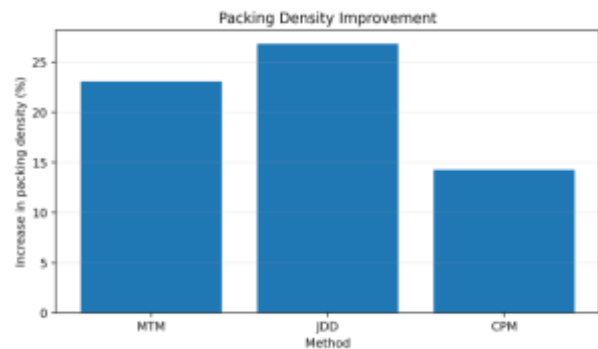


Fig. 1: Relative improvement in packing density reported for particle-packing approaches

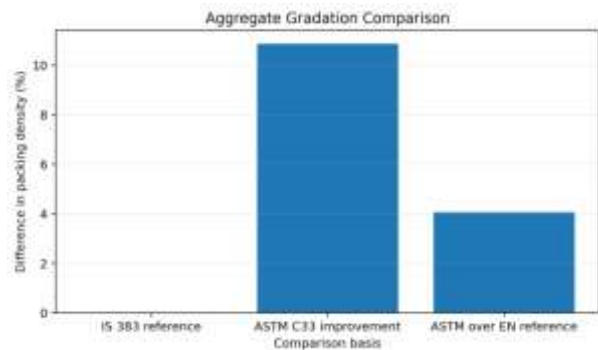


Fig. 2: Packing-density improvement relative to IS 383:2016

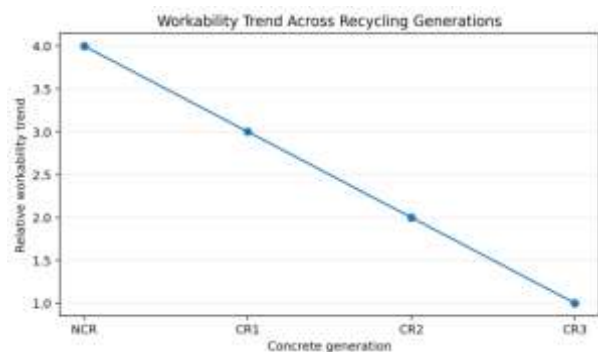


Fig. 3: Workability trend across recycling generations

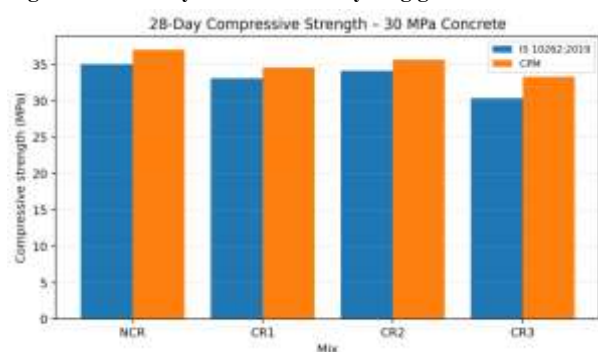


Fig. 4: 28-day compressive strength of 30 MPa concrete

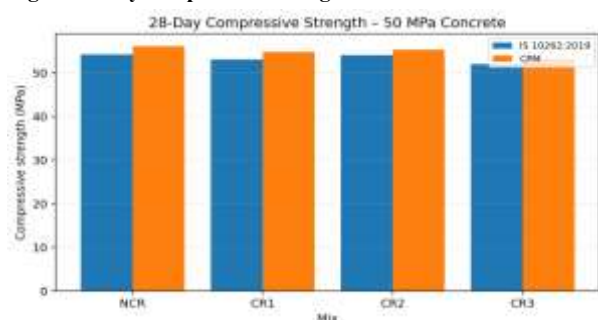


Fig. 5: 28-day compressive strength of 50 MPa concrete

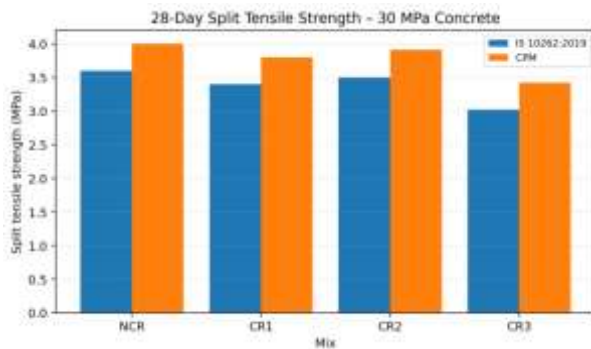


Fig. 6: 28-day split tensile strength of 30 MPa concrete

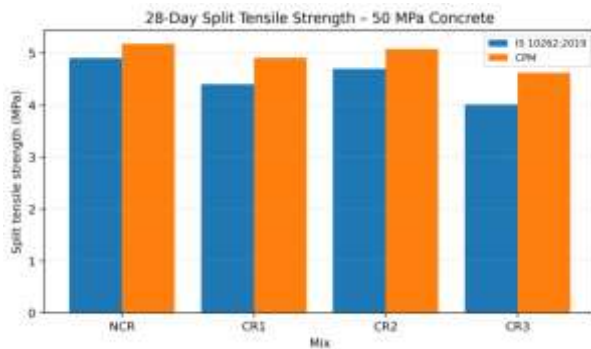


Fig. 7: 28-day split tensile strength of 50 MPa concrete

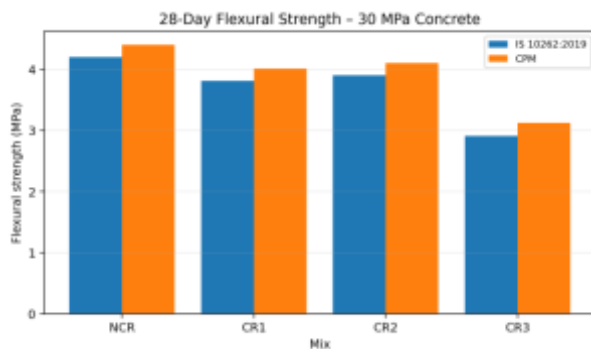


Fig. 8: 28-day flexural strength of 30 MPa concrete

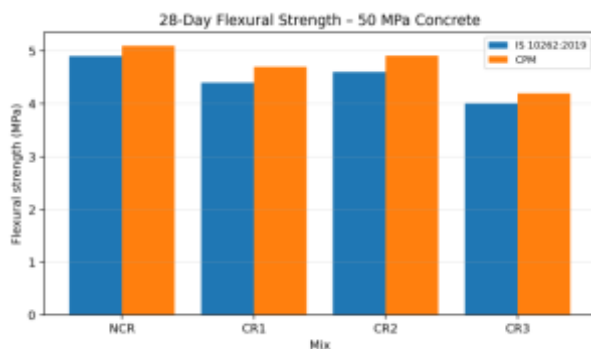


Fig. 9: 28-day flexural strength of 50 MPa concrete

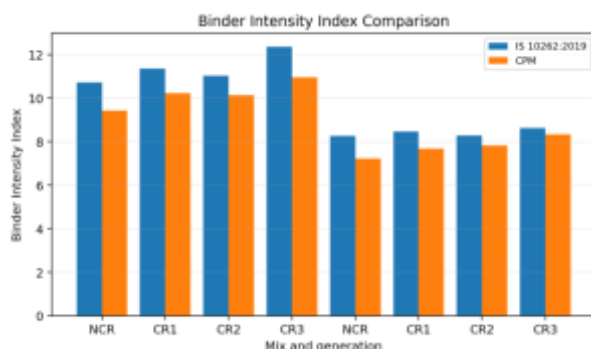


Fig. 10: Binder Intensity Index comparison

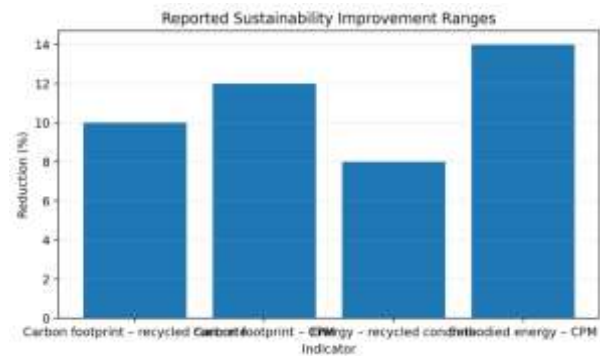


Fig. 11: Reported sustainability improvement ranges

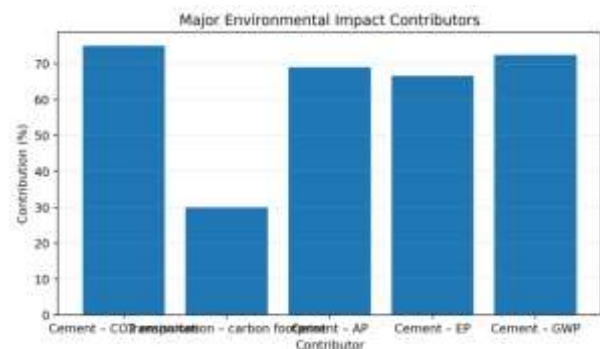


Fig. 12: Major environmental impact contributors

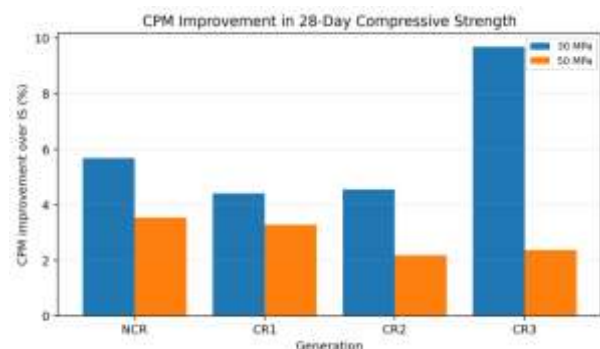


Fig. 13: CPM improvement in 28-day compressive strength

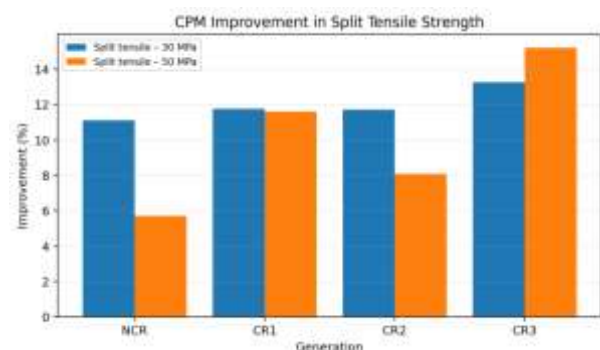


Fig. 14: CPM improvement in split tensile strength

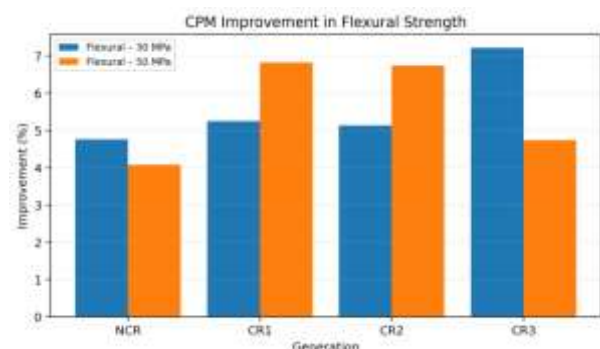


Fig. 15: CPM improvement in flexural strength

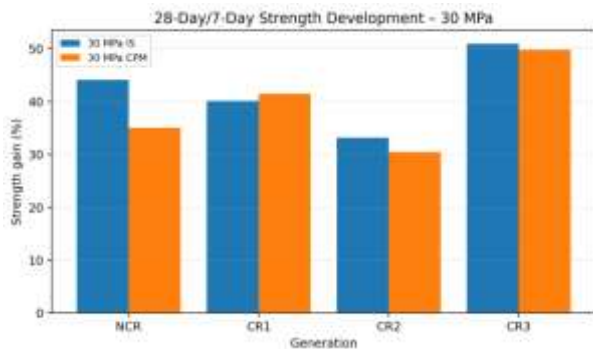


Fig. 16: 28-day/7-day strength development for 30 MPa concrete

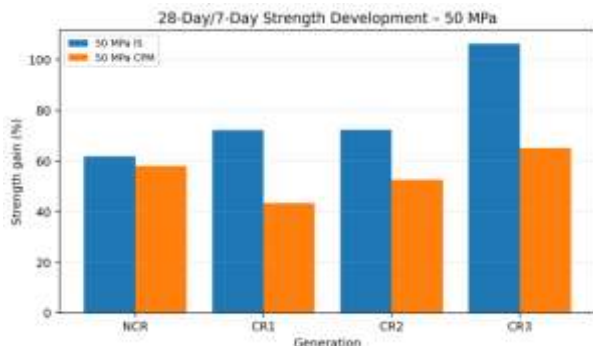


Fig. 17: 28-day/7-day strength development for 50 MPa concrete

5. CONCLUSIONS

- Successive recycling generations increase aggregate water absorption and alter density and specific gravity because of accumulated adhered mortar.
- Particle-packing methods improve aggregate packing efficiency; the reported increases over IS 383:2016 were 23.07% for MTM, 26.83% for JDD and 14.28% for CPM.
- CPM-based proportioning reduces binder intensity compared with IS 10262:2019 while maintaining the required strength levels.
- Workability decreases with recycling generation, making moisture conditioning and controlled admixture dosage important for production.
- For 30 MPa concrete, 28-day CPM compressive strengths were 37.01, 34.53, 35.65 and 33.28 MPa for NCR, CR1, CR2 and CR3.
- For 50 MPa concrete, the corresponding 28-day CPM compressive strengths were 56.14, 54.76, 55.27 and 53.23 MPa.
- Split tensile and flexural strengths followed the general compressive-strength trend, with reported relationships of approximately 8–10% and 5–7% of compressive strength, respectively.
- The reported mechanical-property relationships produced R^2 values of approximately 0.91–0.96, indicating strong correlation.
- Life-cycle assessment indicates reductions in carbon footprint and energy demand through recycling and CPM-based proportioning; cement and transportation remain the major environmental contributors.

- The combined use of multi-recycled aggregate and particle-packing-based proportioning provides a technically viable pathway for resource-efficient concrete when fresh-state and mechanical requirements are satisfied.

6. FUTURE SCOPE

- Long-term durability under chloride, sulphate, acid and freeze–thaw exposure should be evaluated using standardized durability indices.
- Reinforced concrete beams, slabs and columns should be tested to establish member-level strength, cracking, ductility and serviceability.
- Modulus of elasticity, Poisson's ratio, fracture energy and fatigue behaviour should be quantified for structural design applications.
- Aggregate treatment methods should be compared with untreated multi-recycled aggregate to quantify improvements in absorption, surface quality and interfacial transition zones.
- Field-scale batching, transport distance and regional inventory data should be incorporated into project-specific life-cycle studies.
- Optimization algorithms can be coupled with particle packing and LCA to identify mixtures that simultaneously reduce binder demand and environmental impact.

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