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Strength and sustainability of concrete with partial replacement of cement by marble powder: an experimental study to IS 10262:2019

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ABSTRACT :

Marble processing generates large volumes of calcitic fine powder, while cement production contributes 7–8 % of global CO_2 emissions. This study examines the partial replacement of cement by marble powder (0–25 % by mass, in steps of 5 %) in a superplasticised M30 concrete proportioned according to IS 10262:2019 at a constant water–cement ratio of 0.42. The fresh properties, compressive strength (7, 28 and 56 days), split tensile and flexural strength, static modulus of elasticity, ultrasonic pulse velocity (UPV) and water absorption were measured, and the data were analysed by ANOVA, Dunnett's test and regression. Marble powder shortened the setting times and reduced the slump from 100 mm to 70 mm at 25 % replacement. Strength increased up to 10 % replacement: the 28-day strength of the 10 % mix was 42.7 MPa, 7.3 % above the control (39.8 MPa; Dunnett $p < 0.01$), the 15 % mix matched the control, and the 20 % and 25 % mixes were 7.0 % and 15.6 % lower. Split tensile strength, flexural strength, modulus, UPV and water absorption followed the same pattern. A quadratic model ($R^2 = 0.925$) placed the optimum at 8.2 % replacement. Flexural strength and modulus were consistent with IS 456:2000 expressions. The cost and embodied CO_2 per MPa of strength were lowest at 10 % replacement, 10.5 % and 15.5 % below the control. Replacing 10 % of cement (up to 15 % at equal strength) with marble powder is therefore technically and environmentally advantageous.

Keywords: marble powder; partial cement replacement; IS 10262:2019; compressive strength; ultrasonic pulse velocity; embodied CO_2

1. Introduction

Concrete is the most widely used construction material, and the clinker in its cement binder is responsible for about 0.8–0.9 t of CO_2 per tonne of cement (Andrew, 2018; Scrivener et al., 2018). Partial replacement of cement by finely ground mineral additions is the most direct way to lower this burden. Fly ash and slag are established but unevenly available; a locally abundant alternative is marble powder, a calcitic by-product of sawing and polishing that is commonly estimated at 20–30 % of processed stone (Corinaldesi et al., 2010; Rana et al., 2015). It is usually dumped, where it causes dust, soil and water pollution.

Fine calcite is not inert in cement paste. It provides nucleation sites for hydration products, accelerates alite hydration, improves particle packing and reacts slowly with aluminate phases to form carboaluminates (Soroka and Stern, 1976; Lothenbach et al., 2008, 2011). At low levels these effects can offset the dilution of reactive clinker, whereas at high levels dilution dominates (Tennis et al., 2011). Studies on marble powder broadly agree on this pattern, with reported optima near 10 % (Shirule et al., 2012; Aliabdo et al., 2014; Singh et al., 2017), but the optimum depends on powder fineness, water–binder ratio and admixture use (Corinaldesi et al., 2010; Talah et al., 2015). Most work reports only 28-day compressive strength, uses foreign or superseded mix-design methods, and omits statistical confirmation and strength-normalised cost and CO_2 appraisal.

This paper addresses these gaps for a superplasticised M30 concrete designed to the revised IS 10262:2019. Cement was replaced by marble powder at 0–25 %, and fresh, mechanical and durability-related properties were measured, tested statistically and compared with the expressions of IS 456:2000. Cost and embodied CO_2 were expressed per unit strength to identify the replacement level that is best technically and environmentally.

2. Materials and methods

2.1 Materials

Ordinary Portland cement (OPC) of 43 grade (IS 269:2015) was used; its tests (IS 4031) met all requirements (initial and final setting 95 and 215 min, soundness 1.5 mm, 28-day mortar strength 47.2 MPa). Marble powder was collected dry from a cutting and polishing unit, oven-dried at 105 °C, sieved through 150 µm and stored sealed. It is predominantly calcite (52.4 % CaO, 43.2 % loss on ignition) with a median size of 18.5 µm, finer than the cement (Table 1). River sand of Zone II (fineness modulus 2.76) and crushed granite of 20 mm nominal size (fineness modulus 6.92) conforming to IS 383:2016 were used. A polycarboxylate-ether superplasticiser (IS 9103:1999, relative density 1.08) was dosed at 1.0 % of the binder mass (3.76 kg/m³) in all mixes.

Table 1. Properties of cement and marble powder

Property	OPC 43	Marble powder	Aggregates (FA / CA)
Specific gravity	3.15	2.71	2.62 / 2.68
Blaine fineness (m²/kg)	295	365	–
Median size D_{50} (µm)	24.0	18.5	–
CaO / SiO_2 (%)	62.8 / 20.6	52.4 / 1.4	Water absorption 1.2 / 0.6 %
Al_2O_3 / Fe_2O_3 (%)	5.1 / 3.4	0.4 / 0.2	Fineness modulus 2.76 / 6.92
MgO / SO_3 (%)	1.9 / 2.1	1.1 / 0.1	Crushing / impact value (CA) 21.4 / 17.8 %
Loss on ignition (%)	2.0	43.2	Bulk density, compacted 1690 / 1620 kg/m³

FA: fine aggregate; CA: coarse aggregate. Chemical composition by XRF.

2.2 Mix proportioning

The control mix was designed for M30 (moderate exposure, 20 mm aggregate, 100 mm slump, superplasticiser) following IS 10262:2019. The target mean strength is given by Eq. (1), with s = 5.0 N/mm²:

$$f_{target} = f_{ck} + 1.65\, s = 30 + 1.65 \times 5.0 = 38.25 \text{ N/mm}^2 \quad (1)$$

A free water–cement ratio of 0.42 was adopted. The water content, 186 × 1.06 × (1 − 0.20) = 158 kg/m³, gives a cement content of 376 kg/m³, within the limits of IS 456:2000 (300–450 kg/m³). With a coarse-aggregate volume fraction of 0.636 and 1 % entrapped air, the aggregates are 1209 kg/m³ (coarse) and 676 kg/m³ (fine). Six mixes (MP0–MP25, where the number is the percentage of cement replaced by mass) were prepared with constant water, aggregates and superplasticiser, so that the water–binder ratio is 0.42 in all mixes (Table 2).

Table 2. Mix proportions (kg/m³, SSD) and fresh properties

Mix	Cement	Marble powder	Water	Fine agg.	Coarse agg.	SP	Slump (mm)	Comp. factor	Fresh density (kg/m³)
MP0	376.0	0.0	158	676	1209	3.76	100	0.93	2478
MP5	357.2	18.8	158	676	1209	3.76	98	0.92	2475
MP10	338.4	37.6	158	676	1209	3.76	94	0.91	2472
MP15	319.6	56.4	158	676	1209	3.76	88	0.90	2468
MP20	300.8	75.2	158	676	1209	3.76	80	0.88	2462
MP25	282.0	94.0	158	676	1209	3.76	70	0.86	2455

SP: superplasticiser. Water–binder ratio = 0.42 for all mixes.

2.3 Specimens and testing

Concrete was mixed in a pan mixer (dry blending of cement and powder, aggregates, then water with superplasticiser), compacted on a vibrating table and water-cured at 27 ± 2 °C after demoulding at 24 h. Per mix, nine 150 mm cubes (7, 28, 56 days), three 150 × 300 mm cylinders each for split tensile strength and modulus of elasticity, three 100 × 100 × 500 mm prisms for flexural strength and three 100 mm cubes for water absorption were cast (126 specimens in total). Normal consistency and setting time followed IS 4031 (Parts 4, 5); slump and compaction factor IS 1199 (Part 2):2018; compressive strength IS 516 (Part 1/Sec 1):2021 in a 2000 kN digital machine; split tensile strength IS 5816:1999; UPV IS 516 (Part 5/Sec 1):2018 by direct transmission; and water absorption ASTM C642. Each value is the mean of three specimens.

2.4 Statistical analysis

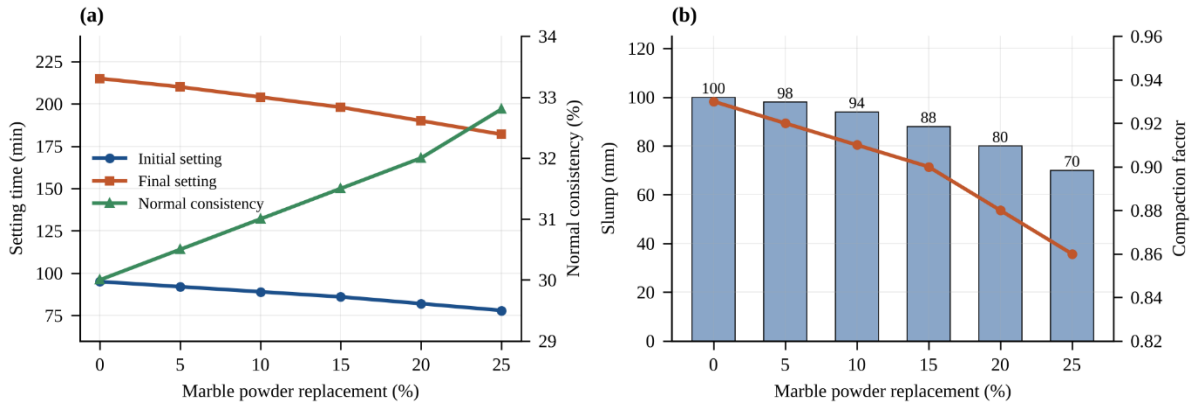
The effect of replacement level on 28-day compressive strength was tested by one-way ANOVA (six treatments, three replicates), followed by Dunnett's test against the control (Montgomery, 2017). A quadratic model $f_c = a + bx + cx^2$ was fitted by least squares to all individual cube results at each age, the optimum being $x_{opt} = -b/(2c)$. Power laws between strength properties were fitted on log-transformed data. The strength activity index (SAI) is the strength of a mix as a percentage of the control at the same age.

3. Results and discussion

3.1 Paste and fresh properties

Normal consistency rose from 30.0 % to 32.8 % and the initial and final setting times fell from 95 and 215 min to 78 and 182 min as replacement increased to 25 % (Fig. 1a), consistent with nucleation of silicate hydrates on calcite and with the larger surface area of the finer powder (Lothenbach et al., 2011). All values satisfy IS 269:2015. Slump decreased monotonically from 100 to 70 mm and the compaction factor from 0.93 to 0.86 (Fig. 1b; Table 2), because water and superplasticiser were fixed while the binder surface area increased (Topçu et al., 2009). Mixes up to 15 % retained ≥ 88 mm slump; 20 % and 25 % would need more superplasticiser to restore 100 mm.

Fig. 1. Effect of marble powder on (a) normal consistency and setting times of paste, and (b) slump and compaction factor of concrete.



3.2 Compressive strength

The control mix reached 39.8 MPa at 28 days, above the target mean of 38.25 MPa, confirming the IS 10262:2019 design (Table 3, Fig. 2a). Strength rose with marble powder up to 10 % at all ages: the 28-day strength of MP10 was 42.7 MPa, 7.3 % above the control. MP15 (40.2 MPa) equalled the control, whereas MP20 (37.0 MPa) and MP25 (33.6 MPa) fell 7.0 % and 15.6 % below it. The coefficients of variation were ≤ 3 %. The behaviour reflects two opposing mechanisms: the filler and nucleation effect of fine calcite raises strength at low replacement, while removal of reactive clinker lowers it; the former prevails to about 10 % and the latter beyond 15 % (Soroka and Stern, 1976; Lothenbach et al., 2008). The 7-day strength was 63.4–68.8 % of the 28-day strength, lower at higher replacement, and the 28- to 56-day gain of 9–11 % was similar for all mixes, so later hydration of the cement fraction was unimpaired. The SAI at 28 days was 107.3 % for MP10 and exceeded 84 % even for MP25, above the 75 % limit used for mineral additions in ASTM C618. Using the acceptance criterion of IS 456:2000 (mean ≥ f_{ck} + 0.825s = 34.1 MPa), MP25 (33.6 MPa) is marginally non-compliant, which limits replacement to 20 % for this design.

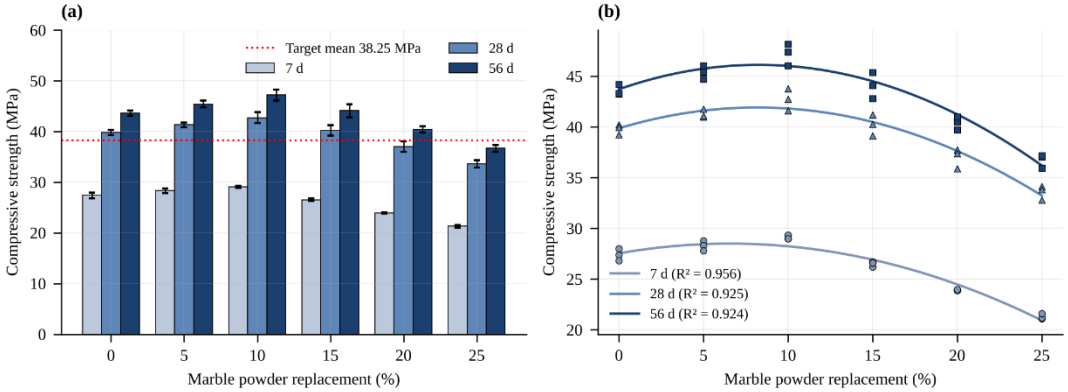


Fig. 2. (a) Compressive strength at 7, 28 and 56 days (mean ± SD), and (b) quadratic regression of strength on replacement level.

The quadratic fit explained more than 92 % of the variance at every age (R^2 = 0.956, 0.925 and 0.924 at 7, 28 and 56 days; Fig. 2b). At 28 days, f_c = 39.86 + 0.502x − 0.0307x^2 gives a maximum of 41.9 MPa at x = 8.2 %; since 10 % was the best mix tested, the optimum lies between 5 % and 10 %.

Table 3. Mechanical and durability-related properties (mean; SD in parentheses for 28-day compressive strength)

Mix	7 d (MPa)	28 d (MPa)	56 d (MPa)	Split tensile (MPa)	Flexural (MPa)	E (GPa)	UPV (km/s)	Absorption (%)	SAI 28 d (%)
MP0	27.4	39.8 (0.52)	43.6	3.14	4.98	31.8	4.42	2.84	100.0
MP5	28.3	41.3 (0.42)	45.4	3.26	5.15	32.3	4.46	2.71	103.8
MP10	29.1	42.7 (1.08)	47.2	3.39	5.34	33.1	4.53	2.58	107.3
MP15	26.5	40.2 (1.04)	44.1	3.19	5.05	31.9	4.44	2.77	101.0
MP20	23.9	37.0 (0.99)	40.4	2.96	4.70	30.2	4.32	3.10	93.0
MP25	21.3	33.6 (0.71)	36.7	2.72	4.34	28.7	4.19	3.46	84.4

E: static modulus of elasticity; SAI: strength activity index (28-day strength relative to MP0).

3.3 Tensile and flexural strength, modulus and UPV

Split tensile strength, flexural strength and modulus followed compressive strength (Table 3, Fig. 3a). From MP0 to MP10 the split tensile strength increased by 8.0 % and the flexural strength by 7.2 %; at MP25 they were 13.4 % and 12.9 % below the control, consistent with a denser interfacial transition zone at low replacement. The measured flexural strength exceeded the IS 456:2000 value 0.7$\sqrt{f_{ck}}$ (computed with the measured cube strength) by 7–17 %, and the measured modulus was within 1 % of 5000$\sqrt{f_{ck}}$ for every mix (Fig. 4b), so the code expressions remain applicable. Across the six mixes, $f_{sp} = 0.115 f_c^{0.90}$ (R^2 = 0.997) and $f_{cr} = 0.218 f_c^{0.85}$ (R^2 = 0.998) (Fig. 3b); these are valid only for the strength range studied (33–43 MPa). UPV ranged from 4.19 to 4.53 km/s and rose linearly with strength (V = 0.0366f_c + 2.963, R^2 = 0.996; Fig. 3c). By the classification of IS 516 (Part 5/Sec 1):2018, MP10 is ‘excellent’ (> 4.5 km/s) and all other mixes are ‘good’.

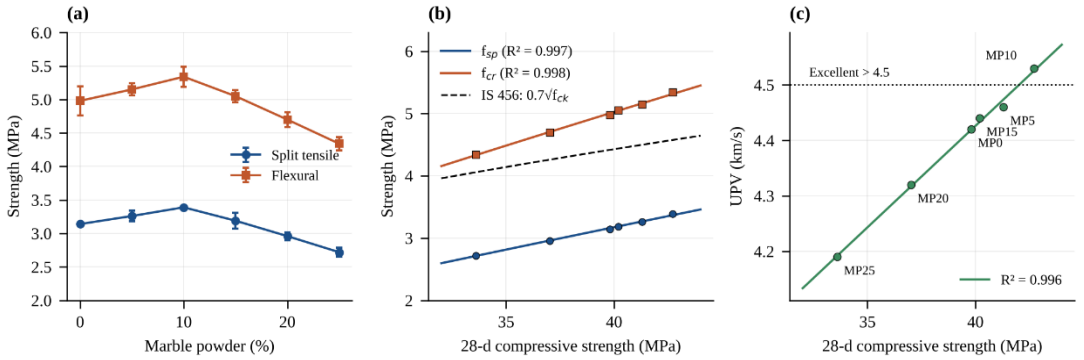


Fig. 3. (a) Split tensile and flexural strength, (b) their relation to compressive strength and to the IS 456:2000 estimate, and (c) UPV versus compressive strength at 28 days.

3.4 Water absorption

Water absorption fell from 2.84 % (MP0) to 2.58 % (MP10), 9.2 % lower, indicating pore refinement by the filler, and then rose to 3.46 % at MP25 (21.8 % above the control) as cement dilution made the matrix more porous (Fig. 4a). Hardened density decreased slightly (2452 to 2428 kg/m³) because marble powder is lighter than cement. Only absorption and UPV were used as durability indicators; resistance to chlorides, sulphates and carbonation, which depends on the hydrated phase assemblage, still needs verification.

3.5 Statistical significance

ANOVA showed a highly significant effect of replacement on 28-day strength ($F(5, 12) = 46.8$, $p < 0.001$). Dunnett's test (Table 4) confirmed that MP10 was significantly stronger and MP20 and MP25 significantly weaker than the control, whereas MP5 and MP15 were statistically equivalent to it. Up to 15 % of cement can therefore be replaced with no significant strength loss.

3.6 Cost and embodied CO_2

Unit rates (INR/kg: cement 7.0, marble powder 1.0, sand 1.5, aggregate 1.4, superplasticiser 90) and CO_2 factors (kg CO_2/kg: cement 0.90, marble powder 0.02, sand 0.005, aggregate 0.0075, superplasticiser 0.70) are assumed and should be updated for a project. Each 5 % of cement replaced reduced the material cost by about INR 113/m³ and the embodied CO_2 by 16.6 kg/m³ (Table 4). Per MPa of strength, however, both indicators have a minimum at 10 % (Fig. 4c): 127.6 INR and 7.50 kg CO_2 per MPa, 10.5 % and 15.5 % below the control, and rise again at 20–25 % where the strength loss outweighs the savings.

Table 4. Statistical comparison with the control, cost and embodied CO_2

Mix	Δ28-d strength vs MP0 (%)	Dunnett p	Cost (INR/m³)	CO_2 (kg/m³)	Cost per MPa (INR)	CO_2 per MPa (kg)	Cement per MPa (kg)
MP0	–	–	5677	353.5	142.6	8.88	9.45
MP5	+3.8	0.162	5564	336.9	134.7	8.16	8.65
MP10	+7.3	0.004	5451	320.4	127.6	7.50	7.92
MP15	+1.0	0.962	5339	303.8	132.8	7.56	7.95
MP20	-7.0	0.006	5226	287.3	141.2	7.76	8.13
MP25	-15.6	< 0.001	5113	270.8	152.2	8.06	8.39

Dunnett p-values from 28-day cube strengths (3 replicates per mix). Costs and CO_2 use the assumed rates and factors stated in Section 3.6.

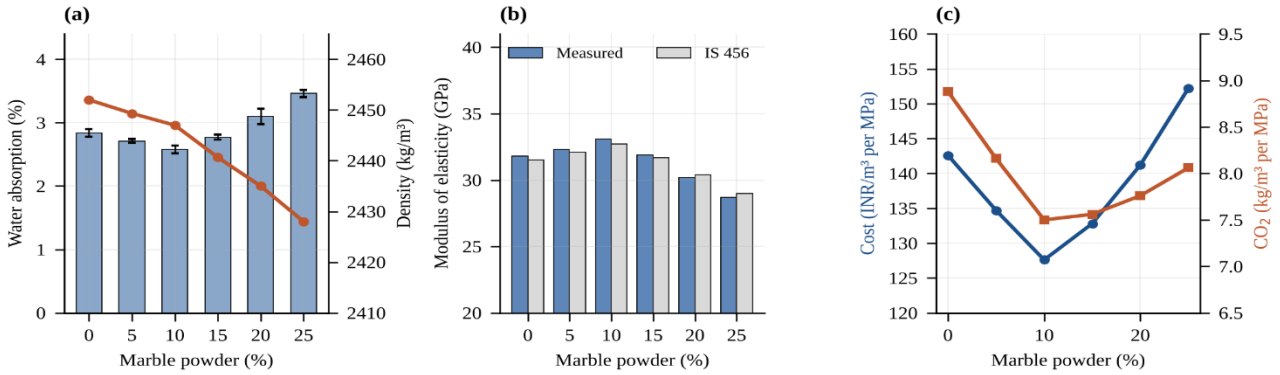


Fig. 4. (a) Water absorption and hardened density, (b) modulus of elasticity compared with $5000\sqrt{f_{ck}}$ (IS 456:2000), and (c) cost and embodied CO_2 per MPa of 28-day strength.

4. Conclusions

For an M30 concrete proportioned by IS 10262:2019 with w/c = 0.42 and constant superplasticiser dosage, replacing cement with a fine calcitic marble powder (0–25 %) led to the following conclusions.

1. Marble powder increased water demand and shortened setting; slump fell from 100 to 70 mm at 25 %, and was ≥ 88 mm up to 15 %.
2. Strength peaked at 10 % replacement (42.7 MPa at 28 days, +7.3 %, significant), equalled the control at 15 % and fell 7.0 % and 15.6 % at 20 % and 25 %. The regression optimum was 8.2 %; MP25 did not meet the IS 456 acceptance criterion.
3. Tensile and flexural strength, modulus and UPV followed the same trend; flexural strength and modulus were consistent with, and on the safe side of, IS 456:2000. UPV rated the 10 % mix 'excellent' and the others 'good'.
4. Water absorption was lowest at 10 % (2.58 %), indicating a refined pore structure, and highest at 25 % (3.46 %).
5. Cost and CO_2 per MPa were lowest at 10 % (−10.5 % and −15.5 %). The recommended replacement is 10 %, with up to 15 % acceptable where equal strength and maximum cement saving are the aim.

Limitations: a single powder source, one water–binder ratio and no microstructural or long-term durability tests. Future work should add XRD/SEM/TGA, chloride, sulphate and carbonation resistance, powder fineness effects and ternary binders with fly ash or slag.

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