

Metakaolin-Modified Hooked-End Steel Fibre Reinforced M60 Concrete: Strength Optimisation, Code Validation and Robust Multi-Criteria Mix Selection

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Highlights

- 10% metakaolin raised 28-d compressive, splitting and flexural strength of M60 concrete by 15.6%, 16.7% and 28.8%.
- Quadratic models place the strength optimum at 10–13% metakaolin; IS 456 underestimates flexural strength by up to 29%.
- 1.5% hooked-end fibres of $l/d = 60$ raised flexural strength to 11.09 MPa, 88% above the control.
- At equal dosage, $l/d = 60$ fibres outperformed $l/d = 80$ fibres by about 10%; the reinforcing index did not rank the mixes.
- MK10 ranked first in 95.7% of 20,000 random weightings of a five-criterion performance index.

Abstract

Metakaolin (MK) and steel fibres are usually studied separately in high-strength concrete, although the case for specifying them in an M60 mix depends on how they work together and on how much cement they save. In this study 0–20% of a 500 kg/m³ OPC-43 binder was replaced with MK at a constant water–binder ratio of 0.28, and the best-performing matrix was reinforced with hooked-end steel fibres at 1.0% and 1.5% by volume and aspect ratios (l/d) of 60 and 80. Slump, 7- and 28-day compressive strength and 28-day splitting tensile and flexural strength were measured. The results were analysed with second-order regression, comparison with five code and model-code tensile expressions, a 2² factorial analysis of the fibre variables, CO₂-intensity indicators and a five-criterion performance index (PI) tested against 20,000 random weight vectors. A 10% MK replacement gave the highest 28-day compressive (70.4 MPa, +15.6%), splitting tensile (4.2 MPa, +16.7%) and flexural (7.6 MPa, +28.8%) strengths, while regression placed the optimum between 10% and 13% MK. IS 456 underestimated flexural strength by 8–29%, whereas ACI 363R predicted it within $\pm 10\%$. MK10 reduced cement intensity by 22% and CO₂ intensity by about 18%, and ranked first in 95.7% of PI weightings. Adding 1.5% fibres of $l/d = 60$ raised flexural strength to 11.09 MPa, 45.9% above MK10 and 88.0% above the control. Increasing l/d from 60 to 80 reduced flexural strength by 1.02 MPa on average, more than the 0.87 MPa gained by increasing fibre content from 1.0% to 1.5%; the 60 mm fibres exceeded the length limit for the 100 mm prisms, which is a likely contributor.

Keywords: metakaolin; steel fibre reinforced concrete; high-strength concrete; fibre aspect ratio; flexural strength; multi-criteria decision making; embodied CO₂

1. Introduction

Portland cement clinker is the main source of embodied CO₂ in concrete, and replacing part of it with supplementary cementitious materials (SCMs) is one of the most practical ways of making a lower-carbon binder without changing how concrete is produced or placed [1,2]. Calcined clays are attractive because kaolinitic clays are widely available and can be activated at far lower temperatures than those required for clinker [3,4]. Metakaolin (MK), the high-purity product of this calcination, reacts with portlandite to form additional C–S–H and aluminate hydrates, refines the pore structure and densifies the interfacial transition zone (ITZ) [5–7]. In high-strength concrete, MK typically increases compressive strength and reduces chloride diffusivity, with optimum replacement levels between about 10% and 20% depending on w/b ratio, MK purity and curing age [8–12].

High-strength matrices are, however, more brittle than normal-strength concrete. Hooked-end steel fibres bridge cracks and raise tensile and flexural capacity, but the size of the gain depends on fibre content, geometry, tensile strength and matrix strength [13–18]. Higher fibre aspect ratios have generally improved flexural performance in normal-strength concrete [19,20], whereas in high-strength concrete the stronger fibre–matrix bond can shift the failure mode from fibre pull-out towards fibre rupture, so that geometry and fibre strength must be matched to the matrix [21,22]. Fibre distribution and orientation, which depend on workability and specimen size, also govern the measured response [23,24].

The two additions have been combined before. Güneyisi et al. found that 10% MK and hooked-end fibres of different aspect ratios significantly affected compressive, flexural, splitting and bond strength at two water–binder ratios [25]. Dou et al. reported that MK raised the long-term compressive strength of fibre-reinforced concrete more than the fibres did, while the fibres mainly added toughness [26]. Similar matrix–fibre synergies have been reported for silica fume [27,28]. Three gaps nevertheless remain. Few studies have applied the combination to an M60 mix proportioned to IS 10262:2019 [29]; the optimum mix is still usually chosen on compressive strength alone, without accounting for workability or cement saving, and without testing whether the choice is robust to the weights given to each criterion; and the applicability of code expressions for tensile and flexural strength to MK-modified high-strength concrete has not been checked.

This study therefore (i) measures the effect of 5–20% MK replacement on the fresh and hardened properties of M60 concrete and models the strength–dosage relationship; (ii) compares measured tensile and flexural strengths with IS 456, ACI 318, ACI 363R and fib Model Code 2010 expressions; (iii) quantifies the main and interaction effects of hooked-end fibre content and aspect ratio on the flexural strength of the optimum MK matrix; and (iv) selects the most balanced mix with a multi-criteria performance index whose ranking is tested against random weightings and complemented by cement- and CO₂-intensity indicators.

2. Materials and Methods

2.1 Materials

The binder was OPC-43 conforming to IS 8112:2013 [30], and the MK was an alumina–silica-rich calcined clay ($\text{SiO}_2 + \text{Al}_2\text{O}_3 = 92.6\%$). Table 1 lists the properties of the binders, aggregates, admixture and steel fibres, together with the fixed mix parameters and the test programme.

Table 1. Constituent materials, steel fibre characteristics, fixed mix parameters and test programme.

Item	Property / condition	Value or description
A. Binders		
OPC-43 (IS 8112:2013)	Specific gravity; normal consistency	3.10; 27%
	Initial / final setting time	149 min / 257 min
Metakaolin	Specific gravity	2.50
	Oxide composition (%)	SiO_2 54.30, Al_2O_3 38.30, Fe_2O_3 4.28, CaO 0.39, MgO 0.08, K_2O 0.50, SO_3 0.22, LOI 0.68
B. Aggregates and admixture		
Fine aggregate	Type; grading; FM	Natural river sand; Zone II (IS 383), 55.6% passing 600 μm ; FM 2.52
Coarse aggregate	Type; blend; water absorption; FM	Crushed angular; 20:10 mm = 60:40; 0.20% and 0.35%; FM 7.01 and 6.66
Superplasticiser	Type; specific gravity	Polycarboxylate ether (IS 9103); 1.20
C. Hooked-end steel fibres (density 7850 kg/m³)		
SF-60	l; d; l/d; fibres per m ³ at 1.0 / 1.5%	45 mm; 0.75 mm; 60; ≈ 0.50 / 0.75 million
SF-80	l; d; l/d; fibres per m ³ at 1.0 / 1.5%	60 mm; 0.75 mm; 80; ≈ 0.38 / 0.57 million
Dosage	$V_f = 1.0\% / 1.5\%$	78.5 kg/m ³ / 117.8 kg/m ³
D. Fixed mix parameters		
Binder; aggregates	Binder; coarse; fine (batched)	500; 1120; 808 kg/m ³
Water; air	Net water; entrapped air	141.0–142.0 kg/m ³ ; 2%
E. Test programme		
Workability	Slump test (IS 1199)	Immediately after mixing; design target 75 mm
Compressive strength	150 mm cubes, IS 516	7 and 28 days; 3000 kN machine, 8–10 kN/s
Splitting tensile strength	150 $\times$ 300 mm cylinders, IS 5816	28 days; Eq. (1)
Flexural strength	100 $\times$ 100 $\times$ 500 mm prisms, two-point loading	28 days; 400 mm span; Eq. (2)

Fibre counts are calculated from fibre geometry (single-fibre volume $\pi d^2 l / 4$) and are given for interpretation; they were not measured. Fibre tensile strength was not reported by the supplier.

2.2 Mix proportions

Mixes were proportioned to IS 10262:2019 [29] for M60 with a total binder content of 500 kg/m³ and w/b = 0.28. MK replaced 0, 5, 10, 15 and 20% of the cement by mass (MK0–MK20). The superplasticiser dose was raised from 0.60% to 0.80% of the binder as the MK content increased,

and the net water was adjusted for the water in the admixture. In the second stage the MK level giving the best plain-concrete performance (MK10) was reinforced with SF-60 or SF-80 fibres at $V_f = 1.0\%$ and 1.5% . These mixes are designated MK10-F1.0-A60, MK10-F1.0-A80, MK10-F1.5-A60 and MK10-F1.5-A80.

2.3 Specimen preparation and testing

Specimens were demoulded after 24 h and cured in water at 27 ± 2 °C until testing. Three specimens were tested for each property and age, and the mean is reported. Splitting tensile strength f_{st} and flexural strength f_b were calculated as

$$f_{st} = 2P / (\pi DL) \quad (1)$$

$$f_b = Pl / (bd^2) \quad (2)$$

where P is the failure load, D and L are the cylinder diameter and length, l is the span, and b and d are the width and depth of the prism.

2.4 Analysis methods

Regression. Each strength property of the plain MK mixes was fitted with a quadratic in MK content m (%), $y = \beta_0 + \beta_1 m + \beta_2 m^2$, and the stationary point $m_{opt} = -\beta_1/(2\beta_2)$ was taken as the model optimum. With five mixes and two residual degrees of freedom, the significance of each fit was assessed with the F-test.

Code expressions. Measured flexural strength was compared with IS 456 ($0.7\sqrt{f_{ck}}$, cube strength) [31], ACI 318 ($0.62\sqrt{f'_c}$) [32] and ACI 363R ($0.94\sqrt{f'_c}$) [33], and splitting tensile strength with ACI 363R ($0.59\sqrt{f'_c}$) [33] and the fib Model Code 2010 mean tensile strength for grades above C50/60, $f_{ctm} = 2.12 \ln(1 + f_{cm}/10)$ [34]. Cylinder strength was estimated as 0.8 times the measured cube strength, the approximate ratio for this strength class [35]; the conversion is an assumption and is applied identically to all mixes.

Fibre parameters. The reinforcing index was $RI = V_f l/d$. The number of fibres per unit volume was $N_V = V_f/(\pi d^2 l/4)$, and the number of fibres crossing a unit area of a plane was estimated as $N_A = \alpha \cdot V_f/A_f$, where $A_f = \pi d^2/4$ and α is the orientation factor (0.5 for three-dimensional random orientation) [23]. Main and interaction effects of V_f (1.0, 1.5%) and l/d (60, 80) were calculated as a 2^2 factorial design [36]; without individual replicate data, their significance could not be tested.

Performance index. The plain MK mixes were ranked on five criteria: 28-day compressive, splitting tensile and flexural strength, slump, and cement reduction. Each criterion was min–max normalised to a score S_i between 0 (worst) and 1 (best), and $PI = \sum w_i S_i$ [37]. Two predefined weightings were used: equal weights ($w_i = 0.20$) and a sustainability-led scheme with 0.40 on cement reduction and 0.15 on each other criterion. Slump was not recorded for MK5 and MK15; it was estimated by linear interpolation between the adjacent measured mixes (117.5 and 107.5 mm). To test robustness, 20,000 weight vectors were drawn from a uniform Dirichlet distribution and the frequency with which each mix ranked first was recorded.

Eco-efficiency. Cement intensity was expressed as kg of cement per m³ per MPa of 28-day compressive strength [38]. CO₂ intensity was calculated with emission factors of 0.9 kg CO₂-eq/kg for OPC and 0.40 kg CO₂-eq/kg for MK, the midpoints of the reported ranges of 0.8–1.0 and 0.09–0.7 kg CO₂-eq/kg, respectively [39]; the bounds of these ranges were used to give an uncertainty band. Aggregates, admixture, fibres and transport were excluded, so the indicator compares binders only.

3. Results and Discussion

3.1 Workability

Table 2. Mix proportions, fresh and hardened properties, derived ratios and performance index of the plain MK concretes.

Property	MK0	MK5	MK10	MK15	MK20
A. Batched proportions (kg/m ³)					
Cement / MK	500 / 0	475 / 25	450 / 50	425 / 75	400 / 100
Water	142.00	141.75	141.40	141.20	141.00
SP, kg (% of binder)	3.00 (0.60)	3.25 (0.65)	3.60 (0.72)	3.80 (0.76)	4.00 (0.80)
w/b; w/c	0.28; 0.284	0.28; 0.298	0.28; 0.314	0.28; 0.332	0.28; 0.353
B. Fresh property					
Slump (mm)	120	(117.5) ^a	115	(107.5) ^a	100
C. Compressive strength (MPa)					
7 days	46.2	51.3 (+11.0%)	53.4 (+15.6%)	52.3 (+13.2%)	50.2 (+8.7%)
28 days, f_c	60.9	64.8 (+6.4%)	70.4 (+15.6%)	68.3 (+12.2%)	67.2 (+10.3%)
$f_{c,7}/f_{c,28}$	0.76	0.79	0.76	0.77	0.75
Cement intensity (kg·m ⁻³ ·MPa ⁻¹)	8.21	7.33	6.39	6.22	5.95
D. Tensile strengths, 28 d (MPa)					
f_{st}	3.6	3.9 (+8.3%)	4.2 (+16.7%)	3.8 (+5.6%)	3.7 (+2.8%)
f_b	5.9	6.9 (+16.9%)	7.6 (+28.8%)	7.2 (+22.0%)	6.6 (+11.9%)
f_{st}/f_c (%); $f_b/\sqrt{f_c}$	5.91; 0.76	6.02; 0.86	5.97; 0.91	5.56; 0.87	5.51; 0.81
E. Normalised scores and performance index					
Compressive; tensile; flexural	0.00; 0.00; 0.00	0.41; 0.50; 0.59	1.00; 1.00; 1.00	0.78; 0.33; 0.76	0.66; 0.17; 0.41
Slump; cement reduction	1.00; 0.00	0.88; 0.25	0.75; 0.50	0.38; 0.75	0.00; 1.00
PI, equal weights (rank)	0.20 (5)	0.52 (3)	0.85 (1)	0.60 (2)	0.45 (4)
PI, 40% cement weight (rank)	0.15 (5)	0.46 (4)	0.76 (1)	0.64 (2)	0.59 (3)

^a Not recorded; linearly interpolated between adjacent mixes for the performance index only. Percentages are changes relative to MK0.

Slump fell from 120 mm (MK0) to 115 mm (MK10) and 100 mm (MK20), although the superplasticiser dose rose by a third (Table 2). This reflects the high fineness, plate-like morphology and water demand of MK [5,6]. All recorded slumps remained above the 75 mm design target, so MK up to 20% did not compromise placeability of the plain mixes. The slump of the fibre-reinforced mixes was not recorded; since hooked-end fibres at 1.0–1.5% usually reduce slump substantially, this must be measured before the fibre mixes are specified (Section 4).

3.2 Compressive strength

Compressive strength increased up to 10% MK and then declined (Fig. 1a). MK10 reached 53.4 MPa at 7 days and 70.4 MPa at 28 days, a 15.6% gain over the control at both ages. The 7/28-day ratio stayed between 0.75 and 0.79, showing that the pozzolanic contribution was already active at early age, as is typical of the fast-reacting MK [8,9]. Beyond 10%, the additional MK has less portlandite available and mainly dilutes the clinker [5,25]; MK15 (68.3 MPa) and MK20 (67.2 MPa) nevertheless remained 10–12% above the control. Only MK10 and MK15 exceeded the IS 10262:2019 target mean strength of 68.25 MPa; the control itself (60.9 MPa) met the characteristic strength but not the target mean.

The quadratic fits (Fig. 1a) placed the stationary points at 11.8% MK for 7-day strength ($R^2 = 0.98$, $p = 0.016$) and 13.2% MK for 28-day strength ($R^2 = 0.91$, $p = 0.089$). The 28-day optimum is therefore slightly above the tested 10% level, which suggests that a 12.5% replacement could perform at least as well as MK10 while saving more cement. Because the 28-day fit is significant only at $\alpha = 0.10$, this should be confirmed experimentally. The range of 10–13% is consistent with optima reported for high-strength MK concretes [9–11].

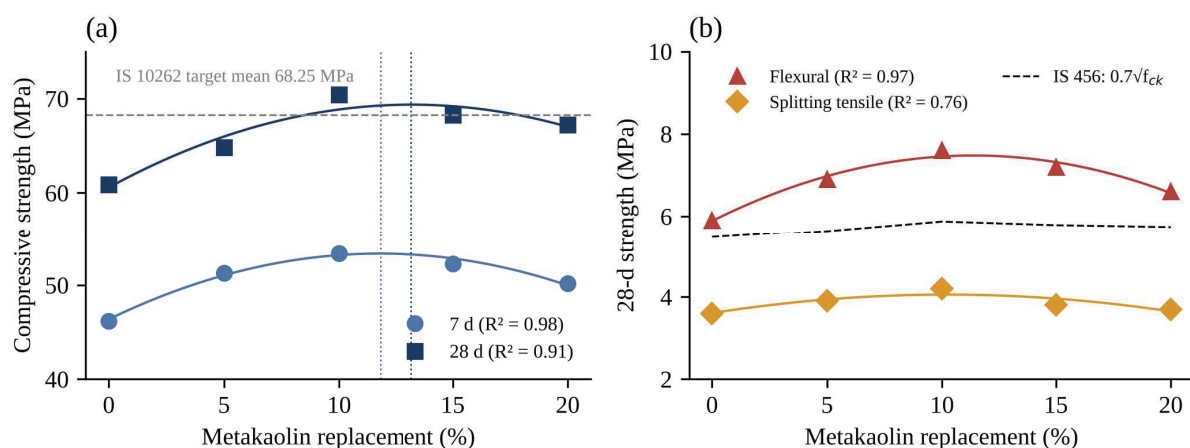


Figure 1. Effect of MK on (a) compressive and (b) tensile strengths, with quadratic fits.

3.3 Splitting tensile and flexural strength

Splitting tensile and flexural strengths followed the same trend and peaked at MK10, at 4.2 MPa (+16.7%) and 7.6 MPa (+28.8%) (Fig. 1b). The relative gain in flexure was nearly twice that in compression, which is consistent with MK densifying the ITZ, which governs crack initiation in bending more than in compression [11,12]. The flexural fit was significant ($R^2 = 0.97$, $p = 0.026$) with an optimum at 11.4% MK; the splitting tensile fit was not ($R^2 = 0.76$, $p = 0.24$). The tensile-to-compressive ratio f_{st}/f_c fell from about 6.0% (MK0–MK10) to about 5.5% (MK15–MK20), so high MK contents make the matrix relatively more brittle, which strengthens the case for fibre reinforcement at those levels.

Table 3. Ratio of measured to predicted tensile strength for code and model-code expressions.

Expression	MK0	MK5	MK10	MK15	MK20	Mean
IS 456, $f_b = 0.7\sqrt{f_{ck}}$	1.08	1.22	1.29	1.24	1.15	1.20
ACI 318, $f_b = 0.62\sqrt{f_c}$	1.36	1.55	1.63	1.57	1.45	1.51
ACI 363R, $f_b = 0.94\sqrt{f_c}$	0.90	1.02	1.08	1.04	0.96	1.00
ACI 363R, $f_{st} = 0.59\sqrt{f_c}$	0.87	0.92	0.95	0.87	0.86	0.89
fib MC2010, $f_{cm} = 2.12 \ln(1 + f_{cmf}/10)$	0.96	1.01	1.05	0.96	0.94	0.98

f_c and f_{cm} taken as $0.8 \times$ measured cube strength.

Table 3 and Fig. 2 compare the measurements with code expressions. IS 456 underestimated flexural strength by 8–29%, and ACI 318 by 36–63%; both expressions are therefore conservative for these mixes, and markedly so at 5–15% MK. ACI 363R, which was calibrated on high-strength concrete, predicted flexural strength within –10% to +8% (mean ratio 1.00). For splitting tensile strength, the fib Model Code 2010 expression gave the best agreement (ratios 0.94–1.05), whereas ACI 363R overestimated it by 5–14%. Code-based designs of MK-modified M60 concrete using IS 456 will therefore be safe but will not exploit the flexural gain delivered by MK, and the more appropriate expressions for this class of concrete are ACI 363R for flexure and fib MC2010 for splitting.

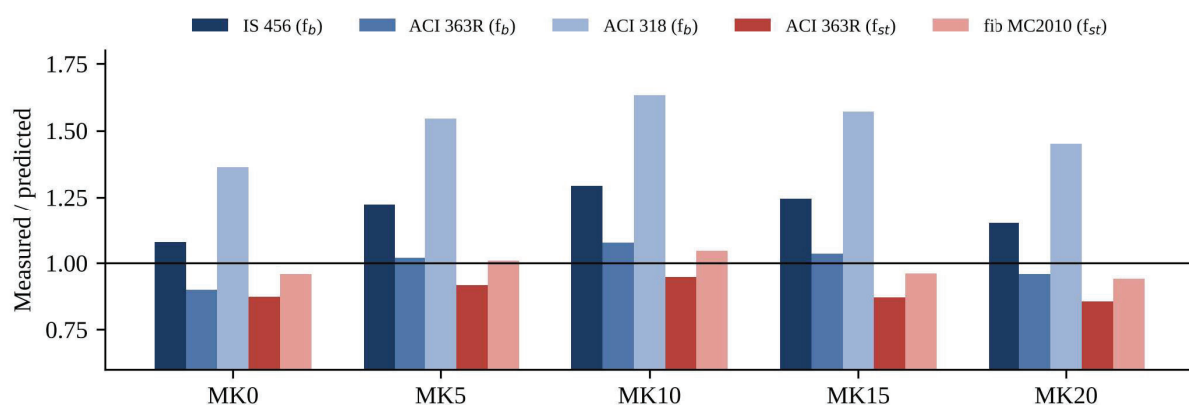


Figure 2. Measured-to-predicted ratios of tensile and flexural strength.

3.4 Effect of fibre dosage and aspect ratio

Table 4. Flexural strength and fibre parameters of the fibre-reinforced MK10 concretes (28 days).

Mix	V_f (%)	l/d	RI	N_V ($10^6/m^3$)	N_A (cm^{-2})	f_b (MPa)	vs MK10 (%)	vs MK0 (%)	$\Delta f_b/RI$ (MPa)
MK10 (no fibre)	0	—	0	—	—	7.60	—	+28.8	—
MK10-F1.0-A60	1.0	60	0.60	0.50	1.1	10.15	+33.6	+72.0	4.25
MK10-F1.0-A80	1.0	80	0.80	0.38	1.1	9.20	+21.1	+55.9	2.00
MK10-F1.5-A60	1.5	60	0.90	0.75	1.7	11.09	+45.9	+88.0	3.88
MK10-F1.5-A80	1.5	80	1.20	0.57	1.7	10.00	+31.6	+69.5	2.00

N_V = fibres per unit volume; N_A = fibres crossing a unit section area for random 3D orientation ($\alpha = 0.5$) [23].

All four fibre mixes raised the flexural strength well above that of plain MK10 (Table 4, Fig. 3a). MK10-F1.5-A60 gave the highest value, 11.09 MPa, 45.9% above MK10 and 88.0% above the control, and a flexural-to-compressive-root ratio $f_b/\sqrt{f_c}$ of 1.32 compared with 0.91 for MK10. Treating the four mixes as a 2^2 factorial design, increasing V_f from 1.0% to 1.5% raised f_b by 0.87 MPa on average, whereas increasing l/d from 60 to 80 lowered it by 1.02 MPa; the interaction effect was negligible (-0.07 MPa), so the two lines in Fig. 3b are almost parallel. The aspect-ratio effect was therefore larger than, and opposite in sign to, the dosage effect over the range tested. As a consequence MK10-F1.5-A80 (RI = 1.20) was weaker than MK10-F1.0-A60 (RI = 0.60), and the reinforcing index did not rank the mixes (Fig. 3c). The gain per unit RI was 3.9–4.3 MPa for SF-60 but only 2.0 MPa for SF-80, and the gain per 10 kg of fibre was 0.30–0.33 MPa for SF-60 against 0.20 MPa for SF-80.

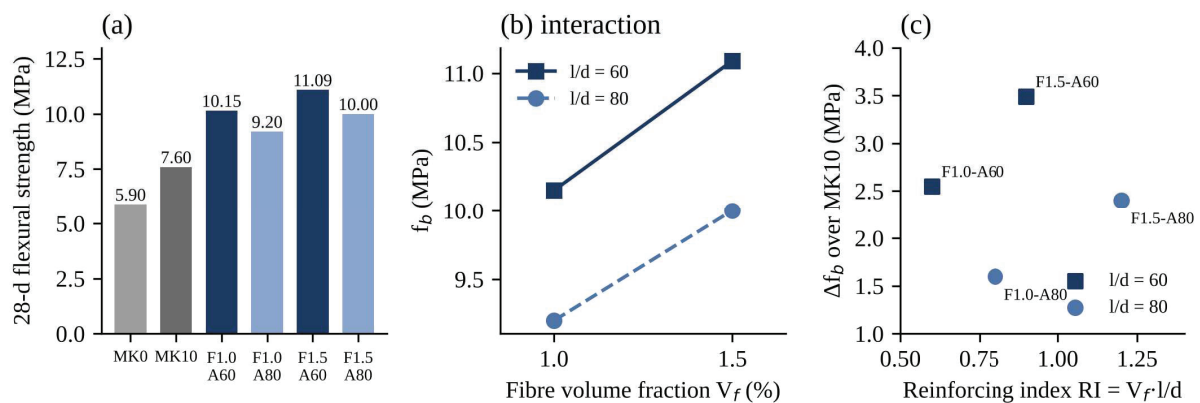


Figure 3. (a) Flexural strengths, (b) $V_f \times l/d$ interaction and (c) gain versus reinforcing index.

This result differs from the general benefit of higher aspect ratio reported for normal-strength concrete [19,20] but is consistent with evidence that fibre efficiency in high-strength concrete depends on the match between fibre geometry, fibre strength and matrix strength [13,21]. Because both fibres have the same 0.75 mm diameter, the number of fibres crossing a section at a given V_f is the same for both under random orientation (about 1.1 and 1.7 fibres/cm² at 1.0% and 1.5%; Table 4), even though SF-60 provides about one-third more fibres per unit volume. A difference in the number of bridging fibres therefore does not by itself explain the result. Three other mechanisms are more likely. First, the 60 mm SF-80 fibres exceed the specimen-size limit: ASTM C1609 requires the prism width and depth to be at least three times the maximum fibre length [40], i.e. 135 mm for SF-60 and 180 mm for SF-80, whereas 100 mm prisms were used. Both fibres therefore violate the limit, SF-80 more severely, and the longer fibres are more prone to wall-effect alignment and to clustering near the mould faces. Second, at $w/b = 0.28$ the stiff matrix makes dispersion of longer fibres more difficult, and balling reduces the effective fibre content [24,41]. Third, in a 70 MPa matrix the longer embedded length of SF-80 increases the anchorage force, which can cause fibre rupture rather than pull-out if the fibre tensile strength is not high enough [21,22]; the tensile strength of the fibres used here was not reported. Fibre

distribution and failure mode were not examined, so these explanations remain to be confirmed, and the flexural results should be regarded as specimen-size dependent until they are repeated on $150 \times 150 \times 500$ mm prisms.

3.5 Cement and CO₂ intensity

Cement use per MPa of 28-day strength fell steadily, from $8.21 \text{ kg} \cdot \text{m}^{-3} \cdot \text{MPa}^{-1}$ for MK0 to 6.39 for MK10 (−22.2%) and 5.95 for MK20 (−27.5%) (Table 2). Because MK carries its own calcination emissions, the CO₂ saving is smaller than the cement saving: CO₂ intensity fell from 7.39 to $6.04 \text{ kg CO}_2\text{-eq} \cdot \text{m}^{-3} \cdot \text{MPa}^{-1}$ (−18.3%) for MK10 and to 5.95 (−19.4%) for MK20 (Fig. 4a). Beyond 10% MK the CO₂ intensity is almost constant (6.04, 6.04 and 5.95 for MK10, MK15 and MK20), because the additional cement saving is offset by the loss of strength and by the emissions of the extra MK. When the full ranges of the emission factors are considered (error bars in Fig. 4a), the MK10 to MK20 values overlap, so they cannot be distinguished on CO₂ grounds; MK10 is preferable because it achieves this CO₂ performance at the highest strength. Fibres were excluded from this indicator; at $78.5\text{--}117.8 \text{ kg/m}^3$ they add a substantial embodied-carbon burden, which should be weighed against any reduction in conventional reinforcement in a full life-cycle assessment.

3.6 Multi-criteria selection and robustness

MK10 ranked first under both predefined weightings (PI = 0.85 and 0.76; Table 2). It was the only mix to score 1.0 on all three strength criteria while retaining 115 mm slump and a 10% cement reduction. MK15 ranked second in both schemes (0.60 and 0.64), and giving more weight to cement saving moved MK20 from fourth to third. These rankings use interpolated slump values for MK5 and MK15; the original assignment of ordinal scores of 0.50 and 0.25 to these mixes was inconsistent with the monotonic decline of slump with MK content and has been replaced by linear interpolation. The change does not affect the first-ranked mix.

The robustness of the selection was tested by drawing 20,000 random weight vectors (Fig. 4b). MK10 ranked first in 95.7% of cases, MK20 in 4.0% (only when cement reduction dominated the weighting), and the other mixes in less than 0.5%. When slump was removed as a criterion, so that the two interpolated values played no role, MK10 still ranked first in 89.1% of weightings. The choice of MK10 as the optimum plain matrix is therefore insensitive both to the weighting scheme and to the unmeasured slump values.

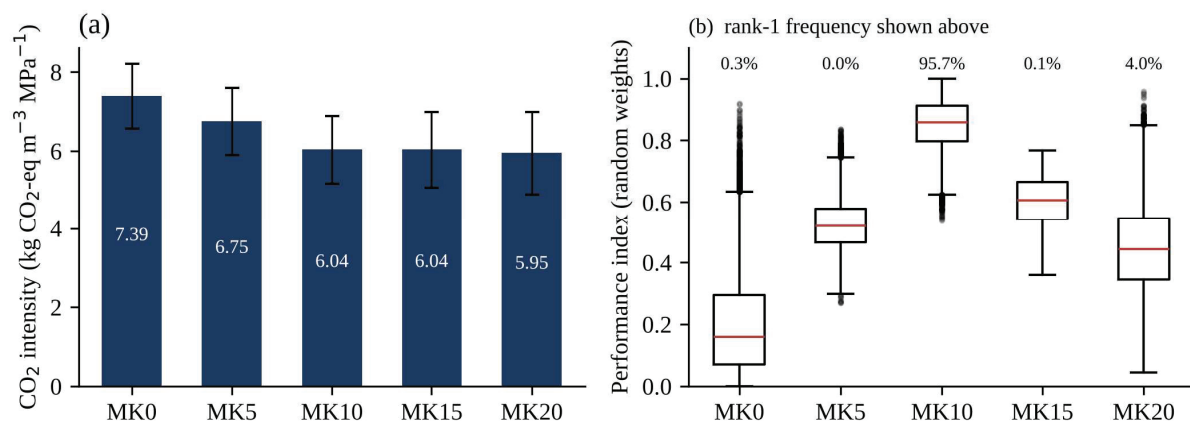


Figure 4. (a) CO₂ intensity of the plain MK mixes; (b) PI under 20,000 random weightings.

3.7 Comparison with previous studies

Table 5. Comparison with previous studies on MK concrete and steel fibre reinforced concrete.

Study	System	Reported finding	Agreement with present results
Wild et al. [8]	Superplasticised MK concrete	MK increased strength, with the pozzolanic contribution active within the first 14 days	Consistent: high 7/28-d ratio and early gain
Poon et al. [9]	High-performance MK and silica fume concrete	MK increased strength and reduced chloride diffusivity and porosity	Consistent; durability not tested here
Güneyisi et al. [25]	10% MK + hooked-end fibres, two w/b	MK and fibre geometry significantly affected flexural, splitting and bond strength	Consistent: both factors significant for f_b
Dou et al. [26]	MK-modified high-fluidity FRC	MK governed long-term compressive strength; fibres mainly added toughness	Consistent: fibres raised f_b ; f_c not tested
Yazıcı et al. [19]; Jang et al. [20]	Normal-strength SFRC	Higher l/d generally increased flexural strength	Differs: l/d = 60 outperformed l/d = 80
Choi et al. [21]	High-strength SFRC	Fracture behaviour depends on fibre tensile strength and aspect ratio	Supports fibre-rupture explanation

The present results agree with the established effects of MK on high-strength concrete (Table 5) and with the finding that MK and fibre geometry act jointly on flexural performance [25,26]. The main departure from the literature is the inverse aspect-ratio effect, which, as discussed in Section 3.4, is plausibly linked to the fibre-length-to-specimen-size ratio and to the high matrix strength rather than to an intrinsic disadvantage of high-aspect-ratio fibres.

4. Limitations and Further Work

The study reports mean values of three specimens; individual results and standard deviations should be added so that differences between mixes can be tested statistically (e.g. one-way ANOVA with post-hoc comparison for the MK series, and a replicated 2² factorial ANOVA for the fibre series). Slump was not recorded for MK5, MK15 or any fibre mix, and the compressive

and splitting tensile strengths and post-cracking response (residual strengths and toughness to ASTM C1609 or EN 14651) of the fibre mixes were not measured. The flexural tests used 100 mm prisms with fibres longer than one-third of the section dimension. Durability (chloride penetration, sorptivity, carbonation, sulphate resistance), microstructure (SEM, XRD, TGA) and a full life-cycle and cost assessment including fibres are needed before the mixes can be recommended for structural use. A test at 12.5% MK is recommended to confirm the regression optimum.

5. Conclusions

- (1) A 10% MK replacement was the best tested level for the M60 matrix. It raised the 28-day compressive, splitting tensile and flexural strengths by 15.6%, 16.7% and 28.8%, to 70.4, 4.2 and 7.6 MPa, and kept the slump at 115 mm. Quadratic regression placed the optimum between 10% and 13% MK.
- (2) All MK mixes exceeded the control, and MK10 and MK15 met the IS 10262:2019 target mean strength. Cement intensity fell by 22.2% at MK10 and 27.5% at MK20, and CO₂ intensity by about 18–19%, with little further CO₂ benefit beyond 10% MK.
- (3) IS 456 and ACI 318 underestimated flexural strength by 8–29% and 36–63%, respectively, whereas ACI 363R predicted it within $\pm 10\%$. The fib Model Code 2010 expression gave the best estimate of splitting tensile strength (ratios 0.94–1.05).
- (4) Hooked-end fibres raised the flexural strength of MK10 to 9.20–11.09 MPa. The best mix, MK10-F1.5-A60, reached 11.09 MPa, 88.0% above the control.
- (5) Increasing l/d from 60 to 80 reduced flexural strength by 1.02 MPa on average, more than the 0.87 MPa gained by increasing V_f from 1.0% to 1.5%, and the reinforcing index did not rank the mixes. Because both fibres exceed the ASTM C1609 length limit for 100 mm prisms, this effect should be re-examined on larger specimens with measured fibre distribution.
- (6) MK10 ranked first under both predefined weightings and in 95.7% of 20,000 random weightings of the performance index (89.1% with slump excluded), so its selection is robust to the weighting scheme and to the unmeasured slump values.

Declarations

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