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Lova Raju Surla

Ph.D. Candidate, Department of Civil Engineering, GIET University, Gunupur, Odisha, India,

lovaraju.surla@giet.edu

Ramprasad Naik Desavathu

Professor, Department of Civil Engineering, GIET University, Gunupur, Odisha, India

Raja Murugadoss Jeyaraju

Professor, Department of Civil Engineering, NSRIT, Visakhapatnam, Andhra Pradesh, India

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RESEARCH ARTICLE

Performance Evaluation and Sustainable Benefits of Using Metakaolin and Recycled Steel Fibers in Concrete

Lova Raju Surla^{a,*}, Ramprasad Naik Desavathu^b, Raja Murugadoss Jeyaraju^c

^a Ph.D. Candidate, Department of Civil Engineering, GIET University, Gunupur, Odisha, India

^b Professor, Department of Civil Engineering, GIET University, Gunupur, Odisha, India

^c Professor, Department of Civil Engineering, NSRIT, Visakhapatnam, Andhra Pradesh, India

ABSTRACT

The rapid accumulation of waste vehicle tires and the increasing demand for cement pose significant environmental challenges through land pollution and CO₂ emissions. The combined use of recycled steel fibers (RSFs) recovered from waste tires and supplementary cementitious materials (SCMs) offers a sustainable solution to these issues. This study investigates concrete incorporating 20% fly ash (FA), varying metakaolin (MK) contents (4–16%), and RSF dosages of 0.5–1.5%. Mechanical properties (compressive, split tensile, and flexural strengths) and durability characteristics (sorptivity, water absorption, chloride permeability, and homogeneity) were evaluated at 7, 28, and 90 days. Results showed that the mixture containing 20% FA and 12% MK exhibited the optimum overall performance among the SCM blends. The incorporation of 1% RSF further enhanced performance, resulting in increases of approximately 44–46% in compressive strength, 41–45% in split tensile strength, and 50–55% in flexural strength compared to the control mix. SEM observations confirmed the formation of a denser and more compact microstructure in the optimized FA–MK blends. Life cycle assessment demonstrated reductions in global warming and water depletion impacts through the combined use of MK and RSF. ANOVA and regression analyses indicated statistically significant effects of MK and RSF on mechanical and durability properties, while response surface analysis identified 12% MK and 1% RSF as the optimum combination within the investigated parameter range.

Keywords: Metakaolin, Recycled steel fibers, Mechanical performance, Environmental impacts, Regression analysis

1. Introduction

The building and construction sector is responsible for nearly 38% of global CO₂ emissions and about 35% of total energy use [1, 2]. With the world's population steadily increasing causes increased demand for infrastructure which might result in escalation of these figures due to the continued reliance on conventional construction materials. Since global concrete production exceeds 25 billion tons annually, reducing the environmental impact of cement-based materials has become a major priority for sustainable construction. One effective strategy involves the use

of supplementary cementitious materials (SCMs) to partially replace ordinary Portland cement (OPC), thereby reducing carbon emissions while improving the performance and durability of concrete. SCMs such as FA, MK, silica fume, rice husk ash, and ground granulated blast furnace slag have been widely investigated for their ability to enhance concrete properties through pozzolanic reactions, micro-filling effects, and nucleation mechanisms that promote the formation of additional calcium silicate hydrate (C–S–H) gel [3–8]. By partially substituting Portland cement or natural sand, these mineral admixtures provide environmental, economic, and social benefits

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* Corresponding author.

E-mail address: lovaraju.surla@giet.edu (L. R. Surla).

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that align with the principles of sustainable development [9–11]. Despite these advantages, research on durability aspects of concrete is scarce and there is insufficient knowledge on how to optimize SCM use for improved long-term performance.

Among the various SCMs, FA remains one of the most extensively used industrial by-products in concrete production [12, 13]. Generated as a residue from coal combustion in thermal power plants, FA contributes to improved durability, reduced permeability, and lower heat of hydration in cementitious systems. However, high replacement levels of FA may delay early-age strength development due to its relatively slow pozzolanic reactivity [14, 15]. On the other hand, MK, a highly reactive aluminosilicate obtained by calcining kaolinite clay, exhibits strong pozzolanic activity and significantly enhances early-age strength and durability characteristics [16–18]. Recent research has demonstrated that combining FA and MK in ternary cementitious systems can produce synergistic effects that improve both mechanical and durability performance [19]. Papp et al., [20] noticed that MK exhibits faster pozzolanic reactivity (immediately after 8 hours) and FA acts as a filler material at later ages. This is due to the high reactivity and fine particle size of MK which accelerate early hydration and refine pore structure, while FA contributes to long-term strength development and improved microstructural densification. Alamri et al., [8] studied the ternary effects of FA and MK on performance evaluation of concrete and concluded that 15% MK and 10% FA significantly enhance the mechanical and durability performance. Though the ternary FA–MK blended systems have shown promising results but the limited research on understanding the synergy of FA–MK systems draws significant research interest.

In addition to binder optimization, improving the crack resistance and toughness of concrete remains an important aspect of structural durability. Fiber reinforcement is widely adopted to control crack propagation and improve post-cracking behaviour of concrete. In recent years, RSF extracted from end-of-life vehicle tires have attracted increasing attention as a sustainable alternative to industrial steel fibers [21–23]. Waste tire disposal represents a significant environmental challenge worldwide, as millions of tires are discarded annually. Approximately 10–15% of a tire's mass consists of steel reinforcement, which can be recovered through mechanical shredding and magnetic separation processes [24, 25]. Among these, mechanical shredding is considered more cost-effective and energy-efficient compared to the production of industrial steel fibers (ISFs) [26, 27]. As a result, RSF are increasingly regarded as a sustainable and economical alternative to ISFs,

offering the potential for environmentally friendly concrete production [28, 29]. These recovered fibers possess irregular geometry but exhibit strong potential as reinforcement in cementitious composites [30].

Previous studies have demonstrated that the incorporation of RSFs can significantly enhance the tensile, flexural, and impact resistance of concrete while improving energy absorption and toughness [28, 29, 32]. Experimental investigations have reported that RSF-reinforced concrete can achieve mechanical performance comparable to that of concrete reinforced with manufactured steel fibers, particularly when appropriate fiber volume fractions (typically 0.5–1.5%) are used [25, 29, 31]. Furthermore, Life-cycle cost analyses indicate that RSF-reinforced concrete delivers superior long-term economic efficiency along with considerable environmental benefits compared to ISF-based concrete [33, 34]. However, the inclusion of RSFs may also reduce workability due to their irregular geometry and surface roughness. Studies showed that higher dosages of RSF (1% - 2.5% by volume of concrete) reduced the workability by nearly 20% to 50% [32–34]. This highlights the importance of optimizing fiber dosage and mix design of ternary blended systems with RSF. Although several studies have examined the individual effects of FA, MK, and RSF on concrete performance, limited research has investigated their combined influence within a single sustainable concrete system. Understanding the synergistic interaction between SCMs and recycled fibers is essential for developing environmentally friendly concrete mixtures with improved mechanical and durability characteristics. Therefore, the present study aims to develop sustainable concrete by incorporating FA and MK as partial cement replacements and reinforcing the matrix with RSF recovered from waste tires. The mechanical and durability properties of the developed mixtures are experimentally evaluated, while microstructural characteristics are investigated using scanning electron microscopy (SEM). In addition, statistical analysis based on response surface methodology is employed to quantify the significance of FA, MK, and RSF incorporation on concrete performance. The findings of this study contribute to advancing sustainable construction practices by promoting the effective utilization of industrial by-products and recycled materials in structural concrete.

2. Materials

Ordinary Portland cement (OPC) is used as a binder which is replaced by suitable proportions of FA and



Fig. 1. Materials used (a) FA (b) MK (c) RSF.

Table 1. Mix proportions of concrete mixtures in kg/m³.

Sl. No.	Mix ID	C	FA	MK	W	S	CA	SP
1	CM	390	-	-	188	689	1267	2.25
2	M (20%FA)	312	78	-	188	689	1267	2.25
3	M (20%FA + 4%MK)	296	78	16	188	689	1267	2.25
4	M (20%FA + 8%MK)	280	78	32	188	689	1267	2.25
5	M (20%FA + 12%MK)	264	78	48	188	689	1267	2.25
6	M (20%FA + 16%MK)	248	78	64	188	689	1267	2.25

CM – Control mix, M – mix, C- Cement, W- Water, S- Sand, CA- Coarse aggregate, Mix (C) – Conventional concrete (control mix).

MK (see Fig. 1), to prepare M40 grade concrete whose mix design details are provided in Table 1. The concrete mixtures were proportioned using the absolute volume method, and the quantities presented in Table 1 correspond to 1 m³ of concrete. FA and MK were used as partial replacements of cement on a mass basis while maintaining a constant binder content. The specific gravities of cement (3.14), FA (2.15), and MK (2.44) were considered during mix proportioning to ensure that the total absolute volume of constituents remained constant. It is targeted to achieve 50 MPa designed following IS 456:200 [35] and IS 10262:2019 [36]. FA, obtained from nearby RMC plant and MK, a byproduct of calcined clay obtained GPR Associates, Visakhapatnam, showed dominant peaks of silica dioxide in XRD analysis (see Fig. 2). The physical and chemical properties of FA, MK and OPC is shown in Tables 2 and 3 respectively. The aggregates used includes manufacturing sand passing through 4.75 mm sieve and conforming Zone II and coarse aggregates of size 12 mm and 20 mm blended in the ratio of 1:1.2. Laboratory tap water is used for mixing the materials. A sulphonated naphthalene-based superplasticizer (Conplast SP 430) was used in all mixes.

RSF used in this study were obtained from mechanically shredded waste vehicle tires (see Fig. 1). The fibers had an average diameter of approximately 0.5 mm and lengths ranging from 10–15 mm, resulting in an aspect ratio between 20 and 30. Due to the recycling process, the fibers exhibited irregular geometries with slight curvature rather than uniform straight or hooked shapes. Residual rubber particles

Table 2. Physical properties of materials used.

Property	Cement	FA	MK
Specific gravity	3.14	2.15	2.44
Blaine's Fineness (m ² /kg)	348	322	1350

were removed through mechanical cleaning prior to use. The tensile strength of RSF is reported to be in a range 1200–2000 MPa [28, 29, 32]. The fiber content reported in this study represents the volume fraction of concrete and mass of RSF required for each inclusion is shown in Table 4. Although recycled fibers may exhibit variability in geometry, it is reported that such irregularity can enhance mechanical interlocking and crack bridging behavior in concrete [37].

3. Test methods

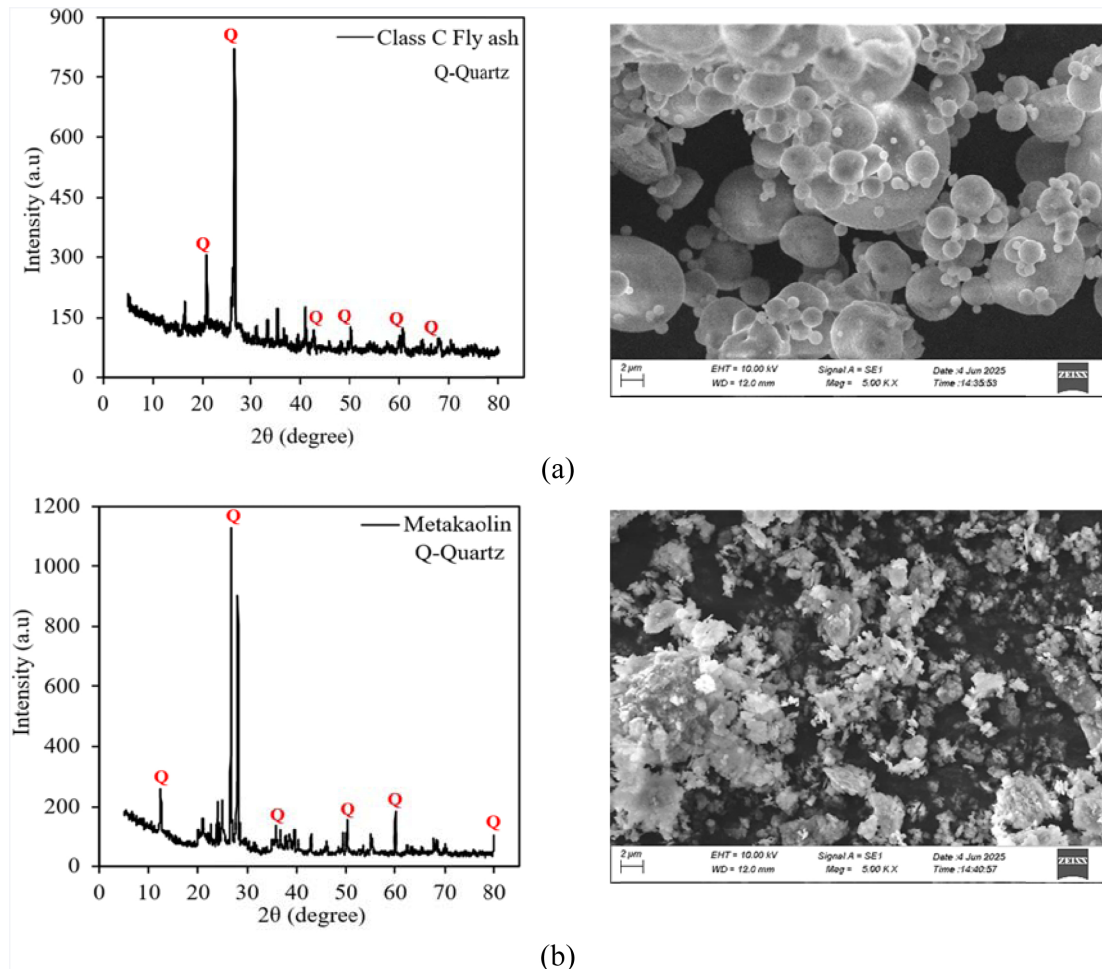
After casting, the specimens were demoulded after 24 hours and cured in a water tank maintained at a temperature of 27 ± 2 °C until the respective testing ages. The curing environment ensured adequate hydration and uniform moisture conditions for all concrete specimens.

3.1. Fresh properties of concrete

Fresh properties of all mixtures are evaluated by slump test following standards specified by ASTM C143/C143M [38].

Table 3. Chemical properties of materials used.

Material	SiO ₂ (%)	Fe ₂ O ₃ (%)	CaO (%)	Al ₂ O ₃ (%)	MgO (%)	SO ₃ (%)	Na ₂ O (%)	LOI (%)
Cement	19.81	3.29	65.87	6.36	1.2	2.24	1.12	1.22
MK	53.26	0.54	0.38	43.86	0.24	0.36	0.18	0.46
FA	54.68	12.26	5.8	19.24	2.44	0.28	2.68	0.88

**Fig. 2.** XRD and SEM of (a) FA (b) MK.**Table 4.** Mass of RSF required for varied % inclusions.

Material	% inclusion by volume	Mass (kg) of RSF required for 1 m ³ concrete
RSF	0.5	39.25
	1	78.5
	1.5	117.75

3.2. Mechanical properties

The mechanical performance of hardened concrete was assessed through compressive strength, split tensile strength and flexural strength as shown in Fig. 3. The splitting tensile strength test was conducted by centrally aligning the cylindrical specimen between the loading platens using alignment aids to ensure

uniform load distribution and minimize eccentric loading throughout the test. The specimen details and the corresponding testing standards are summarized in Table 5.

3.3. Durability properties

3.3.1. Sorptivity

The sorptivity test was carried out in accordance with ASTM C1585 (2020) [42] to assess the rate of water absorption through the capillary pore system of the concrete. For each mixture, three disc-shaped specimens measuring 100 × 50 mm were prepared. All surfaces of the specimens were sealed except the exposed face to ensure one-dimensional water

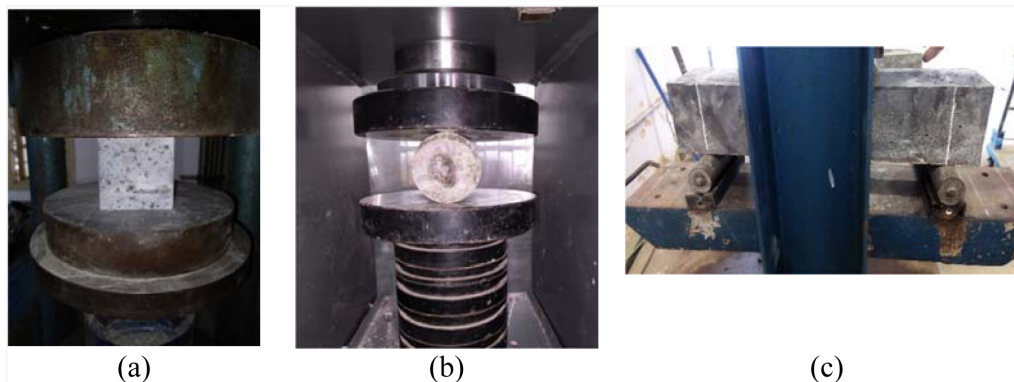


Fig. 3. Test setups for mechanical properties (a) compressive strength, (b) split tensile strength, (c) flexural strength.

Table 5. Specimen configuration for mechanical properties of concrete.

Test	Standard	Specimen	Specimen size (mm)
Compressive strength	IS-516: 1956 [39]	Cube	100×100×100
Split tensile strength	ASTM-C496 (2017) [40]	Cylinder	100×200
Flexural strength	IS 516: 2021 [41]	Beam	100×100×500

absorption. The top surface was covered with a plastic sheet to minimize evaporation losses (see Fig. 4a). Water absorption was measured at predetermined time intervals over a period of 8 days. Capillary absorption was characterized in terms of both primary and secondary absorption, and it is calculated by using

$$I = \frac{\Delta m}{(A \times \delta)}$$

where Δm is the change in mass (g), A - the exposed area, and δ - the density of water.

3.3.2. Water absorption

Water absorption, which serves as an indicator of pore volume, was determined in accordance with ASTM C642 (2021) [43]. For each mixture, three disc shaped specimens of size 100 × 50 mm were prepared. The specimens were oven-dried at 101 °C for 24 h, cooled to room temperature (25 °C), and weighed to obtain the initial dry mass. Subsequently, the specimens were immersed in water for 48 h to determine the saturated mass, followed by boiling in water for 5 h to obtain the saturated-boiled mass (Fig. 4c). These measurements were used to calculate the water absorption (%) and the volume of permeable pores (%).

3.3.3. Rapid chloride permeability test (RCPT)

The Rapid Chloride Permeability Test (RCPT) was conducted in accordance with ASTM C1202 (2019)

[44] to assess the resistance of concrete to chloride ion penetration. Disc specimens measuring 100 × 50 mm were positioned between two cells containing sodium chloride (NaCl) and sodium hydroxide (NaOH) solutions, respectively (Fig. 4d). A constant voltage of 60 V was applied across the specimen, and the total electrical charge passed was monitored at 30 min intervals for a duration of 6 h.

3.3.4. Electrical resistivity test

Concrete electrical resistivity, which serves as an indirect measure of resistance to chloride ingress, was determined using cylindrical specimens of dimensions 100 × 200 mm in accordance with AASHTO T358 [45]. A four-probe resistivity meter operating on the Wenner probe principle was employed. The probes were gently pressed against the surface of the water-saturated specimens to record the resistivity values (Fig. 4e).

3.3.5. Ultrasonic pulse velocity (UPV) test

The Ultrasonic Pulse Velocity (UPV) test was performed following ASTM C597 (2016) [46] to evaluate the quality and homogeneity of the concrete. According to these guidelines, UPV values greater than 4.5 km/s indicate excellent quality concrete, while values between 3.5 and 4.5 km/s represent good quality concrete with a dense internal structure. The test was carried out on cylindrical specimens measuring 100 × 200 mm, with three specimens tested for each mixture (Fig. 4f).

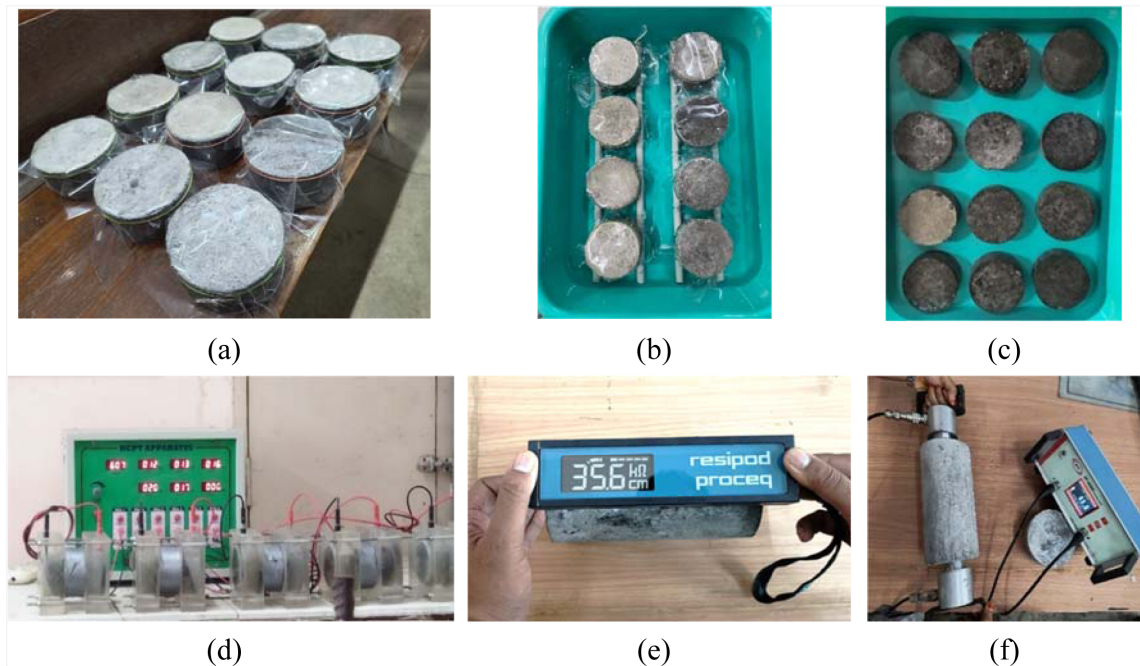


Fig. 4. Test setups for durability properties (a) specimen preparation for sorptivity, (b) sorptivity test setup, (c) water absorption, (d) RCPT, (e) electrical resistivity, (f) UPV.

3.4. Microstructural properties

3.4.1. Scanning electron microscopy (SEM)

The surface morphology of the mortar samples was investigated using a Tescan VEGA-3 Scanning Electron Microscope (SEM). Hardened mortar specimens were cut into fragments measuring approximately $10 \times 10 \times 10$ mm and oven-dried at 60°C for 24 h to arrest further hydration prior to SEM examination. The dried samples were subsequently carbon-coated to prevent surface charging and mounted on specimen stubs. Multiple micrographs were captured for each sample to examine the microstructural features. The SEM images shown correspond to typical regions of the cementitious matrix selected during SEM examination to illustrate the microstructural characteristics of the mixes. However, SEM analysis was performed on mortar specimens without recycled steel fibers to facilitate clearer observation of the cementitious matrix and hydration products. The micrographs primarily illustrate the morphology of hydration products and matrix densification resulting from the incorporation of metakaolin.

3.5. Life cycle analysis (LCA)

To evaluate the potential reduction in environmental footprint of the concrete mix designs, a life-cycle assessment (LCA) was conducted for the above mixtures, designed for cradle (extraction of

raw materials) to gate (production of concrete mixtures). It is mainly focussed on four main parameters, Global warming potential (GWP), Ozone depletion potential (ODP), Acidification and Water depletion potential (WDP). The analysis of these parameters was conducted using ReCiPe 2016 v1.03, midpoint (H) method. LCA is performed in openLCA software using ecoinvent 3.11 database.

3.6. Statistical analysis using surface response methodology

Statistical evaluation was carried out using Analysis of Variance (ANOVA) and regression analysis to identify significant differences among the various mix designs and to ensure the reliability of the experimental results. These statistical techniques were employed to assess the influence of various MK replacement levels on the measured properties, enabling the identification of key trends and optimal substitution levels. Data analysis was performed using the response surface methodology (RSM) tool in Minitab software.

4. Results & discussions

4.1. Fresh properties of concrete mixtures

The slump values presented in Fig. 5 indicate that the workability of concrete mixtures decreases with

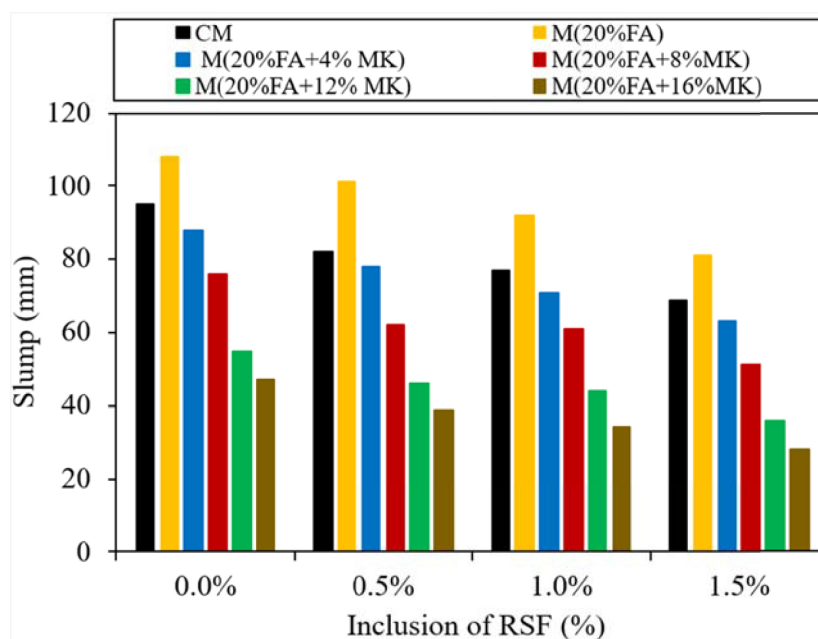


Fig. 5. Slump values of concrete mixtures.

the increase in recycled steel fiber (RSF) content. For all mixtures, the control mix with 20% FA exhibited the highest slump of 108 mm because of its spherical shaped particles (see SEM image in Fig. 2) which induces ball bearing effect, reducing the friction and promotes the flow of the concrete mix. While the inclusion of RSF resulted in a gradual reduction in slump from 0% to 1.5% fiber dosage. The mixtures with 1.5% RSF exhibited much lower slump values. This reduction in workability can be attributed to the increased internal friction and interlocking effect of fibers within the concrete matrix which increases the demand for water. Furthermore, the incorporation of MK also contributed to lower slump values due to its finer particle size and higher surface area, which also increases water demand. The results align well with the observations seen in the past literature [32–34]. Among the ternary mixtures, the mix containing higher MK content showed comparatively lower slump values. Overall, the results demonstrate that both RSF and MK significantly influence the fresh properties of concrete by reducing its flowability. However, while casting, all specimens were consolidated using a vibrating table to ensure proper compaction and minimize entrapped air.

4.2. Mechanical properties of concrete mixtures

4.2.1. Effect of FA and MK blends on mechanical properties of concrete

The mechanical performance of concrete incorporated with blends of FA and MK was assessed

by means of compressive, split tensile and flexural strength as presented in Fig. 6. The compressive strength increased significantly with varying dosages of MK. The control mix attained the compressive strength of 34 MPa and 55 MPa, split tensile strength of 3.68 MPa and 4.89 MPa and flexural strength of 4.38 MPa and 5.56 MPa at 7 and 90 days of curing respectively. Whereas the compressive strength enhanced significantly with the rise in MK dosage and the mix with 20% FA and 12% MK attained the maximum strength of 72 MPa at 90th curing day, reporting an enhancement of 28% over control mix. Similarly, maximum split tensile strength of 6.31 MPa at 90th day was exhibited by the same mix M(20%FA + 12%MK) which is around 29% increase over control mix. And the same mix reported the maximum flexural strength of 6.98 MPa, indicating an increase of 25% over control mix. Therefore, the mix M(20%FA + 12%MK) exhibited the best performance and achieves the optimum mix due to accelerated pozzolanic reactions initiated by MK and FA with the curing age leading to the formation of additional CSH gel, which fills up the voids and offers densified matrix. Mix with 20% FA replacement showed lower mechanical strength at 7 and 28 days of curing compared to control mix but gained strength gradually with curing age and attained higher strength in a range of 8–13% over control mix. This is due to initial slow hydration reactions led by FA particles resulting lower mechanical strength at the initial days but later contributes higher strength due to additional CSH gel formation contributed by the later age pozzolanic

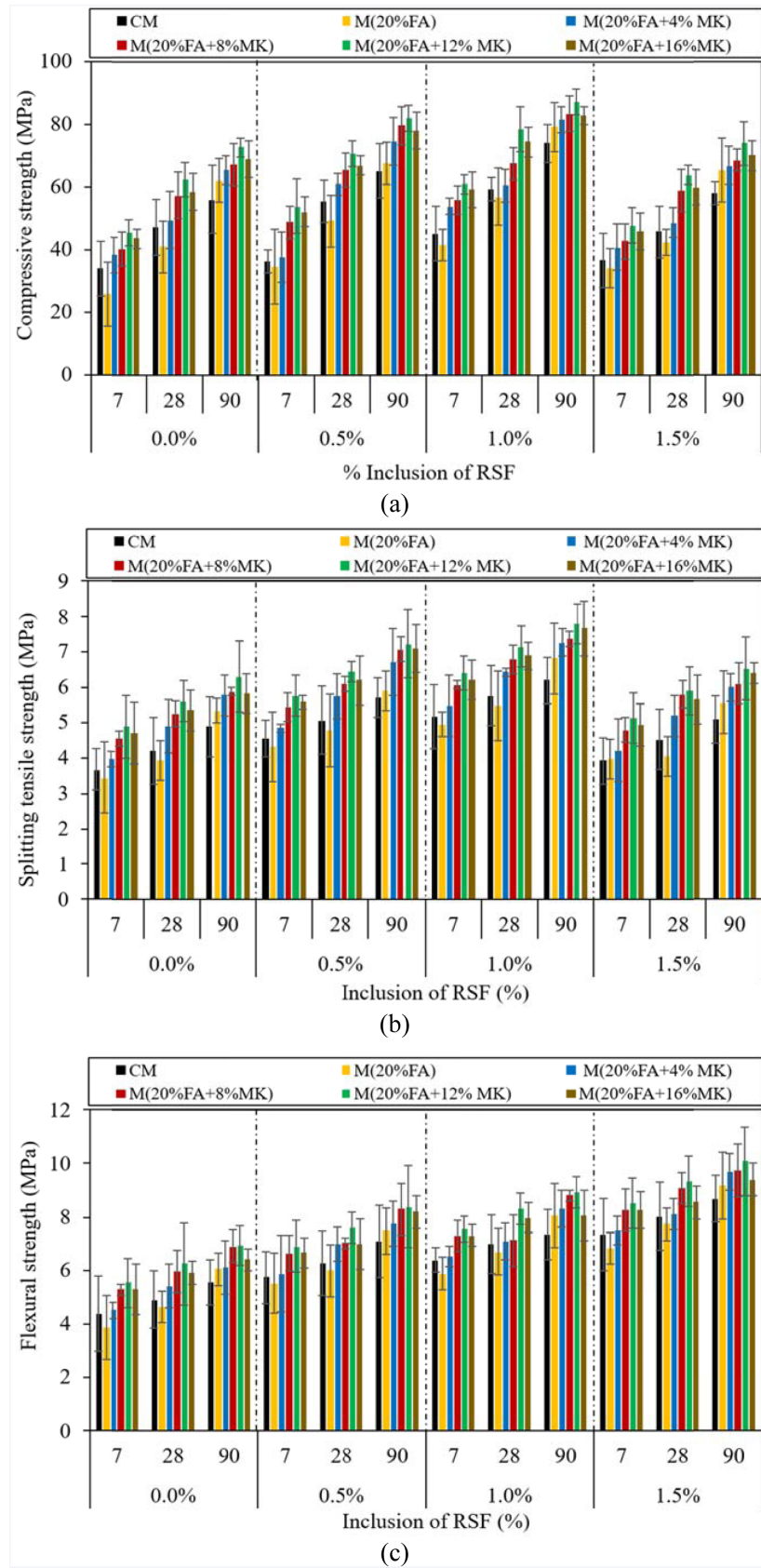


Fig. 6. Mechanical properties of concrete mixtures (a) compressive strength, (b) split tensile strength, (c) flexural strength. (Note: Error bars represent standard deviation of three specimens).

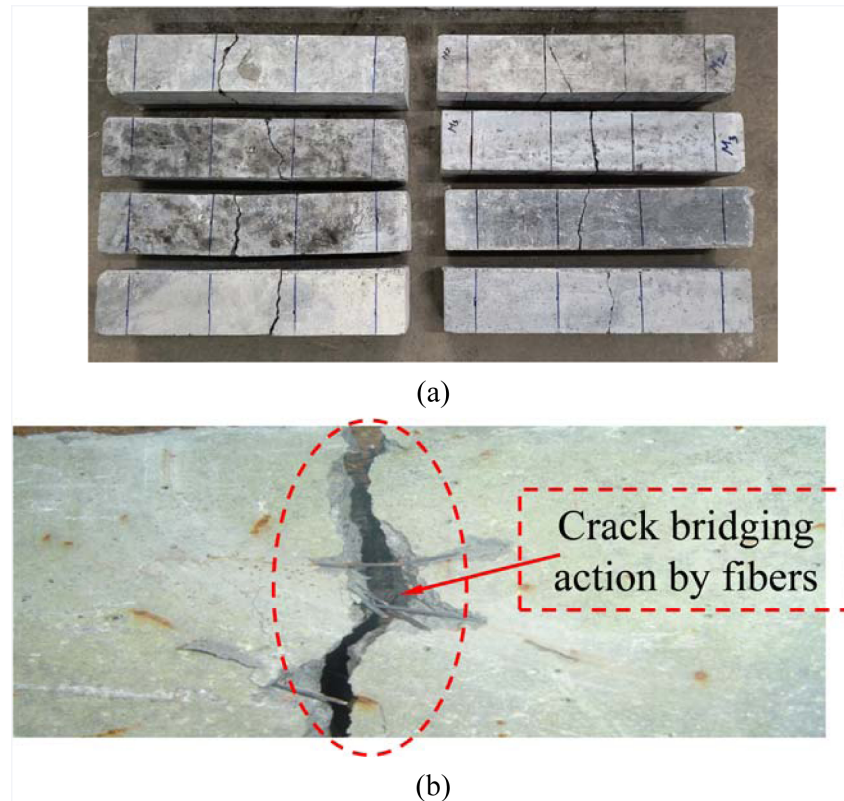


Fig. 7. (a) Flexural cracks of failed specimens (b) Crack bridging mechanism of fibers.

reactions [47, 48]. However, it is to be noted that the mechanical strength increased with the increase in MK dosage up till 12%, which then decreased beyond 12% replacement level (i.e. mix with 16% MK). This is due to the consumption of portlandite in the ongoing pozzolanic reactions initiated by FA and MK, resulting complete utilization of portlandite, leaving no sufficient portlandite to react further beyond 12% MK replacement levels.

4.2.2. Effect of RSF on mechanical properties of concrete

RSFs were included in the above proposed mixes to investigate the enhancement of mechanical properties as shown in Figure. A significant improvement in mechanical properties is noticed till 1% RSF inclusion. Similar observations were noticed by Kumar et al., [49]. The optimum mix M(20%FA + 12%MK) when reinforced with 0.5% RSF, enhanced the compressive strength in a range 11-13%, split tensile strength by 14-16% and flexural strength by 20-22% at 90th day over the same mix without RSF. The same optimum mix with 1% RSF exhibited the maximum improvement in compressive strength by 44-46%,

split tensile strength by 41-45% and flexural strength by 50-55% compared to the control mix. However, optimum mix with 1.5% RSF exhibited a drop in compressive and split tensile strength over 0.5% and 1% inclusion of RSF due to agglomeration of fibers in the matrix leading to the formation of voids, resulting drop in strength. Whereas flexural strength showed a significant improvement by 34-35% with 1.5% inclusion of RSF over optimum mix without fibers, due to enhanced crack bridging mechanism by fibers as shown in Fig. 7, offering higher flexural capacity.

4.3. Durability properties of concrete mixture

It should be noted that sorptivity, rapid chloride permeability (RCPT), and electrical resistivity tests provide indicators of transport properties related to durability, rather than direct measures of durability performance. These tests primarily evaluate the resistance of the concrete matrix to fluid and ionic transport. In addition, the present investigation focused on uncracked specimens, and therefore the influence of cracking on durability behaviour was not studied in the current work.

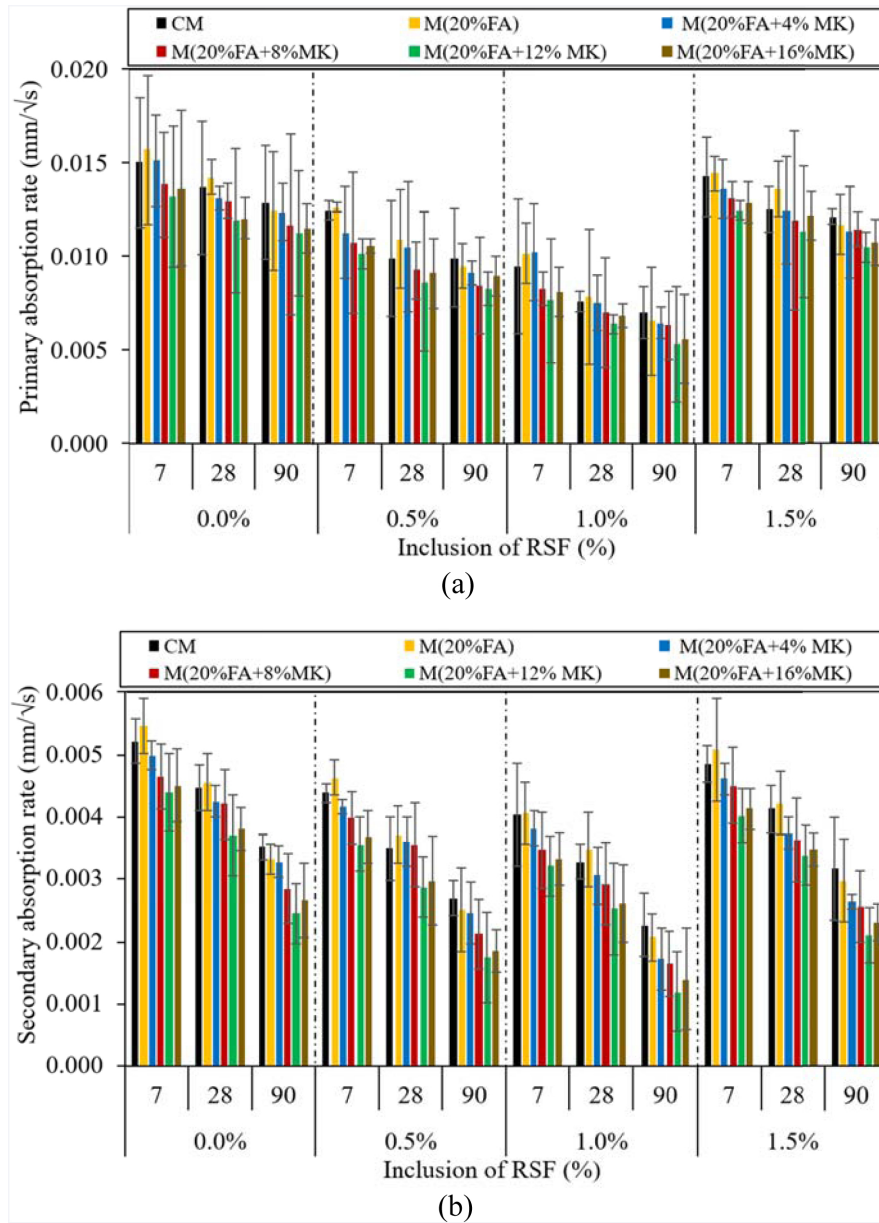


Fig. 8. Capillary absorption rate of concrete mixtures (a) primary absorption rate, (b) secondary absorption rate. (Note: Error bars represent standard deviation of three specimens).

4.3.1. Effect of FA and MK blends on capillary absorption

The combination of FA and MK showed a consistent reduction in capillary absorption with curing age, indicating the steady densification of matrix and capillary pore structure due to ongoing hydration mechanisms as shown in Fig. 8. The capillary absorption is measured by means of primary and secondary stages. The rate of capillary absorption exhibited by a mix with 20% FA is higher at 7 days which later decreased with curing age, outperforming the control mix at 90 days as delayed secondary C–S–H formation

progressively refined the pore structure. However, the inclusion of blends of FA–MK in concrete mixtures, prominently reduced the rate of capillary absorption in both stages. Among all, a mix with 20% FA and 12% MK reported the lowest absorption rates, indicating reductions of 12.6% in primary and 30% in secondary absorption at 90 days of curing over the control mix. This improvement results from the synergistic interaction between FA and MK, wherein MK being extremely fine, promotes the pozzolanic activity which consumes portlandite rapidly to form C–A–S–H and alumina-rich hydrates, contributing to

early pore refinement. FA, on the other hand, complements this activity by generating C–S–H at later stages, ensuring long-term densification.

The reduction in capillary absorption is further boosted by addition of RSF in the blended FA-MK mixtures. The reduction remained consistent till 1% inclusion of RSF beyond which the effect diminished at 1.5% RSF. The inclusion of 0.5% RSF in optimum mix M(20%FA + 12%MK) reduced primary absorption by 16% and secondary absorption by 28.5% at 90 days over optimum without RSF. The inclusion of 1% RSF produced the optimum performance with reduction achieved for primary and secondary absorption is 42% and 58% respectively. This improvement is attributed to the coupling action of FA-MK induced hydration densification and fiber induced restricted capillary pathways. Properly dispersed fibers act as internal barrier that disrupts the pore connectivity which limits water ingress through pores. However, mixtures containing 16% MK demonstrated slightly higher absorption rates due to complete depletion of portlandite, leaving unreacted particles within the matrix and generating localized voids. Likewise, mixtures with 1.5% RSF showed inferior performance due to fiber clustering agglomeration, which creates localised voids, permitting capillary suction.

4.4. Water absorption and volume of permeable pores

A steady reduction in water absorption and porosity is noticed for all concrete mixtures, indicating a progressive densification of internal pore matrix due to ongoing pozzolanic reactions. As shown in Fig. 9(a) and (b), At 7 days, the mix with 20% FA showed 6-8% higher water absorption and 5-6% higher porosity than the control, which with prolonged curing conditioning, owing to its ongoing microstructural densification induced by delayed FA pozzolanic reactivity had reduced absorption and porosity values than that of control mix at 90 days. The coupling mechanism induced by MK and FA had significantly accelerated the reduction in both water absorption and porosity. Both water absorption and porosity consistently decreased with increased dosages of MK. Among all mixtures, the ternary blend containing 20% FA and 12% MK exhibited the lowest values of water absorption and porosity, showing reductions by 28% and 18% respectively at 90 days, confirming this as an optimum mix. The improvement results from the dual effect of FA-MK blending, where early-age refinement by MK and long-term densification by FA collectively minimize pore connectivity and reduce accessible void space.

The incorporation of RSF in the blended mixtures further reduced the water absorption and porosity, reporting consistent decrement till 1% RSF. The inclusion of 0.5% RSF in optimum mix reduced water absorption and porosity, followed by significant reduction of water absorption by 51% and porosity by 27% with 1% inclusion of RSF over optimum mix without RSF due to the physical blocking action of uniformly dispersed fibers. These discrete fibers disrupt pore connectivity and act as internal barriers, which is additionally complemented by the dual synergistic effects of FA and MK in matrix densification. However, mixtures with 16% MK showed higher porosity and absorption due to complete consumption of portlandite preventing further pozzolanic reactivity, leaving unreacted MK clusters and generating localized voids. Similarly, mixtures with 1.5% RSF showed slightly higher values due to fiber agglomeration, which creates weak zones and increases pathways for water ingress. The strong inverse relationship between compressive strength and water absorption ($R^2 = 0.84$) (see Fig. 9c) indicates that strength development is governed by progressive matrix densification and reduced permeability. Similarly, the pronounced negative correlation between compressive strength and pore volume ($R^2 = 0.92$) (see Fig. 9d) confirms that pore refinement and reduced connectivity are the primary mechanisms enhancing mechanical performance.

4.5. Chloride permeability by RCPT and surface resistivity

All blended mixtures exhibited a significant reduction in chloride permeability with curing age followed by corresponding increase in electrical resistivity with curing age, confirming the progressive enhancement in ionic transport resistance as shown in Fig. 10(a) and (b). At early ages (7 days), the mix containing 20% FA recorded higher charge passed and lower resistivity than the control, which with prolonged curing has performed better than control due to ongoing delayed FA's secondary pozzolanic reactions, resulting impermeable pore network and reduced ionic permeability at 90 days. However, the incorporation of MK along with FA significantly improved chloride resistance, with both RCPT values and ionic conductivity decreasing significantly with increase in MK content. The results agree with the observations by Cheng et al. [50]. The synergistic interaction between FA and MK is the main reason for such improvements, where MK's high fineness promotes rapid pozzolanic reactions, leading to the formation of C–A–S–H. This refines the microstructure and reduces the pore solution conductivity which further

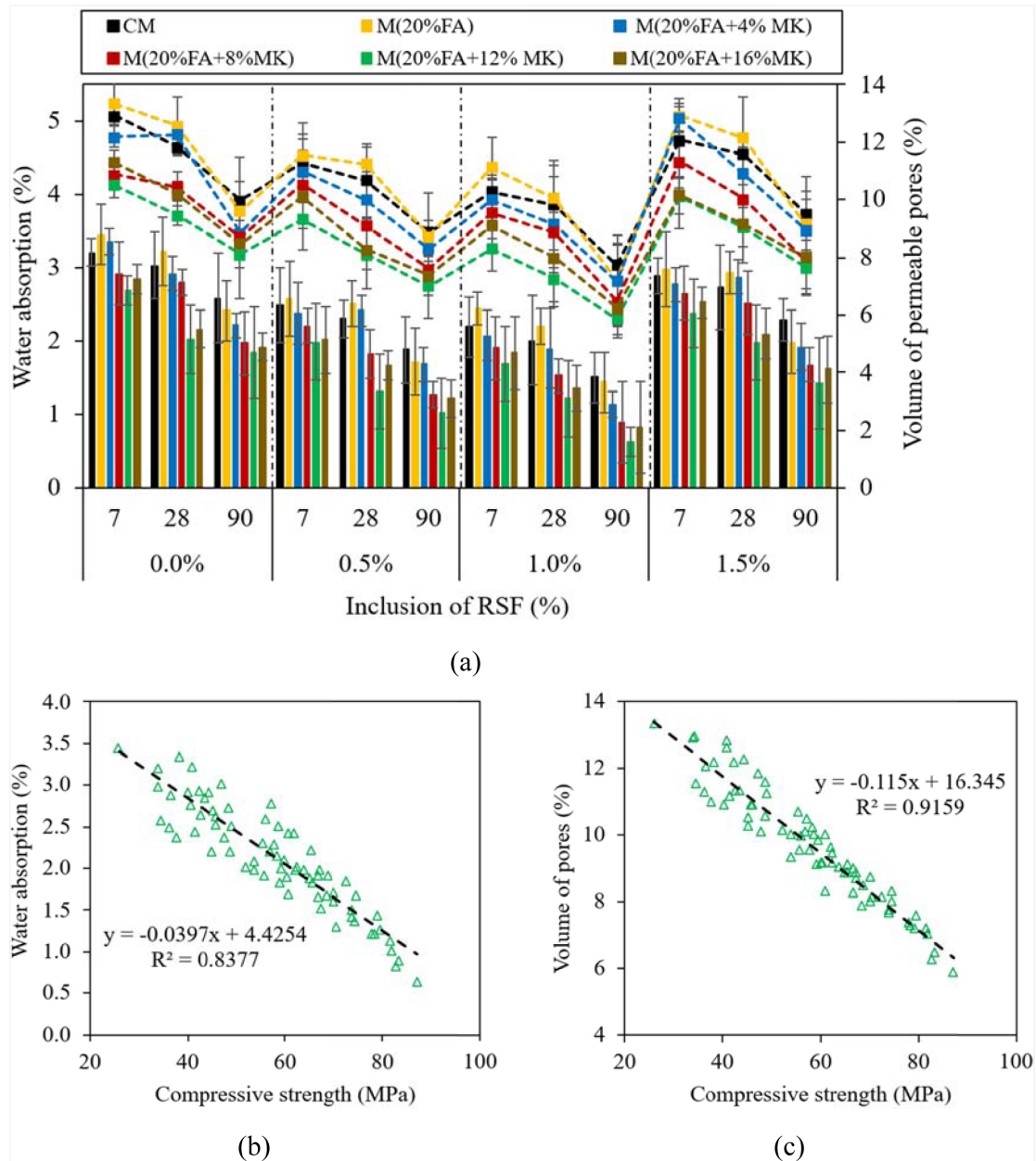


Fig. 9. (a) Water absorption & Porosity, (b) correlation plot for water absorption Vs compressive strength, (c) correlation plot for porosity Vs compressive strength. (Note: Error bars represent standard deviation of three specimens).

limit the ionic transport. As a result, the ternary blend containing 20% FA and 12% MK exhibited the lowest charge passed with a reduction of 51% and the highest resistivity with an increment of 56% at 90 days over control mix, emerging as an optimum mix.

The enhanced performance of this FA–MK blended mixtures is further accelerated with the addition of RSF. The mixes exhibited improved chloride impermeability with varied percentage inclusion of RSF. The optimum mix with 1% RSF delivered the best performance with reduction in charge passed by 67%

and increase in resistivity by 76% over control mix without RSF at 90 days. The improvement is attributed to the physical barrier induced by uniformly dispersed fibers, which disrupt the pore connectivity and restrict ionic mobility. The combination of microstructural densification and physical bridging effects led to a substantial improvement in chloride impermeability. However, the mix containing 1.5% RSF showed slightly higher chloride permeability due to fiber agglomeration, which creates weak zones and interconnected pathways for ion migration,

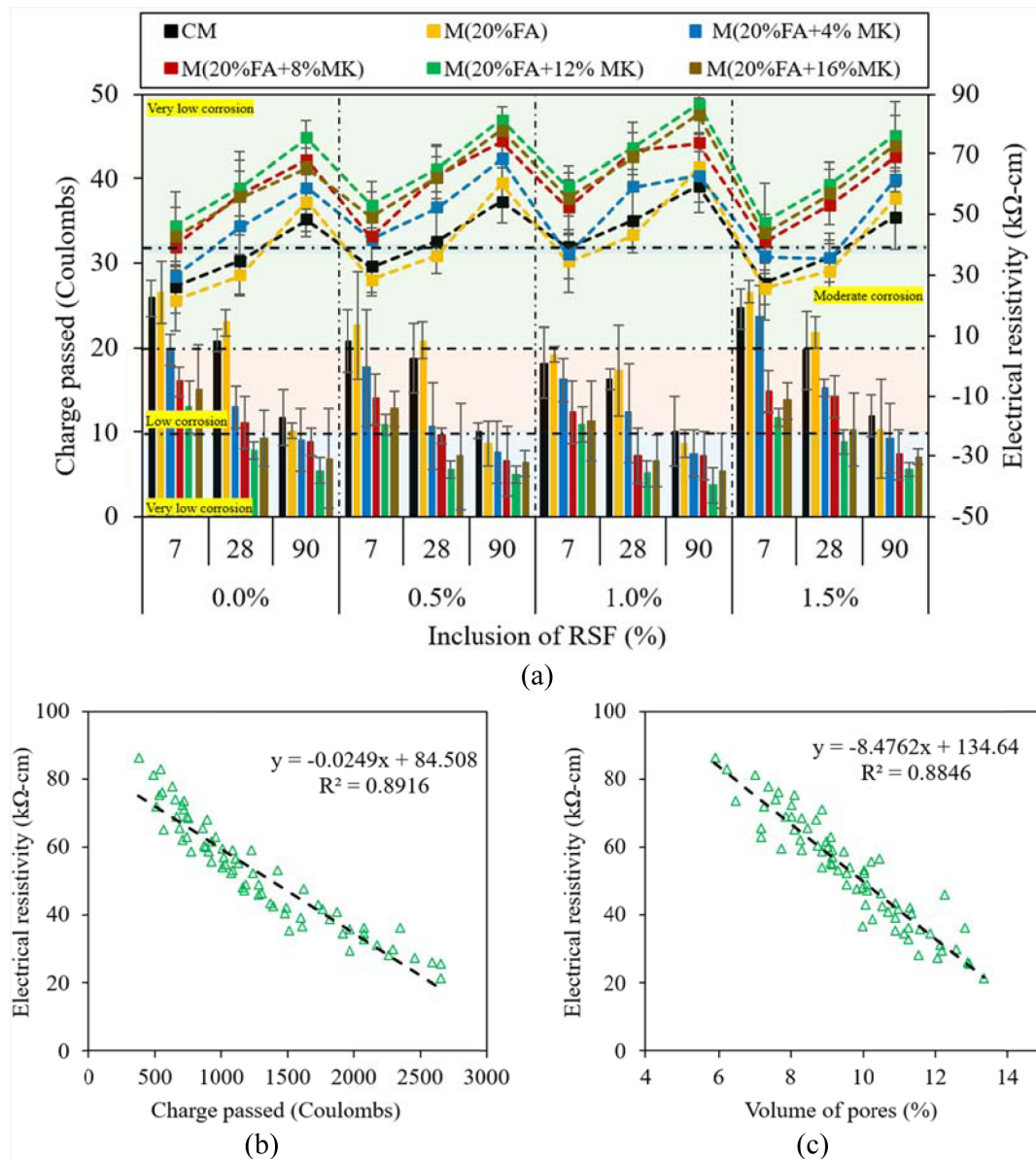


Fig. 10. (a) RCPT & Electrical resistivity, (b) correlation plot for electrical resistivity Vs charge passed, (c) correlation plot for electrical resistivity Vs volume of pores. (Note: Error bars represent standard deviation of three specimens).

thereby reducing resistivity and increasing charge passed.

It should be noted that electrical-based durability tests such as RCPT (ASTM C1202) and surface electrical resistivity may be influenced by the presence of conductive steel fibers within the concrete matrix. The inclusion of RSF can create conductive pathways that affect the measured electrical response [52]. Therefore, the RCPT and resistivity results presented in this study should be interpreted primarily as indicative trends of ionic transport characteristics, rather than direct measures of chloride permeability. However, the comparative trends among mixtures

remain useful for evaluating the relative influence of SCMs and fiber content on durability performance. The strong inverse relationship between electrical resistivity and charge passed ($R^2 = 0.89$) (see Fig. 10b) confirms that higher ionic mobility corresponds to increased permeability and reduced resistance to electrical flow. The pronounced negative correlation between electrical resistivity and pore volume ($R^2 = 0.88$) highlights the dominant role of pore connectivity in governing transport properties. As pore volume increases, continuous conductive pathways facilitate ion migration, leading to lower resistivity values.

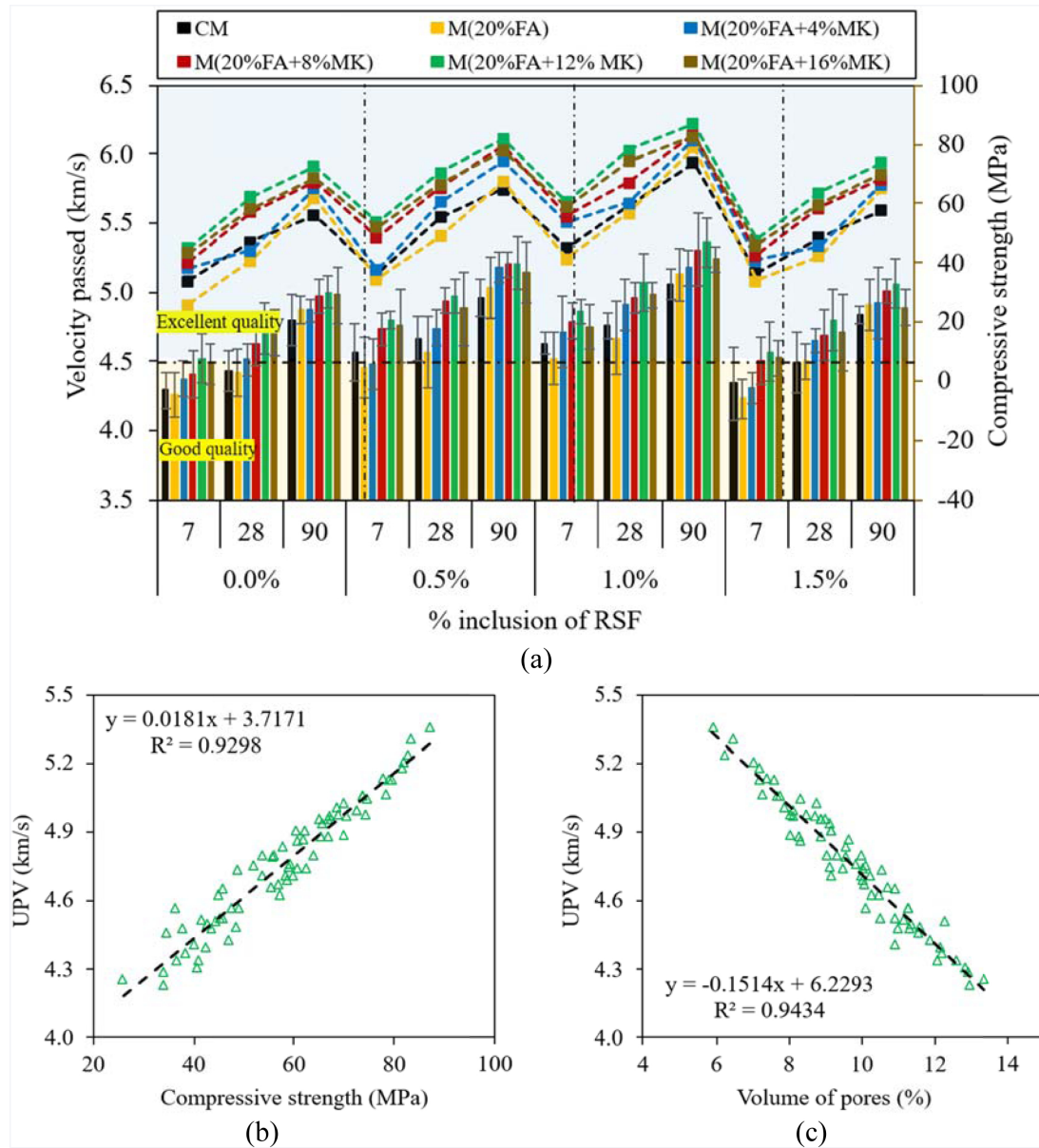


Fig. 11. (a) UPV & Compressive strength, (b) correlation plots for UPV Vs compressive strength, (c) correlation plot for UPV Vs volume of pores. (Note: Error bars represent standard deviation of three specimens).

4.6. Homogeneity

The quality and homogeneity of the concrete mixtures are assessed by ultrasonic pulse velocity (UPV) which showed a steady increase in velocity passed with curing age as shown in Fig. 11. UPV values consistently rose with increase in MK dosage in FA-MK blended mixtures across all curing ages. Among all mixtures, the ternary blend containing 20% FA and 12% MK exhibited the maximum UPV at 90 days, confirming its superior internal homogeneity. The addition of RSF further increased UPV values for the optimized FA-MK blend, particularly at 0.5% and 1%

dosage levels. The optimum mixture with 1% RSF exhibited the highest UPV, arising from the combined hydration refinement induced by FA and MK followed by physical crack-arresting mechanisms provided by the fibers. Well-dispersed fibers enhanced wave transmission by bridging microcracks, reducing localized discontinuities, and enhancing the overall stiffness of the matrix. However, the mix containing 1.5% RSF showed a reduction in UPV values due to fiber agglomeration. This introduces localised voids that creates scattering interfaces, obstructing ultrasonic wave propagation. Similarly, the mixture with 16% MK exhibited comparatively lower UPV because of

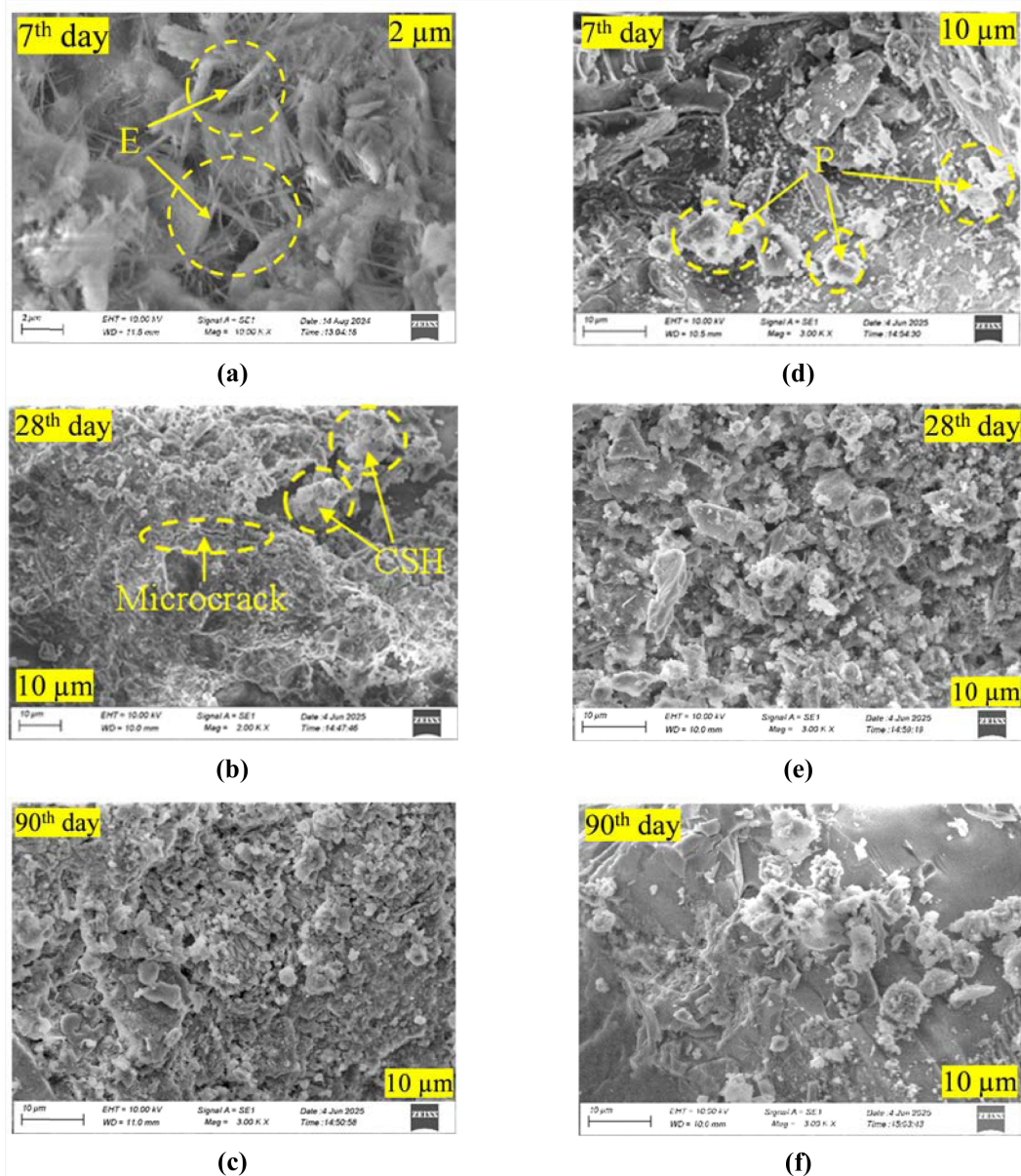


Fig. 12. SEM analysis (a) control mix, 7th day, (b) mix (20%FA+12%MK), 7th day, (c) control Mix, 28th day, (d) mix (20%FA+12%MK), 28th day, (e) control Mix, 90th day, (f) mix (20%FA+12%MK), 90th day.

insufficient availability of portlandite, limiting MK's hydration, leaving unreacted clusters that disrupts matrix uniformity. The strong positive correlation between UPV and compressive strength ($R^2 = 0.93$) (see Fig. 11b) indicates that ultrasonic wave propagation is governed by matrix densification and stiffness enhancement. Conversely, the pronounced negative correlation between UPV and pore volume ($R^2 = 0.94$) (see Fig. 11c) confirms that increased porosity would disrupt wave transmission and increases scattering losses. These relationships highlight porosity as the primary microstructural parameter control-

ling both mechanical performance and ultrasonic response.

4.7. Microstructural properties of concrete mixtures

4.7.1. Influence of FA and MK on microstructure densification

The control mix and blended mix M(20%FA + 12%) are studied for microstructural observations by SEM analysis. At 7 days, the control mix (Fig. 12a) exhibited a clustered matrix characterized by dominant needle-shaped ettringite and voids, indicating

Table 6. Input database for raw materials.

Raw material	Distance from source (km)	Source
Cement, Portland	50	cement production, Portland cement, Portland Cutoff, U - IN
Fly ash	50	fly ash and scrubber sludge market for fly ash and scrubber sludge Cutoff, U - GLO
Metakaolin	70	kaolin, calcined market for kaolin, calcined Cutoff, U - GLO
Sand	30	market for sand sand Cutoff, U - IN
Gravel	30	gravel production, crushed gravel, crushed Cutoff, U - IN
Superplasticizer (Polycarboxylates)	-	polycarboxylates production, 40% active substance polycarboxylates, 40% active substance Cutoff, S - RER
Electricity	-	market for electricity, low voltage electricity, low voltage Cutoff, U - IN-Southern grid
Virgin steel fibers	40	steel production, converter, low-alloyed market for steel, low-alloyed Cutoff, U - GLO
Recycled steel fibers	40	iron scrap, sorted, pressed Recycled content Cutoff, U - GLO
Tap water	-	tap water production, conventional treatment market for tap water Cutoff, U - IN
Transportation	-	transport, freight, lorry, 16-32 metric ton, diesel, EURO 1 Cutoff, U - BR

Note: Transport distances are expressed as approximate one-way distances (km) from the material source to the concrete production site.

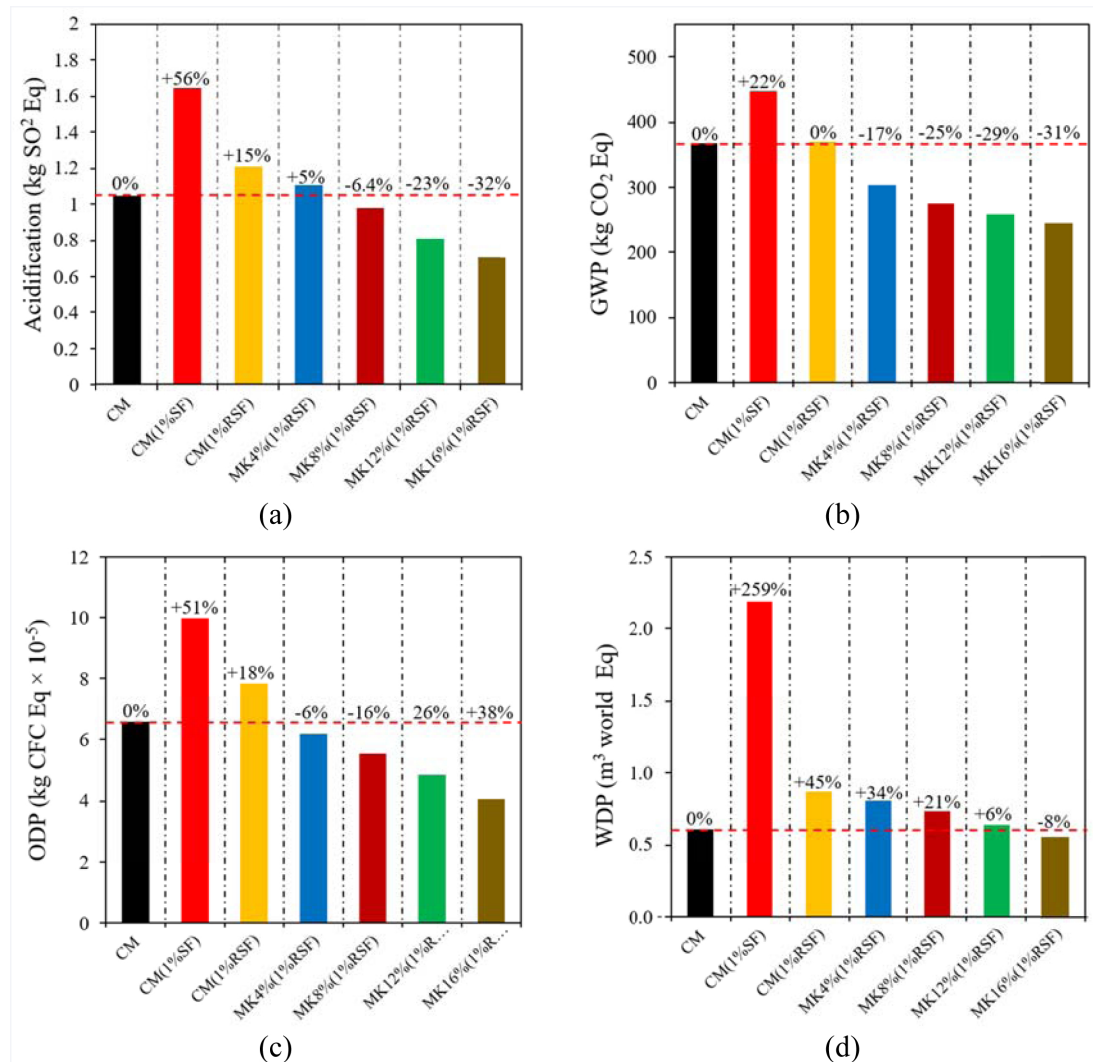
**Fig. 13.** Sustainability indicators (a) Acidification, (b) Global warming potential, (c) Ozone depletion potential, (d) Water depletion potential.

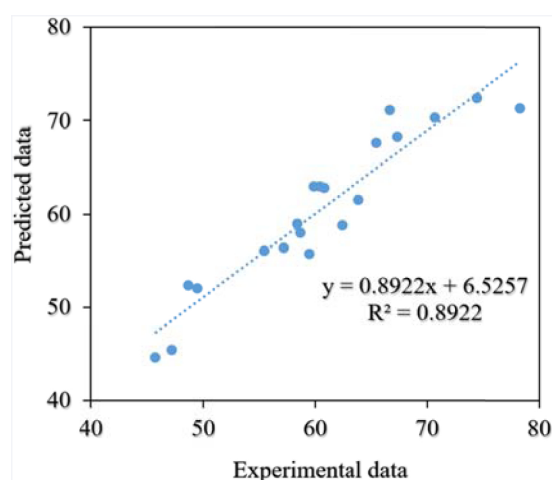
Table 7. ANOVA for compressive strength.

Compressive strength						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant effect
Regression	5	1289.13	257.827	23.18	0.000	Yes
A	1	443.39	443.387	39.86	0.000	Yes
B	1	158.78	158.778	14.27	0.002	Yes
A ²	1	579.79	579.785	52.12	0.000	Yes
B ²	1	59.80	59.796	5.38	0.036	Yes
A×B	1	7.99	7.992	0.72	0.411	No
Error	14	155.73	11.123			
Total	19	1444.86				

Where A is % RSF and B is % MK.

Table 8. Regression statistics of the model.

Standard error (S)	R ²	R ² (Adjusted)
3.33	89.22%	85.37%

**Fig. 14.** Line fit plot for compressive strength.

a slightly porous microstructure, consistent with observations reported by Younis et al. [53]. In contrast, the blend containing 20% FA and 12% MK exhibited a comparatively denser matrix with sign of portlandite formations resulting from early hydration reactivity of MK at initial days. By 28 days, both mixes showed improved densification.

However, blended FA–MK mix exhibited a uniform matrix with refined pore structure, and evenly distributed hydration products, especially portlandite deposition throughout the matrix (see Fig. 12e). This indicates an active early-age pozzolanic interactions within the matrix. At 90 days, both mixtures developed a dense and well-interconnected hydration phases, but the FA–MK mixture demonstrated much better refinement. The continued hydration and pozzolanic activity led to substantial microstructural densification, with MK contributing to early C–A–S–H and C–S–H formation [50] and FA supporting

later-age portlandite consumption. This synergistic dual reaction mechanism produced a more compact, uniform, and durable matrix in the blended concrete (see Fig. 12f).

4.8. Environmental benefits of using FA, MK and RSF

Life cycle analysis of concrete mixtures was conducted for seven mixtures which are mentioned below to evaluate the environmental benefits of using MK, FA and RSF and compared with two control mixes, one is control mix without fibers, another one is control mix with virgin steel fibers. The functional unit adopted in this study is 1 m³ of M40 concrete, which enables consistent comparison between the control and modified mixtures. Fly ash was treated as an industrial by-product of coal combustion and was modelled using a cut-off allocation approach, where no upstream environmental burdens from electricity generation were assigned to fly ash except for transportation and processing. RSF were considered as a by-product recovered from waste tires, therefore, the primary environmental burden associated with tire production was not allocated to RSF. It is to be noted that the present LCA adopts a cut-off allocation approach, where fly ash and recycled steel fibers are treated as secondary materials and their upstream production burdens are not allocated. Consequently, the reported environmental impacts primarily reflect transportation and concrete production stages, and the sustainability benefits should be interpreted within the context of the adopted system boundary and allocation assumptions. A limitation is that the analysis was restricted to production-stage impacts under a cradle-to-gate boundary. Future studies should consider whole-life assessments incorporating service-life performance, maintenance requirements, and end-of-life scenarios to provide a more comprehensive evaluation of the sustainability benefits associated with FA, MK, and RSF incorporation.

- Control mix denoted by (CM),

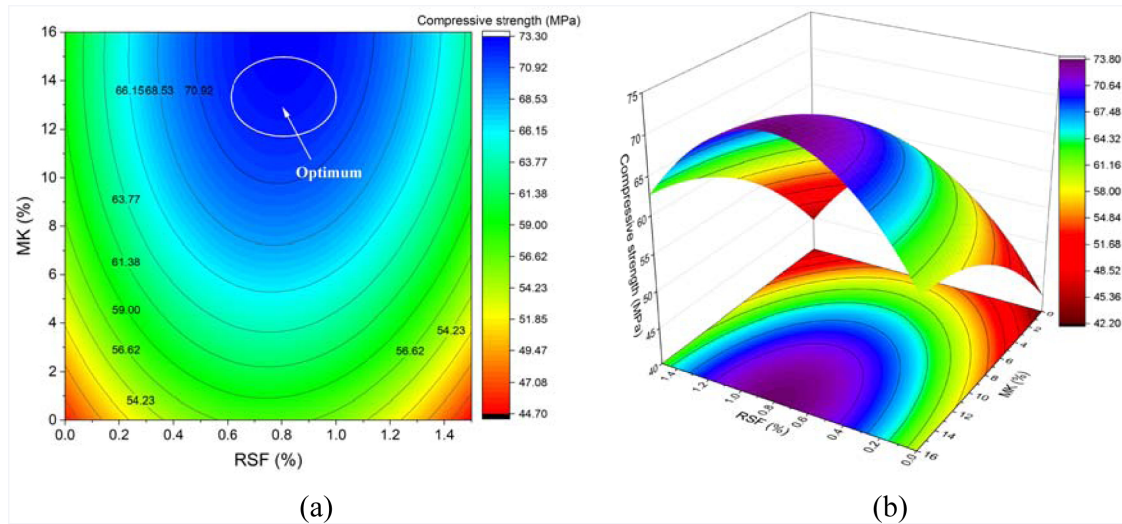


Fig. 15. (a) Contour and (b) surface plot for compressive strength.

Table 9. Regression models for durability properties.

Durability property	Regression equation
Capillary absorption rate	$0.015 - 0.016 A - 0.000187 B + 0.0097 A^2 + 0.00004 (A \times B)$
Volume of pores	$12.34 - 5.21 A - 0.26 B + 3.13 A^2 + 0.0067 B^2 - 0.0038 (A \times B)$
RCPT	$2025 - 916 A - 169 B + 619 A^2 + 6.07 B^2 + 5.69 (A \times B)$
UPV	$4.38 + 0.83 A + 0.047 B - 0.50 A^2 - 0.0017 B^2 - 0.003 (A \times B)$

Where A is % RSF and B is % MK.

Table 10. Regression statistics of the durability models.

Capillary absorption rate		
Standard error (S)	R ²	R ² (Adjusted)
0.0009	87.92%	83.61%
Volume of pores (%)		
Standard error (S)	R ²	R ² (Adjusted)
0.48	90.34%	86.90%
Chloride permeability (RCPT)		
Standard error (S)	R ²	R ² (Adjusted)
132.64	94.12%	92.03%
Homogeneity (UPV)		
Standard error (S)	R ²	R ² (Adjusted)
0.049	94.22%	92.16%

- Control mix with 1% steel fibers denoted by CM(1%RSF),
- Control mix with 1% RSF denoted by CM(1%RSF)
- Mix with 20% FA, 4% MK and 1% RSF denoted by MK4%(1%RSF)
- Mix with 20% FA, 8% MK and 1% RSF denoted by MK8%(1%RSF)
- Mix with 20% FA, 12% MK and 1% RSF denoted by MK12%(1%RSF)
- Mix with 20% FA, 16% MK and 1% RSF denoted by MK16%(1%RSF)

The necessary inputs to model the raw materials for LCA evaluation are given in Table 6. For inventory items such as electricity, transportation im-

pacts were not separately considered because these inputs were represented using regional grid-based datasets available within the LCA database. Accordingly, transport distances for such entries are reported as not applicable (-). Similarly, transport distances for superplasticizers are also embedded in the inventory and hence not considered.

Control mix with 1% virgin steel fibers showed significant rise in Acidification by 56%, Global warming potential (GWP) by 22%, Ozone depletion potential (ODP) by 51% and Water depletion potential by 259% over control mix (see Fig. 13). The significantly higher water depletion potential (259%) for concrete with virgin steel fibers is primarily due to extensive usage of water involved in primary steel production, including iron ore beneficiation, coke production, and cooling operations in blast furnace–basic oxygen furnaces. However, incorporation of RSF in control mix had showed minimal impacts in terms of Acidification, GWP, ODP and especially WDP which was only 45% higher than control mix, conserving a huge amount of water by 214% compared to the same mix with virgin steel fibers. Similarly, introduction of FA and MK in 1% RSF reinforced concrete mixtures further reduced the environmental impacts. An increase in environmental benefits is obtained with the rise in MK dosage in the mix. Especially, the optimum mix Mix(20%FA + 12%MK)

Table 11. ANOVA for durability properties.

Capillary absorption rate						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant effect
Regression	5	0.000093	0.000019	20.39	0.000	Yes
A	1	0.000079	0.000079	87.32	0.000	Yes
B	1	0.000001	0.000001	1.64	0.221	No
A ²	1	0.000084	0.000084	92.35	0.000	Yes
B ²	1	0.000000	0.000000	0.33	0.575	No
A×B	1	0.000000	0.000000	0.39	0.542	No
Error	14	0.000013	0.000001			
Total	19	0.000106				
Volume of pores (%)						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant effect
Regression	5	30.5304	6.1061	26.20	0.000	Yes
A	1	11.9463	11.9463	51.26	0.000	Yes
B	1	3.0893	3.0893	13.26	0.003	Yes
A ²	1	12.2868	12.2868	52.72	0.000	Yes
B ²	1	0.6562	0.6562	2.82	0.116	No
A×B	1	0.0029	0.0029	0.01	0.912	No
Error	14	3.2629	0.2331			
Total	19	33.7932				
Chloride permeability (RCPT)						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant effect
Regression	5	3945806	789161	44.85	0.000	Yes
A	1	367769	367769	20.90	0.000	Yes
B	1	1282370	1282370	72.88	0.000	Yes
A ²	1	479261	479261	27.24	0.000	No
B ²	1	528574	528574	30.04	0.000	Yes
A×B	1	6464	6464	0.37	0.554	No
Error	14	246323	17595			
Total	19	4192129				
Homogeneity (UPV)						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant effect
Regression	5	0.558726	0.111745	45.67	0.000	Yes
A	1	0.307650	0.307650	125.74	0.000	Yes
B	1	0.101379	0.101379	41.43	0.000	Yes
A ²	1	0.315005	0.315005	128.74	0.000	No
B ²	1	0.045244	0.045244	18.49	0.001	Yes
A×B	1	0.002221	0.002221	0.91	0.357	No
Error	14	0.034255	0.002447			
Total	19	0.592980				

Where A is % RSF and B is % MK.

with 1% RSF showed significant benefits by reducing Acidification potential by 23%, GWP by 29%, ODP by 26% over control mix. WDP exhibited by the optimum mix is comparable to control mix (see Fig. 13d). The relatively small variation observed in ozone depletion potential (ODP) and acidification potential (AP) across mixtures can be attributed to the fact that these impact categories are largely governed by upstream energy production processes such as energy production, fuel combustion, and transportation activities, which might remain almost similar for all concrete mixes.

4.9. Statistical optimization of concrete mixtures

The mix proportions of the control and modified concrete mixtures, along with the experimental re-

sults for mechanical and durability properties, were utilized for statistical analysis to investigate the interactive effects of MK and RSF on compressive strength, pore structure, chloride permeability, and UPV at 28 days of curing. It is to be noted that the ANOVA and response surface models developed in this study were based on the available factorial experimental dataset comprising three replicate specimens for each test condition. The primary objective of the statistical analysis was to evaluate the relative influence of MK and RSF and to identify interaction trends and approximate optimum regions within the investigated parameter range. Since independent validation runs and centre points were not included in the experimental design, the developed models should be interpreted as indicative rather than universally predictive. Therefore, the conclusions drawn from

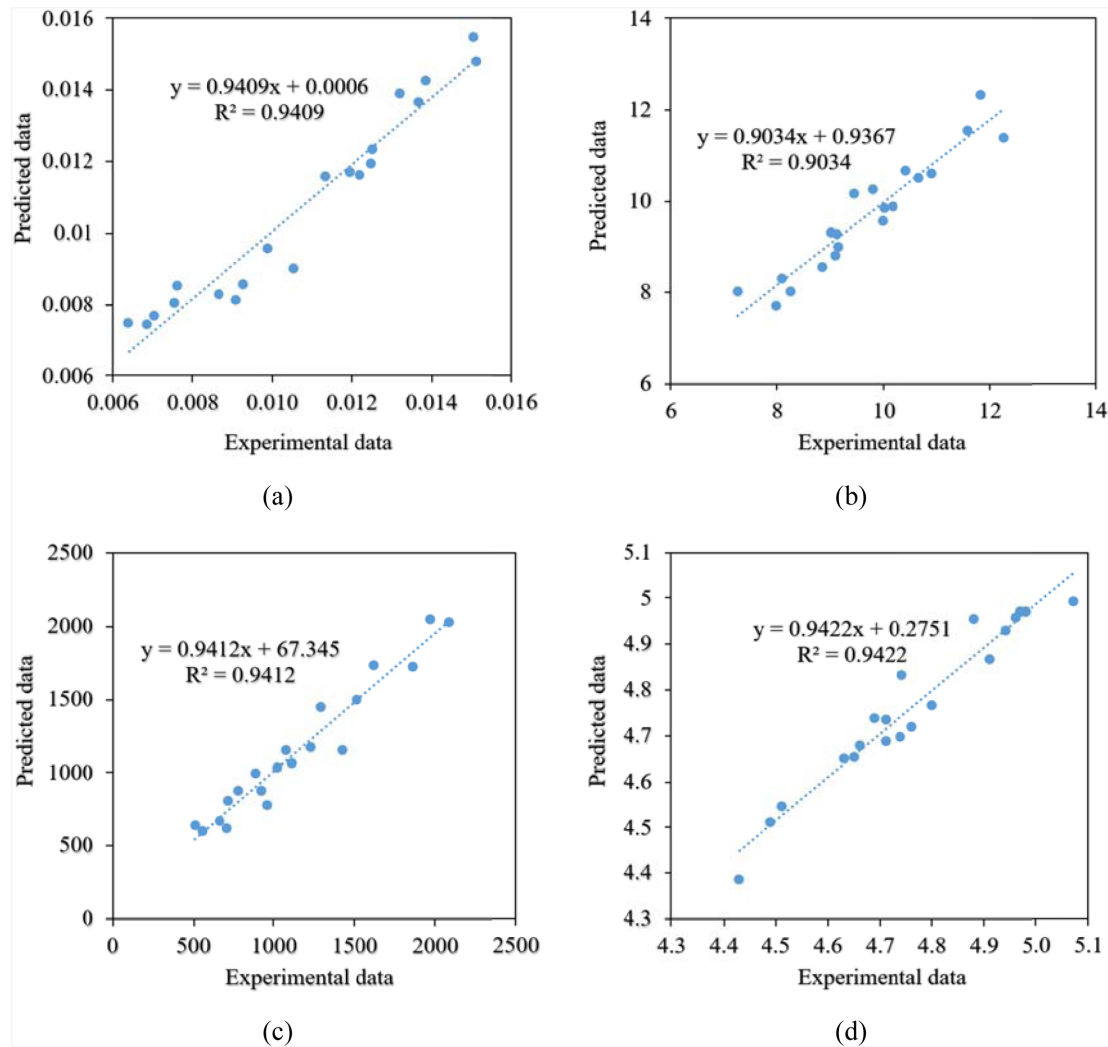


Fig. 16. Line fit plots for durability properties (a) capillary absorption, (b) volume of pores (%), (c) chloride permeability, (d) UPV.

the statistical analysis are limited to the investigated range of variables and should be considered as trend-based guidance for mixture optimization.

4.9.1. Statistical significance of RSF and MK on mechanical properties

The regression model obtained from regression analysis for compressive strength demonstrates a significant statistical model with high F value of 23.18 and $p < 0.05$, indicating highly significant overall regression (see Table 7). The model shows an excellent fit between the experimental and predicted data with $R^2 = 0.89$ (see Table 8 and Fig. 14). Both %RSF (denoted as A) and %MK (denoted as B) exhibit statistically significant linear effects, with %RSF being the dominant contributor, reporting its crucial role in boosting strength parameters. The significant negative quadratic terms for %RSF² and %MK² indicate a clear nonlinear response, reflecting compressive strength enhances up to optimal replacement

levels, beyond which compressive strength decreases. This aligns with the experimental observation indicated by clustering of fibers and increased water demand at higher dosages results in reduction in strength. The interaction term (%RSF $\times$ %MK) is insignificant, suggesting that the effects of RSF and MK on compressive strength are largely independent. Overall, the contour plot (see Fig. 15a) confirms that maximum compressive strength is achieved at intermediate levels of both variables (i.e. 0.8–1.2% of RSF and 10–14% of MK), providing a reliable basis for mix proportion optimization within the studied domain.

Regression equation

Compressive strength = $45.52 + 31.80 A + 1.87 B - 21.54 A^2 - 0.064 B^2 + 0.2 (A \times B)$

4.9.2. Statistical significance of RSF and MK on durability properties

The regression models (see Table 9) developed for capillary absorption rate, volume of pores, RCPT, and

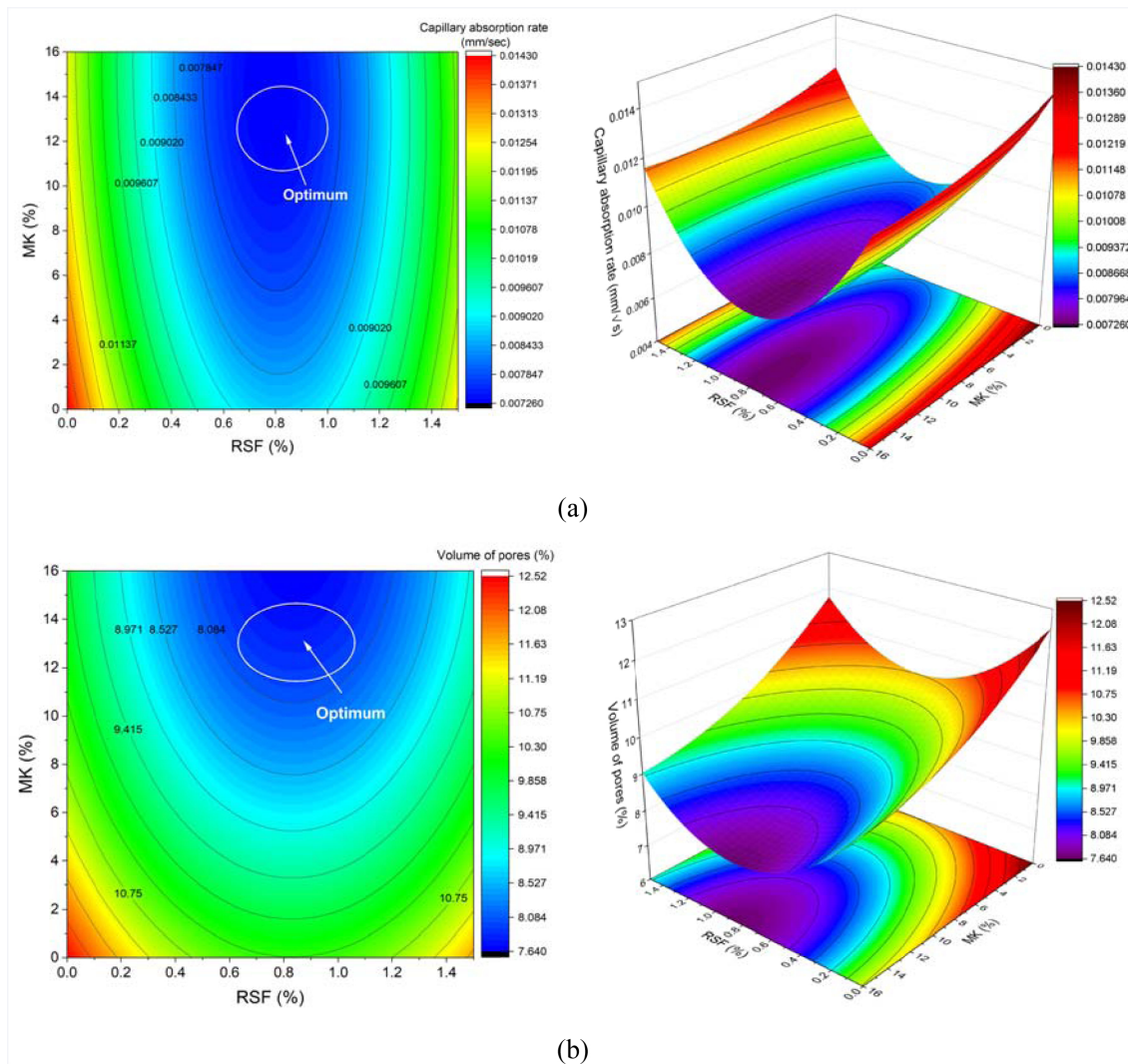


Fig. 17. Contour and surface plot for durability properties (a) capillary absorption, (b) volume of pores (%), (c) chloride permeability (RCPT), (d) UPV.

UPV having F-values 20.39, 26.20, 44.85 and 45.67 respectively, demonstrate strong statistical significances, with highly significant overall regressions ($p < 0.05$) as shown in Table 11. The regression models for durability properties exhibits an excellent fit with R^2 - 0.87, 0.90, 0.94 and 0.94 for capillary absorption, volume of pores, RCPT and UPV respectively (see Table 10 and Fig. 16). Across all durability indices, %RSF emerges as the most dominant parameter, exhibiting statistically significant linear and quadratic effects, while %MK also contributes significantly, particularly to pore structure refinement, chloride ion penetration, and ultrasonic wave transmission. The negative linear coefficients observed for capillary absorption, pore volume, and RCPT indicate that moderate replacements of RSF and MK effectively

enhances matrix densification, reduces connected porosity, and limits ionic transport. This arises from the dual mechanism of SCM induced hydration densification and improved crack-bridging mechanism induced by fibers. However, positive quadratic terms for both $\%RSF^2$ and $\%MK^2$ highlight a clear nonlinear response, which signifies that inclusions MK and RSF beyond optimal dosage would adversely affect durability, likely due to insufficient portlandite availability the limits further pozzolanic reactivity of MK and due to fiber agglomeration, which creates local voids within the cementitious matrix. The UPV response shows increased pulse velocity at intermediate replacement levels, indicative of a denser homogeneous internal matrix, followed by a decline at higher contents. The interaction terms ($\%RSF \times \%MK$) are con-

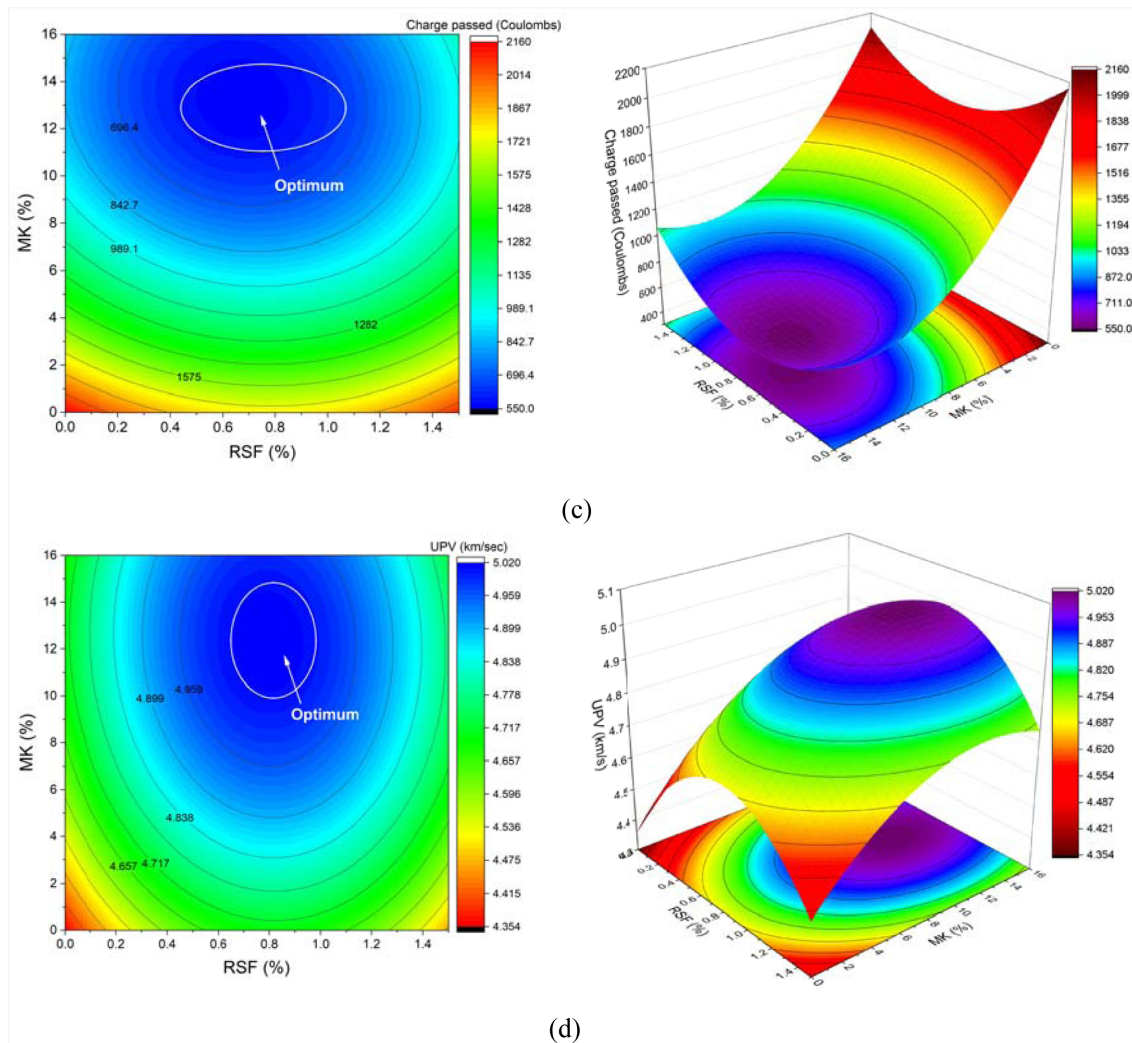


Fig. 17. Continued.

sistently insignificant ($p > 0.05$), suggesting that the durability enhancement mechanisms of RSF and MK act largely independently rather than synergistically.

The contour plots (Fig. 17) highlight the optimal region for durability performance, indicating that the best results occur within the range of 0.8–1.2% RSF and 10–14% MK. This optimal region closely aligns with the experimental observations, confirming the reliability of the developed statistical model and its ability to capture the interaction effects between RSF and MK on durability properties. Overall, the combined durability response surfaces clearly demonstrate the existence of optimal RSF–MK combinations that significantly improve transport resistance and microstructural integrity. It also suggests that the increased dosages beyond optimal replacement levels can adverse these benefits, underscoring the importance of performance-based optimization in durable concrete mix design.

5. Conclusions

An extensive investigation is conducted to study the effect of FA, MK and RSF on mechanical and durability properties of concrete at various curing periods of 7, 28 and 90 days. The experimental results are compared with control mix and the improvements in mechanical and durability performance is critically analysed at the micro levels through XRD and SEM analysis. In addition, statistical analysis has been conducted to evaluate the statistical significance of MK and RSF on mechanical and durability properties. The conclusions drawn from the experimental observations are presented below.

- The synergy of FA and MK enhanced mechanical properties with rise in compressive strength by 20–25%, split tensile strength by 25–29% and flexural strength by 23–28%, especially at a replacement

level of 20% FA and 12% MK, emerging as the optimum mix.

- Addition of RSF to all concrete mixtures further enhanced mechanical properties by 30-50% especially at 1% inclusion of RSF, showing huge sustainability benefits in the construction sector.
- The combined use of FA and MK with RSF showed significant increase in resistance to chloride permeability with reduction in chloride ingress by 60-70% and increase in ionic resistivity by 70-80%. This combination of FA, MK and RSF becomes an excellent synergy for structures exposed to aggressive environment such as coastal constructions.
- The improved transport properties observed in the present study indicate the potential of the developed concrete mixtures to enhance durability performance. However, it should be noted that these results are based on laboratory transport indicators such as sorptivity, RCPT, and electrical resistivity. Therefore, the conclusions regarding durability in coastal environments should be interpreted cautiously, and further long-term exposure studies are required to verify compliance with durability provisions specified in standards such as IS 456.
- Microstructural observations by SEM confirmed the densification of FA-MK blended matrix showing evidence of additional formation of CSH gel right after 7 days of curing.
- Life cycle analysis reported significant environmental benefits in terms of Global warming and water depletion potential with the use of MK and RSF in concrete mixtures, enhancing sustainability in the construction sector.
- The regression models confirm the significant role of combination of MK and RSF in enhancing the mechanical and durability properties and densification of matrix. The ANOVA results across all models confirm the statistically significance of MK and RSF.
- Overall, the excellent synergy of FA, MK and RSF enhances sustainability and offers a huge scope in designing low carbon high performance and ultra-high performance precast concrete structural elements, especially paving way for practical implications to coastal infrastructure.

Limitations and future work

The present study primarily focuses on the evaluation of fresh, mechanical, and transport-related durability indicators under laboratory conditions. The durability performance was assessed using tests

such as sorptivity, RCPT, and electrical resistivity, which provide indirect indicators of long-term durability. However, the influence of cracking, long-term environmental exposure, and field conditions was not investigated in this study. Future research should focus on evaluating the long-term performance of these concrete mixtures under realistic exposure conditions, including marine environments, as well as studying the influence of cracking and fiber distribution on durability behaviour.

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Conflicts of interest

The authors declare no conflict of interest.

Authors contribution

Lova Raju Surla – Investigation, Conceptualization, Methodology, Data curation, Software, Supervision, Original draft preparation, **Dr. Ramprasad Naik Dasavathu** - Supervision, Original draft preparation, Reviewing and Editing, **Dr. Raja Murugadoss Jeyaraj** – Conceptualization, Software, Supervision, Reviewing and Editing.

Data availability

The data will made available on request.

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