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# Mechanical and Piezoresistive Properties of Fiber-Reinforced Cement Mortar Incorporating IOW as Fine Aggregate

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***Abstract*—This study examines the piezoresistive behavior, mechanical properties, and durability characteristics of cement mortar with fine aggregate partially and fully substituted by iron ore waste (IOW) at replacement levels of 25%, 50%, 75%, and 100% by weight. Micro steel fibers (2% by cement weight) and a chemical admixture were incorporated to enhance composite performance. Compressive strength, split tensile strength, water absorption, and piezoresistive behavior under compressive loading were evaluated. Results demonstrate that the 50% IOW replacement mix (Mix-3) achieves the highest compressive strength of 27.62 N/mm² (36.32% above control) and split tensile strength of 3.92 N/mm² (29.4% above control). Piezoresistive testing revealed systematic decreases in electrical resistivity with increasing stress, with Mix-4 (75% IOW) exhibiting the maximum fractional change in resistance (FCR = −0.403), demonstrating superior self-sensing capability. These findings confirm IOW as an effective, sustainable fine aggregate replacement in smart cement mortar applications for structural health monitoring.**

***Keywords*—Cement mortar; Iron ore waste (IOW); Steel fiber; Piezoresistivity; Compressive strength; Split tensile strength; Water absorption; Structural health monitoring.**

## I. INTRODUCTION

Cement mortar, composed of cement, fine aggregate, and water, is a fundamental construction material widely employed in masonry, surface finishing, joint filling, and repair works. Its mechanical performance is governed principally by the water–cement ratio: lower ratios promote denser microstructure, higher strength, and improved durability. However, escalating global demand for natural river sand as fine aggregate is causing severe depletion of riverbed resources, leading to ecological degradation, regulatory restrictions, and supply-side cost pressures.

Concurrently, iron ore mining generates large volumes of processing waste. Iron ore waste (IOW) accumulates at mine tailings sites, posing soil contamination and groundwater pollution risks. Its mineralogical composition—primarily iron oxides, silicates, and aluminates—gives it angular grain morphology, relatively high specific gravity (~3.2–3.5), and adequate hardness, making it a physically suitable substitute for river sand in cementitious composites.

Beyond structural performance, smart monitoring of civil infrastructure has gained prominence following several high-profile structural failures attributed to undetected internal damage. Piezoresistive cement composites, which exhibit measurable changes in electrical resistivity under mechanical load, offer a compelling, cost-effective alternative to embedded sensor networks. Incorporating conductive inclusions such as steel fibers into the cement matrix creates percolating conductive networks; when the matrix deforms under stress, contact topology changes produce quantifiable resistance variations. The fractional change in resistance (FCR = $\Delta R/R_0$) serves as the primary piezoresistive metric for assessing self-sensing performance.

This investigation aims to evaluate the combined influence of IOW as a fine aggregate replacement (0–100%) and 2% micro steel fiber addition on the mechanical and piezoresistive properties of cement mortar. The dual objective—sustainable waste utilization and smart material development—addresses key priorities in green construction and intelligent infrastructure monitoring.

## II. LITERATURE REVIEW

**Qasim et al. [1]** investigated mechanical properties and piezoresistive behavior of fiber-reinforced cement composites incorporating carbon black (7.5%) with 1% carbon fiber and polypropylene fibers. They reported that carbon black significantly enhances matrix conductivity while carbon fiber improves ductility and post-crack load-carrying capacity.

**Sasmal et al. [2]** studied piezoresistive properties of cementitious nanocomposites incorporating multi-walled carbon nanotubes (MWCNT). The optimal MWCNT dosage

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of 0.5% by binder weight yielded the most stable and repeatable piezoresistive response, demonstrating the potential of nano-fillers for self-sensing.

**Dinesh et al. [3]** analyzed piezoresistive properties of cement mortar with 0.5%, 1%, and 2% carbon nanofiber. Carbon nanofiber provided excellent electrical conductivity and improved sensor linearity compared with unreinforced mortar at all test proportions.

**Liu et al. [4]** examined the combined addition of nano carbon black (NCB) and nickel nanofiber (NiNF) in cement mortar. A combination of 2% NCB and 0.5% NiNF produced stable electrical response and reduced signal noise, improving signal-to-noise ratio in stress-sensing applications.

**Wen and Chung [5]** performed a comparative study of steel fiber and carbon fiber cement as piezoresistive strain sensors. A steel fiber volume fraction of 0.36% outperformed 0.72% in both piezoresistive sensitivity and compressive strength, suggesting that optimal fiber dosage is critical for sensing performance.

**Garg et al. [6]** investigated split tensile strength of cement mortar incorporating micro silica and nano silica. Micro silica at 15% replacement and nano silica at 1% replacement produced maximum tensile strength improvements, confirming the pozzolanic densification mechanism.

**Yerramala et al. [7]** examined the influence of fly ash replacement on cement mortar strength, concluding that an optimum fly ash dosage of 10% maximizes mechanical performance while providing workability benefits.

The reviewed literature confirms that conductive fibers and fillers enhance both mechanical and piezoresistive properties of cementitious composites. However, the use of IOW as a fine aggregate replacement in conjunction with steel fiber for simultaneous structural improvement and self-sensing capability remains largely unexplored, representing the key research gap addressed by this work.

## III. MATERIALS

Ordinary Portland Cement (OPC 53 Grade) conforming to IS 12269 was used as the binding material. The cement was stored in sealed bags in a dry environment to prevent moisture ingress prior to testing. Natural river sand (Zone II, IS 383), with a fineness modulus of 2.7 and specific gravity of 2.65, served as the control fine aggregate.

Iron ore waste (IOW) was sourced from an iron ore processing facility. The material was dried and sieved to achieve a particle size distribution matching natural river sand. IOW exhibited a specific gravity of approximately 3.3, an angular grain shape, and was free of organic impurities or deleterious substances that could impair cement hydration. Its higher specific gravity relative to natural sand contributes to improved packing density at intermediate replacement levels, enhancing matrix impermeability.

Brass-coated micro steel fibers with an aspect ratio of 60 (length = 30 mm, diameter = 0.5 mm) were incorporated at 2% by cement weight. Steel fibers develop mechanical interlocking and bridging mechanisms that resist crack propagation, significantly improving post-crack ductility and tensile strength. Additionally, steel fibers form conductive percolation networks within the mortar matrix, enabling piezoresistive behavior. A polycarboxylate-based chemical admixture was used at 1% by cement weight to maintain workability and achieve a consistent water–cement ratio of 0.5 across all mixes. Potable water free from harmful dissolved salts and organic contaminants was used for mixing and curing.

## IV. METHODOLOGY

### *A. Mix Design and Proportions*

A standard 1:3 cement-to-aggregate ratio by volume was adopted for all mixes. Five mixes were prepared: Mix-1 (control, 0% IOW), Mix-2 (25% IOW), Mix-3 (50% IOW), Mix-4 (75% IOW), and Mix-5 (100% IOW). Fine aggregate was progressively replaced by IOW on an equivalent weight basis. Steel fiber (2% by cement weight) and chemical admixture (1% by cement weight) were held constant across all mixes, with a water–cement ratio of 0.5. Table I presents the detailed mix proportions.

**TABLE I. MIX PROPORTIONS OF CEMENT MORTAR (IN GRAMS PER BATCH)**

| Mix | IOW (%) | Cement (g) | Sand (g) | IOW (g) | Water (g) | S.Fiber (g) | Admix. (g) |
|---|---|---|---|---|---|---|---|
| M-1 | 0 | 169 | 507 | 0 | 63 | 2 | 2 |
| M-2 | 25 | 169 | 380 | 127 | 63 | 2 | 2 |
| M-3 | 50 | 169 | 254 | 253 | 63 | 2 | 2 |
| M-4 | 75 | 169 | 127 | 380 | 63 | 2 | 2 |
| M-5 | 100 | 169 | 0 | 507 | 63 | 2 | 2 |

### *B. Specimen Preparation and Curing*

For each mix, cube specimens of 70.6 × 70.6 × 70.6 mm were cast for compressive strength and water absorption tests, while cylindrical specimens (100 mm diameter, 200 mm height) were cast for split tensile strength and piezoresistive tests. Three specimens per test configuration were prepared, and the mean was reported. After casting, specimens were covered with wet burlap for 24 hours and subsequently immersed in potable water for curing at 7, 14, and 28-day test ages. Copper electrodes were embedded at 20 mm spacing (contact area 1200 mm²) in cylindrical

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specimens during casting to facilitate four-probe resistance measurement.

*C. Test Methods*

*C.1 Compressive Strength Test*

Compressive strength was measured using a Compression Testing Machine (CTM) on 70.6 mm cube specimens cured for 7, 14, and 28 days, in accordance with IS 4031 (Part 6). Load was applied at a uniform rate of 140 kg/cm²/min until failure. Results are expressed in N/mm².

*C.2 Split Tensile Strength Test*

Split tensile strength was determined on cylindrical specimens (100 mm × 200 mm) at 7, 14, and 28 days per IS 5816. Specimens were loaded horizontally along the diametral plane at a controlled rate until failure. Split tensile strength was computed as $f_t = 2P / (\pi DL)$, where P is the failure load, D the diameter, and L the length.

*C.3 Water Absorption Test*

Hardened cube specimens were oven-dried at 100°C to constant weight, then immersed in water for 24 hours. Water absorption (%) was calculated as [(wet weight − dry weight) / dry weight] × 100. This metric reflects porosity and long-term durability potential.

*C.4 Piezoresistive (FCR) Test*

Electrical resistance was measured using a four-probe technique to eliminate contact resistance errors. A 12 V DC power source drove current through the outer electrodes; voltage was measured across the inner electrodes (spacing 20 mm). Cylindrical specimens were loaded incrementally in compression while resistance was recorded at each load step. The fractional change in resistance is defined as:

$$FCR = \Delta R / R_0 = (R - R_0) / R_0 \qquad (1)$$

where R is the resistance at any given stress increment and $R_0$ is the initial resistance at zero load. A decreasing (more negative) FCR with increasing stress indicates enhanced electrical conductivity as fiber contacts multiply, signifying better piezoresistive sensitivity.

## V. RESULTS AND DISCUSSION

*A. Compressive Strength*

Table II presents compressive strength values at 7, 14, and 28 curing days. All mixes exhibit the expected strength gain with curing age. The control mix (Mix-1) achieved 20.26 N/mm² at 28 days. Mix-3 (50% IOW) recorded the maximum 28-day strength of 27.62 N/mm², representing a 36.32% improvement over the control. This enhancement is attributed to the higher specific gravity and angular particle shape of IOW, which improves aggregate–paste interlocking and reduces matrix porosity. Mix-2 (25% IOW) also exceeded the control (24.68 N/mm²), while Mix-4 (75% IOW) and Mix-5 (100% IOW) showed progressively lower strengths at 23.14 and 22.54 N/mm², respectively.

The observed strength reduction beyond 50% IOW replacement can be attributed to excess angular particles disrupting optimal aggregate packing, increasing interparticle voids and internal friction during mixing, and potentially reducing workability despite the admixture. The 7-day anomalously low strength of Mix-2 (8.83 N/mm²) is consistent with IOW's slower initial hydration kinetics, as the angular particles delay early cement–aggregate bond development. By 28 days, however, Mix-2 fully recovered, indicating that long-term strength gain is unimpaired.

TABLE II. COMPRESSIVE STRENGTH (N/MM²)

| Mix | IOW (%) | 7 Days | 14 Days | 28 Days |
|---|---|---|---|---|
| M-1 | 0 | 15.38 | 15.98 | 20.26 |
| M-2 | 25 | 8.83 | 20.80 | 24.68 |
| M-3 | 50 | 18.66 | 24.34 | 27.62 |
| M-4 | 75 | 12.44 | 18.52 | 23.14 |
| M-5 | 100 | 13.98 | 12.77 | 22.54 |

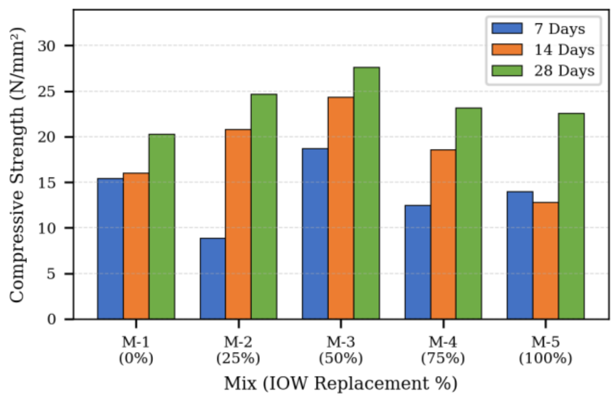


Fig. 1. Variation of compressive strength with IOW replacement percentage.

*B. Split Tensile Strength*

Split tensile strength results are presented in Table III. The control mix (Mix-1) achieved 3.03 N/mm² at 28 days. Mix-3 (50% IOW) produced the highest split tensile strength of 3.92 N/mm²—approximately 29.4% above the control—demonstrating that steel fiber bridging and improved matrix densification from moderate IOW replacement act synergistically. Mix-4 (75% IOW) achieved 3.62 N/mm² and Mix-5 (100% IOW) reached 3.30 N/mm², both exceeding the control, suggesting that steel fibers effectively compensate for reduced matrix cohesion at higher IOW levels.

The sustained tensile strength enhancement at high IOW replacement levels (75–100%) underscores the role of steel fiber crack-bridging in resisting diametral splitting. As the

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matrix cracks, fibers crossing the fracture plane maintain load transfer, delaying complete separation. This synergy between fiber reinforcement and IOW-improved aggregate-paste bond is the primary mechanism enabling tensile performance exceeding that of the unreinforced control mix across all replacement levels.

**TABLE III. SPLIT TENSILE STRENGTH (N/MM²)**

| Mix | IOW (%) | 7 Days | 14 Days | 28 Days |
|---|---|---|---|---|
| M-1 | 0 | 2.07 | 2.35 | 3.03 |
| M-2 | 25 | 2.40 | 2.77 | 3.08 |
| M-3 | 50 | 2.77 | 2.84 | 3.92 |
| M-4 | 75 | 2.63 | 2.72 | 3.62 |
| M-5 | 100 | 2.14 | 2.67 | 3.30 |

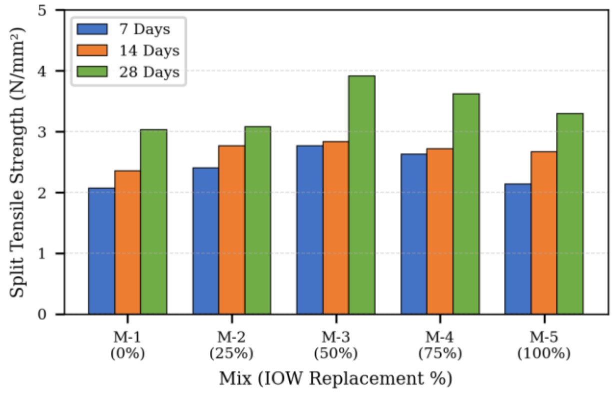


Fig. 2. Variation of split tensile strength with IOW replacement percentage.

*C. Water Absorption*

Water absorption decreased consistently from Mix-1 (0.57%) to Mix-5 (0.11%), as shown in Fig. 3. Higher IOW content progressively reduced porosity by improving aggregate packing density. The angular IOW particles fill interstitial voids more effectively than rounded river sand particles, creating a denser, less permeable mortar matrix. This densification effect is reinforced by the chemical admixture, which reduces water demand and improves cement hydrate distribution. The 80.7% reduction in water absorption from Mix-1 to Mix-5 confirms that IOW-incorporated mortars will exhibit superior durability against water-borne degradation mechanisms—including chloride ingress, carbonation, and sulfate attack—compared to conventional cement mortar.

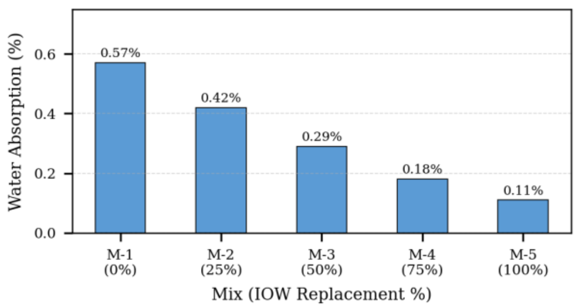


Fig. 3. Water absorption (%) versus IOW replacement level.

*D. Piezoresistive Behavior*

The electromechanical response of each mix was characterized by loading cylindrical specimens incrementally while recording resistance at each stress step. Figures 4–8 illustrate the FCR versus compressive stress relationships for Mix-1 through Mix-5.

Mix-1 (0% IOW, Fig. 4) exhibited a relatively modest piezoresistive response, with a maximum FCR of −0.129 at near-failure stress (20.06 N/mm²). The limited IOW content means that steel fiber is the sole conductive network element; its relatively low volume fraction (2%) produces a sparse conductive network with limited stress-induced topology changes.

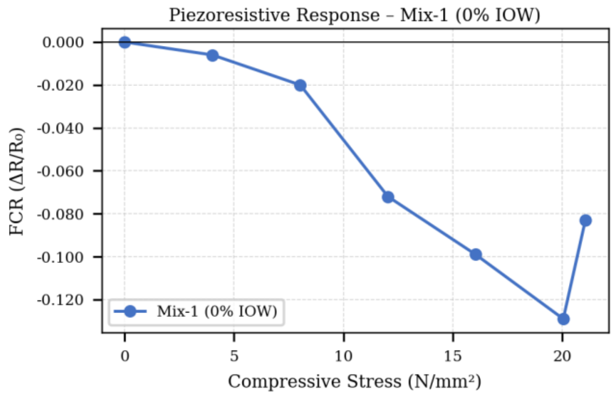


Fig. 4. FCR vs. compressive stress for Mix-1 (0% IOW, control).

Mixes 2–5 (25–100% IOW, Figs. 5–8) show progressively larger FCR magnitudes with increasing IOW content up to 75%. IOW particles, owing to their higher electrical conductivity compared with siliceous sand, augment the conductive network established by steel fibers. As stress increases, the matrix microcracking and compaction cause greater fiber–IOW contact events, producing more pronounced resistance changes. Mix-3 (50% IOW) achieves a maximum FCR of −0.326 at 28 N/mm², demonstrating good sensor linearity in the 0–24 N/mm² range. Mix-4 (75% IOW) exhibits the highest peak FCR of −0.403, confirming the best self-sensing performance.

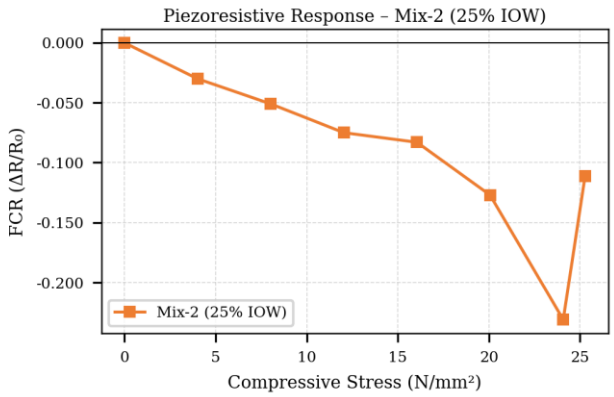


Fig. 5. FCR vs. compressive stress for Mix-2 (25% IOW).

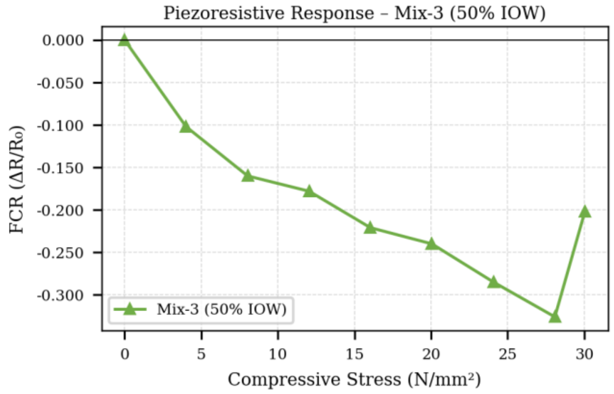


Fig. 6. FCR vs. compressive stress for Mix-3 (50% IOW).

At near-failure loads, all mixes exhibit a partial FCR recovery (less negative values), attributable to extensive matrix cracking causing fiber pull-out and rupture of the conductive network, thereby increasing resistance. This non-monotonic behavior near failure is characteristic of fiber-reinforced piezoresistive composites and provides a useful pre-failure warning signal for structural monitoring applications.

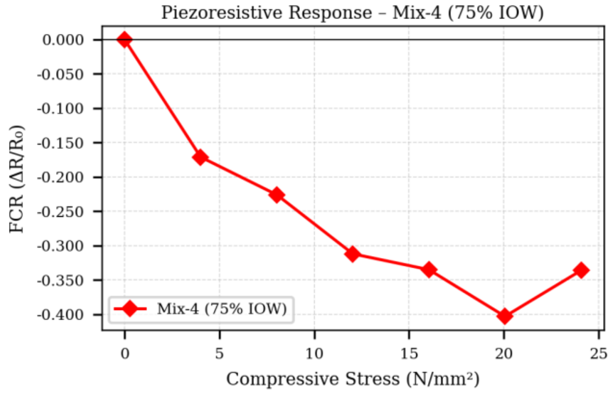


Fig. 7. FCR vs. compressive stress for Mix-4 (75% IOW) — best piezoresistive response.

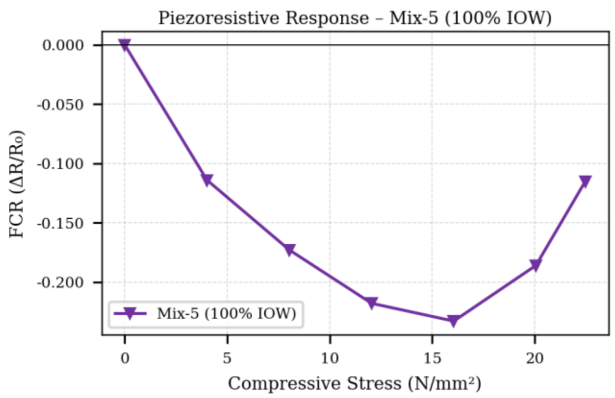


Fig. 8. FCR vs. compressive stress for Mix-5 (100% IOW).

Mix-5 (100% IOW) exhibits a maximum FCR of −0.233 at 16 N/mm², lower than Mix-4, with premature FCR recovery—likely due to the adverse effect of excess IOW on fiber dispersion and matrix cohesion. Table IV summarizes the peak FCR and corresponding stress for all mixes, confirming that intermediate to high IOW replacement (50–75%) optimizes piezoresistive sensitivity.

**TABLE IV. SUMMARY OF PIEZORESISTIVE PERFORMANCE**

| Mix | IOW (%) | Peak FCR | Stress at Peak (N/mm²) | Self-sensing Rating |
|---|---|---|---|---|
| M-1 | 0 | −0.129 | 20.06 | Poor |
| M-2 | 25 | −0.231 | 24.08 | Fair |
| M-3 | 50 | −0.326 | 28.09 | Good |
| M-4 | 75 | −0.403 | 20.06 | Excellent |
| M-5 | 100 | −0.233 | 16.05 | Moderate |

## VI. CONCLUSION

**1.** Replacing 50% of fine aggregate with IOW and adding 2% micro steel fiber yields maximum compressive strength of 27.62 N/mm² (36.32% above control) and split tensile strength of 3.92 N/mm² (29.4% above control) at 28 days. These improvements are driven by IOW's angular morphology improving aggregate–paste interlocking and steel fiber crack-bridging enhancing post-crack ductility.

**2.** Water absorption decreases monotonically with increasing IOW content, falling from 0.57% (control) to 0.11% (100% IOW), reflecting progressive matrix densification and improved packing efficiency. This confirms enhanced durability at all IOW replacement levels.

**3.** Piezoresistive testing demonstrates consistent self-sensing behavior across all mixes. FCR magnitude increases with IOW content up to 75%. Mix-4 (75% IOW) achieves the best piezoresistive performance (peak FCR = −0.403), while Mix-3 (50% IOW) offers the best trade-off between mechanical performance and sensing sensitivity.

**4.** IOW is validated as a technically viable and environmentally sustainable replacement for natural river sand in smart cement mortar formulations. At 50% replacement, it simultaneously improves structural performance, reduces industrial waste accumulation, and enables structural health monitoring capability without requiring dedicated sensor instrumentation.

## VII. FUTURE SCOPE

Future investigations should employ impedance analyzers and high-precision data acquisition systems to improve measurement accuracy and enable frequency-domain characterization of piezoresistive behavior. Exploring varied steel fiber dosages (0.5–3%) alongside other conductive inclusions—such as carbon nanotubes, graphene nanoplatelets, or hybrid fiber combinations—may further optimize the conductivity–strength trade-off. Long-term durability studies under cyclic mechanical loading, elevated temperature exposure, and aggressive chemical environments are essential to validate the sustained smart-sensing capability of IOW-based mortars. Scaling the study to structural concrete level, including beam and slab specimens, will help determine whether the piezoresistive mortar can function as a distributed sensor embedded within structural members, enabling real-time load and damage monitoring in full-scale infrastructure applications.

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