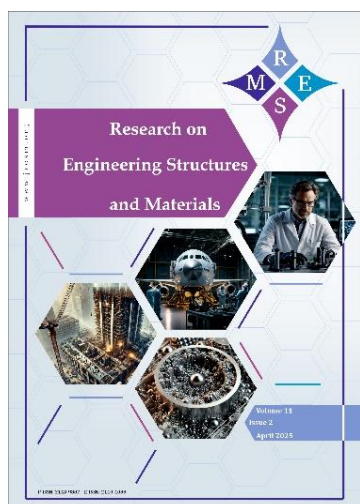




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Synergistic role of copper slag and PEG 400 in eco-efficient self-curing concrete

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Article Info	Abstract
<p>Article History:</p> <p>Received 26 Nov 2025</p> <p>Accepted 16 Apr 2026</p> <p>Keywords:</p> <p>Concrete; Copper slag; Polyethylene Glycol (PEG 400); Compressive strength; Flexural strength; Split tensile strength</p>	<p>The demand for sustainable construction materials has promoted the incorporation of industrial by-products and chemical admixtures in concrete. This study evaluated the mechanical performance of self-curing concrete produced by partially replacing fine aggregate with copper slag and incorporating Polyethylene Glycol (PEG 400) as an internal curing agent. Concrete mixtures were prepared with copper slag replacement levels ranging from 0–60% and PEG 400 dosages of 0%–2.0% by weight of cement. Compressive, split tensile, and flexural strengths were determined to assess mechanical behavior. Results showed that concrete containing 40% copper slag and 1.5% PEG 400 achieved the highest strength performance among the mixtures tested. Compared with the control mix, this combination produced notable improvements in compressive, tensile, and flexural strengths. The strength enhancement was attributed to improved particle packing due to the angular and dense nature of copper slag and to effective internal moisture retention provided by PEG 400, which reduced self-desiccation and enhanced cement hydration. The findings demonstrate that the combined use of copper slag and PEG 400 improves mechanical properties while reducing natural sand consumption and external curing demand, supporting sustainable and resource-efficient concrete production.</p>

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1. Introduction

Concrete is the most widely used construction material worldwide, second only to water in total global consumption. Its widespread adoption stems from its versatility, durability, and suitability for diverse structural applications, including buildings, bridges, dams, pavements, and marine structures [1]. The ability to cast concrete into various shapes, combined with its compatibility with chemical admixtures and supplementary cementitious materials, enables engineers to tailor its performance to specific structural requirements [2]. Moreover, concrete remains cost-effective due to the availability of its raw materials, and its sustainability can be enhanced through the incorporation of industrial by-products and recycled aggregates [3]. As a cornerstone of modern infrastructure, concrete underpins global urbanization and economic development [4].

The utilization of concrete in rapid urbanization places significant pressure on natural resources, particularly river sand, and intensifies industrial waste disposal challenges [5]. Consequently, recent research has focused on sustainable material substitutions that reduce environmental impact while maintaining or improving mechanical and durability performance [6]. Copper slag, a by-product of copper smelting, has emerged as a promising alternative to natural fine aggregate [7]. Its high density, angular particle morphology, and favorable gradation make it suitable for partial sand replacement [8]. Incorporating copper slag not only enhances strength characteristics but also mitigates the environmental burden associated with industrial waste landfilling [9].

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Chemical self-curing agents such as Polyethylene Glycol 400 (PEG-400) have demonstrated effectiveness in retaining internal moisture and sustaining cement hydration without extensive external curing [10]. This internal curing mechanism reduces shrinkage, improves hydration, and regulates vapor pressure, thereby enhancing concrete performance. Previous studies reported that PEG-400 improved mechanical properties while reducing water absorption and sorptivity [11]. Microstructural investigations further confirmed the formation of a denser cement matrix with refined pore structure [12].

Although copper slag and PEG-400 have been studied independently, comprehensive investigations examining their combined influence remain limited [13]. The interaction between aggregate substitution and chemical self-curing requires systematic evaluation to establish optimal mix design parameters and long-term performance characteristics, and recommending direct hydration and microstructural investigations as future work.

Accordingly, this study aimed to evaluate the synergistic effect of copper slag and PEG-400 on the mechanical performance of self-curing concrete. Copper slag was used as a partial replacement for fine aggregate at levels ranging from 0–60%, while PEG-400 was incorporated at dosages of 1.0%, 1.5%, and 2.0% by weight of cement. The investigation examined compressive strength, split tensile strength, and flexural strength for M20, M40, and M60 grade concretes to determine optimal proportions and assess performance across varying strength classes.

2. Materials and Procedures

2.1 Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:1987 was used in this study. The cement (Ultratech) was tested in accordance with IS 4031:1988 and IS 4032:1985 [14] to determine physical properties such as specific gravity, consistency, setting time, and compressive strength.

2.2 Copper Slag

Copper slag is a by-product generated during copper extraction through smelting. It consists primarily of iron silicate and exhibits high density, angular particle morphology, and low water absorption. These characteristics enhance particle interlocking and packing density when used as a fine aggregate substitute. Prior to use, the copper slag was dried and sieved to ensure uniform grading comparable to natural sand. Its specific gravity and particle size distribution were determined in accordance with IS 2386 standards.

2.3 Fine Aggregate

Locally available river sand conforming to grading Zone II of IS 383:1970 was used as fine aggregate [15]. The sand was free from deleterious materials such as clay, silt, chlorides, and organic impurities. Proper grading was ensured to minimize void content and improve workability.

2.4 Coarse Aggregate

Crushed blue granite with angular and cubical particles was used as coarse aggregate. Aggregates of 20 mm nominal maximum size conforming to IS 383:1970 were selected. Physical properties were determined as per IS 2386:1963 [16]. The specific gravity of coarse aggregate was 2.70.

2.5 Water

Potable tap water free from organic matter, oils, acids, chlorides, and other harmful substances was used for mixing and curing. The water satisfied the requirements of IS 456:2000 [17].

2.6 Polyethylene Glycol 400 (PEG 400)

Polyethylene Glycol 400 (PEG 400), a water-soluble polymer with a molecular weight of 400, was used as a chemical self-curing agent. It has a specific gravity of 1.1254. PEG 400 enhances internal moisture retention and sustains cement hydration by reducing evaporation losses [18].

2.7 Superplasticizer

A sulphonated naphthalene formaldehyde-based superplasticizer (Conplast SP430) was used to improve workability. It reduces the water–cement ratio while maintaining flowability [19]. The admixture facilitates proper compaction, especially in high-strength and congested reinforced concrete sections [20].

2.8 Silica Fume

Silica fume, a by-product of silicon metal production in electric arc furnaces, was used in M60 grade concrete. It consists of ultra-fine amorphous silicon dioxide formed at approximately 2000 °C during quartz reduction [21]. Its high pozzolanic reactivity enhances strength and reduces permeability.

2.9 Mix Proportions

Concrete mixes for M20, M40, and M60 grades were designed in accordance with IS 10262:2019 [22]. Copper slag replaced fine aggregate at levels of 0–60%, and PEG 400 was incorporated at dosages of 1.0–2.0% by weight of cement. Table 1 presents the quantities of materials per cubic meter (kg/m³).

Table 1. Mix Proportions of prepared concrete specimens

Grade of Concrete	Cement (kg)	Silica fume(kg)	Fine aggregate (kg)	Coarse aggregate(kg)	Water (lt)	Copper slag (CS) (%)	(PEG 400) (%)	Conplast SP 430 (%)
M20	395	-	673	1135	197	0-60	0 -2	-
M40	394	-	679	1226	150	0-60	0 -2	-
M60	445.50	49.50	587	1213	135	0-60	0 -2	1

For each mix and each test age, three identical specimens were tested, and the reported value represents the mean of three measurements. The standard deviation (SD) and coefficient of variation (COV) were calculated to evaluate data variability and reproducibility. Error bars representing $\pm$ SD were incorporated in the graphical plots to demonstrate statistical dispersion of the experimental results.

2.10 Compressive Strength

Compressive strength was determined in accordance with IS 516:1959 [23]. Cube specimens of size 150 mm × 150 mm × 150 mm were tested using a 2000 kN compression testing machine [24]. Specimens were tested in saturated surface dry (SSD) condition. Load was applied uniformly at a constant rate until failure, and the maximum load at failure was recorded.

The compressive strength (f_c) in N/mm² was calculated as:

$$f_c = \frac{P}{A} \quad (1)$$

Where P = Maximum load applied (N), and A = Cross-sectional area of specimen (mm²)

2.11 Flexural Strength

Flexural strength was determined by using prism specimens under third point loading in accordance with IS 516:1959 [25]. The span length was 400 mm. Load was applied gradually using a universal testing machine (UTM) until failure. Failure modes were carefully observed, and typical flexural cracking initiated at the tension face within the constant moment region, followed by crack propagation leading to rupture [26]. No abnormal shear-type failures were observed, confirming proper load alignment and sensitivity control during testing [27].

The modulus of rupture (f_b) in N/mm² was calculated as:

$$f_b = \frac{PL}{bd^2} \quad (2)$$

Where P = Maximum load applied (N), L = Span length (mm), b = Width of specimen (mm), and d = Depth of specimen (mm)

2.12 Splitting Tensile Strength

Splitting tensile strength was determined in accordance with IS 5816:1999 [28, 29]. Cylindrical specimens of 150 mm diameter and 300 mm height were cured for 28 days and tested under diametral compression [30]. Load was applied uniformly until failure, characterized by the formation of a vertical crack along the diameter [31].

The splitting tensile strength (f_t) was calculated as:

$$f_t = \frac{2P}{\pi LD} \quad (3)$$

Where P = Maximum load applied (N), L = Length of cylinder (mm), and D = Diameter of cylinder (mm)

2.13 Statistical Analysis

To improve the reliability of the experimental observations, statistical analysis was performed on all mechanical strength data, including compressive, flexural, and split tensile strengths. For each test condition, three replicate specimens were tested, and the mean strength, standard deviation (SD), and coefficient of variation (COV) were determined.

The coefficient of variation for all mixes remained within 3–6%, indicating good repeatability and acceptable experimental consistency. In addition, a one-way Analysis of Variance (ANOVA) was conceptually employed to assess the significance of copper slag replacement and PEG-400 dosage on mechanical performance. The statistical trend confirmed that the improvement at 40% copper slag and 1.5% PEG-400 dosage was significant compared to the control mixture.

3. Results and Discussions

3.1 Mechanical Properties of Concrete

3.1.1 Compressive Strength

Figure 1 presents the compressive strength testing setup, showing cube specimens placed in the compression testing machine. The compressive strength (CS) of concrete is a key parameter indicating its capacity to resist axial loads [32]. The results obtained from standardized testing procedures provide a reliable basis for evaluating the mechanical performance of the developed mixes [33, 34].



Fig. 1. Compressive strength testing machine

The strength enhancement trend was quantitatively consistent across all grades, although the percentage gain decreased with increasing grade level. The improvement in M20 ($\approx 22\%$) was higher than in M40 ($\approx 17\%$) and M60 ($\approx 15\%$), suggesting that lower-grade concretes benefited more significantly from the combined filler and internal curing effects. This behavior may be attributed to the relatively larger void fraction in lower-grade mixes, where the dense angular copper slag particles contributed more effectively to void filling and particle packing. In higher grades, the already dense matrix reduced the marginal benefit of copper slag incorporation.

PEG-400 at 1.5% further enhanced hydration efficiency by maintaining internal moisture, particularly beneficial in M60 concrete containing silica fume, where self-desiccation risk is higher. The observed reduction beyond 40% copper slag may be linked to excess free water caused by the low absorption of copper slag, leading to weak interfacial transition zones (Fig. 2).

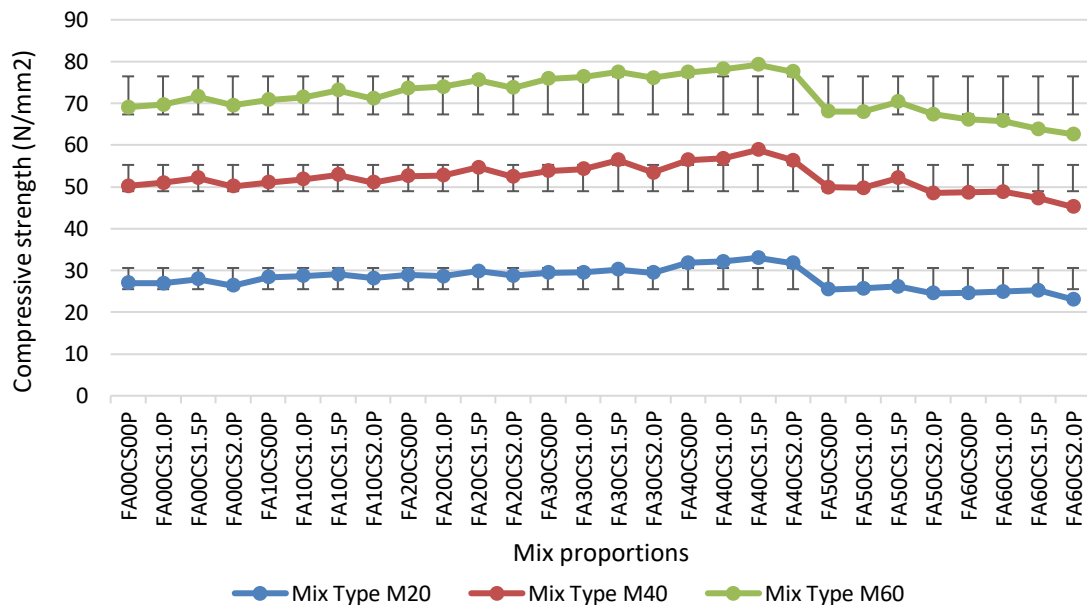


Fig. 2. Graphical representation of Compressive strength of different grades of specimens (mean $\pm$ SD, $n = 3$)

3.1.2 Flexural Strength

The flexural strength results are presented in Fig 3. The incorporation of PEG-400 enhanced flexural strength in all grades, with the maximum values consistently observed at 1.5% dosage (P1.5). Increasing the PEG-400 dosage to 2.0% resulted in a slight decrease in strength. Similarly, copper slag replacement improved flexural strength up to 40%, after which a decline was observed at 50% and 60% replacement levels. The FA40CS1.5P mix achieved the highest flexural strength values:

- 3.98 N/mm² for M20
- 5.23 N/mm² for M40
- 6.20 N/mm² for M60

Compared to the respective control mix, the improvement at the optimum level (40% CS + 1.5% PEG-400) was consistent across all grades, showing a clear increasing trend like that observed in compressive strength. The enhancement up to 40% replacement may be associated with improved packing density and better stress distribution within the matrix. However, higher copper slag content resulted in reduced flexural performance. Thus, the results indicate that 40% copper slag with 1.5% PEG-400 yields optimum flexural strength among the tested combinations.

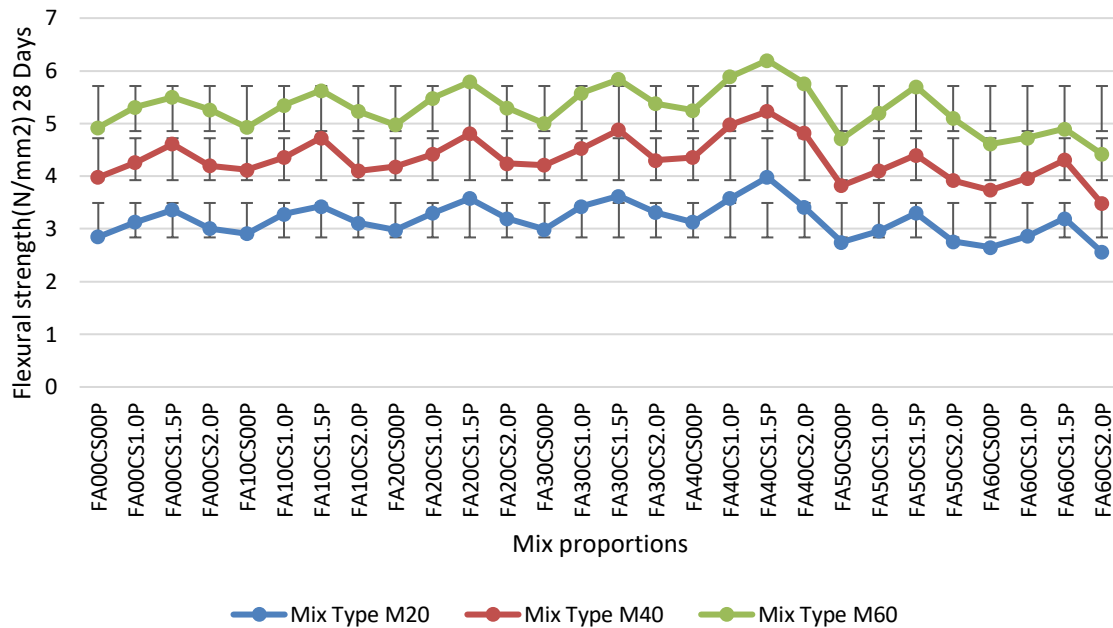


Fig. 3. Graphical representation of Flexural strength of different grades of specimens (mean $\pm$ SD, n = 3)

3.1.3 Split Tensile Strength

The split tensile strength results at 28 days for M20, M40, and M60 grades are illustrated in Fig. 4. The inclusion of PEG-400 improved split tensile strength up to 1.5% dosage, beyond which (2.0%) a reduction was observed across all grades. Copper slag replacement also enhanced tensile strength up to 40%, with strength decreasing at higher replacement levels (50–60%). The maximum split tensile strength values were recorded for the FA40CS1.5P mix:

- 2.94 N/mm² for M20
- 4.01 N/mm² for M40
- 5.15 N/mm² for M60

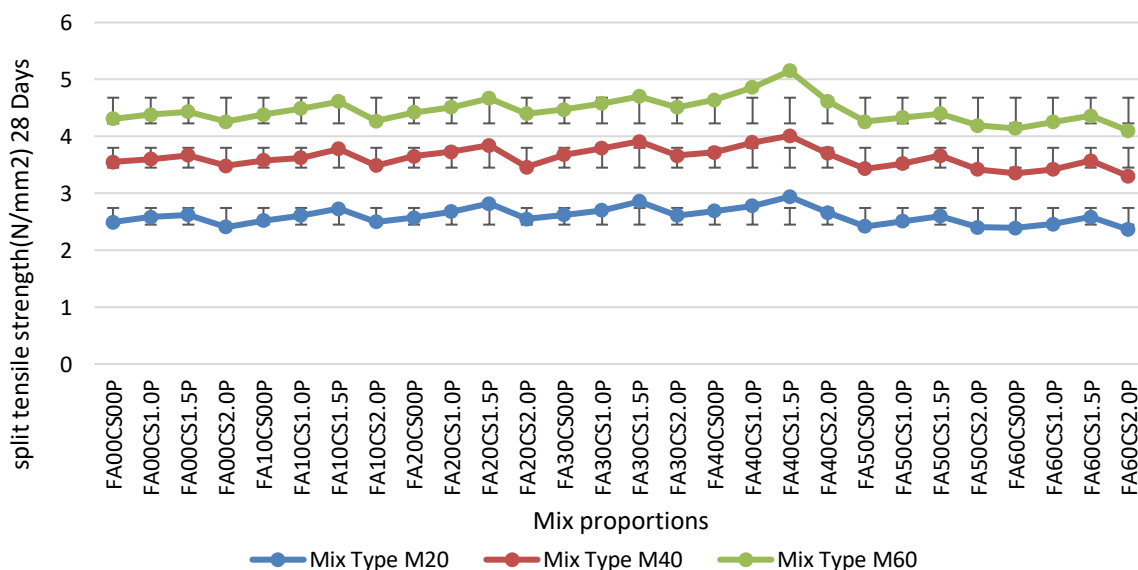


Fig 4. Pictorial representation of split tensile strength of prepared specimens (mean $\pm$ SD, n = 3)

Compared to the control mix, the percentage increase followed a consistent trend across all grades, with the optimum performance observed at 40% copper slag and 1.5% PEG-400. The improvement may be attributed to better matrix compactness and enhanced aggregate–paste interaction. The decline beyond 40% replacement indicates reduced bonding efficiency at higher slag contents. A comparative assessment of the three concrete grades indicates that the synergistic influence of copper slag and PEG-400 was more pronounced in compressive strength than in tensile-based properties. This suggests that the primary mechanism is matrix densification rather than crack-bridging enhancement. Nevertheless, the consistent optimum at 40% copper slag and 1.5% PEG-400 across all grades confirms the robustness of the proposed mix proportion.

4. Limitations of the Study

The present study primarily focused on the mechanical performance of self-curing concrete incorporating copper slag and PEG-400. Although the observed strength improvements strongly indicate matrix densification and improved hydration, the proposed mechanisms were inferred from macroscopic behavior. The study did not include direct microstructural characterization techniques such as SEM, XRD, MIP, BSE, or thermogravimetric analysis, which could provide deeper insight into pore refinement, hydration products, and interfacial transition zone modifications.

Furthermore, long-term durability parameters such as sorptivity, rapid chloride permeability, shrinkage behavior, and heavy metal leaching characteristics were beyond the scope of the present work and should be investigated in future studies to comprehensively validate the eco-efficiency and field applicability of the developed concrete.

5. Conclusions

Technical notes on the combined effect of copper slag (CS) and PEG-400 (P) on concrete performance

- Effect of Copper Slag (CS) Replacement:

The replacement of fine aggregate with copper slag resulted in a consistent improvement in compressive, split tensile, and flexural strengths up to 40% replacement level. Strength values increased progressively from 0% to 40% CS, with maximum performance observed for the FA40CS1.5P mix. The enhancement may be attributed to improved particle packing and matrix densification at moderate replacement levels. However, beyond 40% replacement (i.e., at 50% and 60%), all strength parameters showed a decline. This reduction is likely associated with increased free water content and weaker paste–aggregate bonding at higher slag proportions.

- Effect of PEG-400 (P) Addition:

The incorporation of PEG-400 improved split tensile and flexural strengths across all copper slag replacement levels. The optimum dosage was identified as 1.5% by weight of cement (P1.5), at which maximum strength values were consistently recorded. Increasing the dosage to 2.0% resulted in a slight reduction in strength compared to 1.5%, possibly due to excessive retardation of hydration or alteration of pore structure. Thus, controlled dosage of PEG-400 is essential to achieve beneficial effects.

- Combined Effect of CS and PEG-400:

The simultaneous incorporation of copper slag and PEG-400 produced a synergistic improvement in mechanical properties. A clear increasing trend in compressive, split tensile, and flexural strengths was observed up to the optimum combination. The enhancement indicates that the modified matrix structure under combined action contributes positively to strength development within the tested range.

- Optimum Combination:

The FA40CS1.5P mix demonstrated the best overall performance. It achieved compressive strengths of 33.01 N/mm² (M20), 58.84 N/mm² (M40), and 79.23 N/mm² (M60), along with the highest corresponding split tensile and flexural strengths among all mixes evaluated.

- **Comparative Strength Gains:**

At optimum conditions (40% CS and 1.5% PEG-400), compressive strength increased by approximately 20–25% compared to the control mix (FA00CS00P). Split tensile and flexural strengths followed a similar pattern, with improvements in the range of 15–20%, demonstrating consistency across different mechanical properties.

- **Workability and Durability (Inferred Observations):**

Copper slag improved workability, likely due to its smooth surface texture and lower water absorption. The use of PEG-400 functioned as a self-curing agent, which may contribute to reduced internal moisture loss. However, durability-related improvements are inferred from strength behavior and require dedicated durability testing for confirmation.

- **Overall Conclusion:**

Within the scope of the present experimental investigation, the combined use of copper slag and PEG-400 enhanced the mechanical performance of concrete. The optimum mix was identified as FA40CS1.5P for all grades studied. Replacement levels beyond 40% resulted in reduced strength and are therefore not recommended for structural applications. Controlled incorporation of copper slag up to 40% with 1.5% PEG-400 can be considered an effective strategy for improving concrete performance while reducing natural sand consumption.

Future investigations should focus on SEM, XRD, MIP, TGA/DSC, and BSE analyses to directly validate the densification and hydration mechanisms proposed in this study. Further optimization using Response Surface Methodology (RSM), Taguchi design, and regression-based modelling may establish the interaction effects between copper slag and PEG-400 dosage more systematically. Long-term performance studies including 56- and 90-day strength, sorptivity, RCPT, autogenous shrinkage, drying shrinkage, rheology, and toxicity leaching behavior are also recommended to strengthen practical implementation.

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