EXPERIMENTAL STUDY OF HIGH-STRENGTH POLYPROPYLENE FIBER-REINFORCED MORTAR MIX FOR BALANCED STRENGTH AND WORKABILITY

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Abstract - In constructing slender structural elements with limited formwork space, where reinforcement density and the presence of other elements are high, using mortar with both high strength and excellent flowability is essential. This study evaluates the effect of mixture composition on the strength and workability of high-strength polypropylene (PP) fiber-reinforced mortar, aiming to provide a dataset for developing high-strength mortars suitable for practical applications. Mortar mixtures were prepared using white Portland cement, ground granulated blast furnace slag (GGBS), silica fume (SF), and varying PP fiber contents (0.1%–0.4% by volume). Investigated properties include flowability, compressive strength, flexural strength, and abrasion resistance. Results showed that mixtures with binder content ranging from 740 to 820 kg/m³ achieved compressive strength over 70 MPa with good abrasion resistance. Chemical admixtures below 1% significantly enhanced workability without reducing mechanical performance. Among all dosages, 0.2% PP fiber content was optimal, yielding balanced improvements in strength and workability.

Key words - Fiber-reinforced mortar; polypropylene fibers; mixture composition; strength and workability; High-strength mortar

1. Introduction

In modern construction practices, there is an increasing demand for high-strength materials that can meet both structural and practical requirements, especially in projects involving slender elements, densely reinforced components, or formworks with restricted space. In such conditions, conventional mortar often fails to satisfy the dual requirements of high mechanical strength, including both compressive and flexural strength, and sufficient workability, which are crucial for ensuring proper compaction, bond with reinforcement, and durability of the structure.

To address these challenges, fiber-reinforced mortar has emerged as a promising solution due to its enhanced crack resistance, improved toughness, and durability. Among various types of fibers, polypropylene (PP) fibers are widely used in cement-based composites owing to their cost-effectiveness, chemical stability, and ability to control plastic shrinkage cracking. Unlike steel fibers, PP fibers are lightweight, chemically inert, and non-corrosive, making them suitable for long-term durability in aggressive environments [1-2]. Several studies have reported that the inclusion of PP fibers, even at low dosages (typically from 0.1 to 0.4% by volume), can significantly improve the tensile and flexural behavior of mortar and concrete [3–7]. However, the hydrophobic and non-reactive nature of PP fibers leads to limited bonding with the cement matrix, especially when the mixture lacks proper particle dispersion or has insufficient binder content [8]. Moreover, PP fibers tend to agglomerate when used in high concentrations, which can disrupt the homogeneity of the mix and reduce its flowability. These challenges necessitate careful adjustment of mix proportions and the use of complementary materials to mitigate workability losses.

In addition to fiber content, the use of supplementary cementitious materials such as ground granulated blast furnace slag (GGBS) and silica fume (SF) has become a common strategy to enhance the performance of fiber-reinforced mortars. GGBS contributes to long-term strength development and improves sulfate resistance, while silica fume, with its ultrafine particles and pozzolanic reactivity, refines pore structure and increases matrix density [7, 9–12]. The synergistic use of GGBS and SF can compensate for the reduction in workability caused by fiber addition by improving the particle packing density and reducing water demand. Previous studies have shown that ternary blends incorporating cement, GGBS, and SF result in mortars with superior mechanical properties and reduced permeability [13–16]. These benefits are especially important in mixes with PP fibers, where maintaining matrix continuity is crucial for effective stress transfer and crack-bridging action.

Moreover, chemical admixtures, particularly high-range water-reducing admixtures, also known as superplasticizers, are commonly used to further enhance the flowability of fiber-reinforced concrete or mortar mixtures. Studies have confirmed that the use of superplasticizers below 1% by weight of binder can restore flow without compromising early-age or long-term strength [17–18]. However, balancing the cost of admixtures is also critical, so finding the optimal ratio for different mix designs could help reduce the cost of PP fiber-reinforced mortars.

While the individual effects of PP fibers, SCMs, and admixtures have been widely investigated, there is limited research on their combined interaction within optimized mix designs aimed at achieving dual enhancement of strength and workability. Moreover, most existing studies focus either on mechanical performance or fresh-state behavior, without integrating both aspects under practical dosage ranges. Furthermore, few studies systematically evaluate these effects using white cement as the primary binder, which is relevant in architectural or decorative applications where surface aesthetics and material consistency are critical.

This study aims to experimentally investigate the influence of mixture composition including PP fiber dosage, binder content, and chemical admixture use, on the mechanical properties and workability of mortar. By systematically varying the key components of the mix, the research seeks to identify an optimal composition that can achieve simultaneous enhancement of strength and workability, thereby contributing to the development of high-strength mortar tailored for construction scenarios with narrow formwork and densely arranged or complex embedded elements.

2. Materials and methods

2.1. Raw materials

To develop a high-strength polypropylene fiber-reinforced mortar with enhanced strength and workability, high-quality raw materials were selected. White Portland cement (WPC), classified as SCG PCW50.I, was used as the primary binder. This cement type has a 28-day compressive strength ranging from 51 to 57 MPa and an absolute whiteness index exceeding 70%, in compliance with ASTM E313-00 and TCVN 5691:2000 standards [22-23]. Its exceptional whiteness and consistent particle properties make it particularly suitable for architectural applications, where surface finish and color uniformity are critical [19].

Ground granulated blast furnace slag (GGBS), type S95, sourced from the Hoa Phat Dung Quat Steel Plant, was incorporated as a supplementary cementitious material (SCM). The chemical composition of this slag (see Table 1) meets the specifications of TCVN 11586:2016 [24]. The inclusion of GGBS not only contributes to the long-term strength development of the mortar but also enhances sulfate resistance and reduces the overall heat of hydration.

Silica fume (SF), designated as BestRefit C40 from BESTMIX, was used to improve matrix densification and stimulate pozzolanic reactivity. The fine aggregate consisted of quartz sand sourced from Phong Dien District (Thua Thien Hue Province, Vietnam), containing more than 98% silica. This sand featured a fineness modulus of 1.65, and its particle size distribution is presented in Figure 1. Compared to conventional concrete sand, the selected sand had a significantly finer particle size, enabling the mortar to effectively penetrate narrow structural components with extremely limited clear spacing between reinforcing bars, or to flow around fiber optic elements in translucent concrete, often spaced just a few millimeters apart [20-21].

Additionally, to improve workability, a third-generation high-range water-reducing admixture (HRWRA) named Lotus 379P was utilized. This polymer-based admixture is specifically engineered to retain workability under hot and humid climatic conditions while minimizing water demand. It complies with the requirements of TCVN 8826:2011 [25], Type F.

Polypropylene (PP) fibers were incorporated as the reinforcing phase. These fibers exhibited a tensile strength of 30 MPa and a specific gravity of 0.95 g/cm³. Both mixing and curing water conformed to the quality standards specified in TCVN 4506:2012 [26].

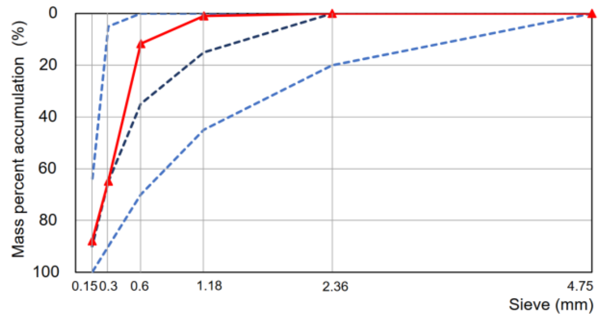

Figure 1. *Particle size distribution of sand*

2.2. Experimental design for mortar mixture

This parametric investigation was designed to clarify the specific influence of each factor on both the strength and workability of the mortar, ultimately providing recommendations for an optimal mix design that achieves simultaneous improvements in both properties. The mixture design was developed using the absolute volume method with a target compressive strength more than 60 MPa. First, an initial water-to-cement (w/c) ratio fixed at 0.5 to ensure consistency in evaluating the effects of other mix parameters. A systematic experimental program was carried out to optimize the mix by investigating the individual and combined effects of (i) total binder content, (ii) silica fume (SF) dosage, (iii) superplasticizer (SP) content, and (iv) polypropylene (PP) fiber volume.

Specifically, four mixtures with increasing total binder contents (700–820 kg/m³) were first prepared to examine the effects of total paste volume on compressive strength and flowability, as shown in Table 1. To isolate the impact of the mineral admixture, the influence of SF content was then studied at three levels (0%, 5%, and 10% of total binder) as shown in Table 2. This step aimed to optimize pozzolanic activity and particle packing while balancing material cost. Next, to evaluate the effectiveness of the high-range water-reducing admixture (Lotus 379P) in restoring workability, three dosages-0.8%, 1.0%, and 1.2% by binder weight-were tested as shown in Table 3. The objective was to determine the minimum effective dosage that could maintain sufficient flowability without compromising mechanical performance. Finally, five selected mixtures were formulated with varying fiber contents ranging from 0% to 0.4% by volume as shown in Table 4. This final phase aimed to identify the optimal fiber dosage that maximizes mechanical performance without significantly reducing workability.

Table 1. *Mix proportions for the experiment on the effect of fine aggregate content on mortar properties*

Mix No. (CP)	Binder			S	PP fiber	SP	Water
	C	GGBS	SF				
CP700B	490.0	140.0	70.0	1324.4	1.940	8.400	245
CP740B	520.0	148.6	74.3	1285.8	1.940	8.914	260
CP780B	546.5	156.2	78.1	1251.6	1.940	9.369	273
CP820B	574.1	164.0	82.0	1216.0	1.940	9.842	287

Table 2. *Mix proportions for the experiment on the effect of silica fume (SF) and ground granulated blast furnace slag (GGBS) content on mortar properties*

Mix No. (CP)	Binder			S	PP fiber	SP	Water
	C	GGBS	SF				
0%SF-30%GGBS	520.0	222.9	0.0	1285.8	1.940	8.914	260
5%SF-25%GGBS	520.0	185.7	37.1	1285.8	1.940	8.914	260
10%SF-20%GGBS	520.0	148.6	74.3	1285.8	1.940	8.914	260

Table 3. *Mix proportions for the experiment on the effect of superplasticizer (SP) on mortar properties*

Mix No. (CP)	Binder			S	PP fiber	SP	Water
	C	GGBS	SF				
SP 0.8	520.0	148.6	74.3	1291.1	0.000	5.943	260
SP 1	520.0	148.6	74.3	1294.8	0.000	7.429	260
SP1.2	520.0	148.6	74.3	1298.6	0.000	8.914	260

Table 4. *Mix proportions for the experiment on the effect of polypropylene fiber content on mortar Properties*

Mix No. (CP)	Binder			S	PP fiber	SP	Water
	C	GGBS	SF				
CP0	520.0	148.6	74.3	1291.1	0.000	8.914	260
CP1	520.0	148.6	74.3	1288.4	0.970	8.914	260
CP2	520.0	148.6	74.3	1285.8	1.940	8.914	260
CP3	520.0	148.6	74.3	1283.1	2.910	8.914	260
CP4	520.0	148.6	74.3	1280.5	3.880	8.914	260

Figure 3. *L-box test apparatus*

2.3. Experimental design for mortar mixture

The experimental program was designed to evaluate the key performance properties of polypropylene fiber-reinforced mortar, with a particular focus on achieving a balance between mechanical strength and workability, two often conflicting criteria in mortar optimization.

To assess mechanical performance, compressive and flexural strength tests were conducted in accordance with TCVN 3121:2003 [27]. While compressive strength is a fundamental parameter in evaluating the load-bearing capacity of mortar, the flexural strength test was particularly important for capturing the contribution of PP fibers in enhancing toughness and crack resistance under tensile stresses. In addition, to evaluate the surface durability of PP-FRM in applications subject to abrasion-such as floors and exposed vertical surfaces, an abrasion resistance test was carried out according to TCVN 3114:2022 [28], using the setup shown in Figure 2.

Figure 2. *Abrasion testing equipment according to TCVN 3114:2022*

On the other hand, to quantify workability, which was a key requirement for the highly flowable mortar being developed, the flow table test was performed following TCVN 9204:2012 [29]. Furthermore, to simulate realistic placement conditions in densely reinforced or geometrically restricted structures, an improved L-box test was conducted as illustrated in Figure 3. The test apparatus was scaled at 1:2 and configured with Ø10 mm bars spaced 20 mm apart to mimic confined flow paths. This setup provided both qualitative and quantitative insights into the mortar's ability to flow through narrow gaps without segregation or blockage, an essential property for applications in complex, space-constrained construction environments.

3. Results and discussions

3.1. Influence of total binder content

The experimental results indicated that increasing the total binder content from 700 to 820 kg/m³ led to a noticeable improvement in compressive strength, particularly in the range of 700 to 780 kg/m³. Compressive strength increased from 63.0 MPa at 700 kg/m³ to 85.9 MPa at 820 kg/m³, while flexural strength rose from 8.0 MPa to 11.2 MPa. The most substantial gains occurred between 700 and 740 kg/m³, where compressive strength increased by more than 10 MPa. This enhancement can be attributed to the higher concentration of reactive components such as C_3S and C_2S in cement and the latent hydraulic phases in ground granulated blast-furnace slag (GGBS), which together promote more robust hydration and densification of the matrix. A richer paste also helps fill the voids between fine sand particles, improving microstructural uniformity and reducing porosity. These factors collectively contribute to better mechanical performance. Beyond 780 kg/m³, although strength continued to increase, the rate of gain slowed, with compressive strength rising from 75.6 MPa to 85.9 MPa. This suggests a limit to how much additional binder contributes to hydration before encountering diminishing returns.

In contrast to the typical trend, a clear increase in flowability was observed with higher binder content while maintaining a constant water-to-binder ratio. As more fine particles are introduced, the water demand of the mix increases, but the higher paste volume, supported by superplasticizer, reduced internal friction and improved particle mobility. The resulting mixture becomes more workable, with flow diameter increasing from 11.5 cm at 700 kg/m³ to 19.5 cm at 820 kg/m³. These findings highlight that while increasing binder content is beneficial to a point, there exists an optimal threshold, around 740 kg/m³, where both strength (compressive strength > 70 MPa, flexural strength around 10 MPa) and flowability are reasonably balanced. Exceeding this level may further improve performance but may not be cost-effective.

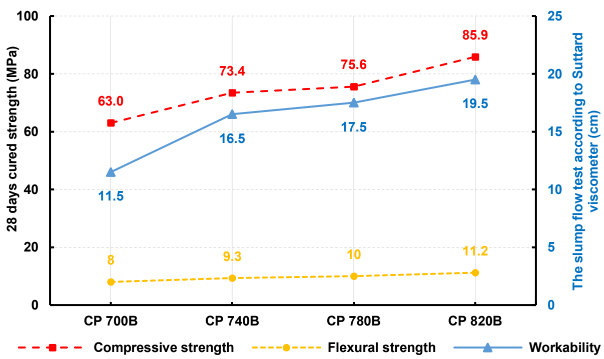

Figure 4. *Effect of binder content on the workability and strength of mortar*

3.2. Influence of silica fume (SF) and GGBS content

The results presented in Figure 5 indicate that the incorporation of silica fume (SF) in replacement of part of ground granulated blast furnace slag (GGBS), while keeping the total binder content constant, has a positive effect on both compressive strength and flowability of the mortar. As the SF content increased from 0% to 5% (with GGBS reduced from 30% to 25%), the compressive strength rose slightly from 71.3 MPa to 71.9 MPa, and then further to 78.4 MPa at 10% SF (corresponding to 20% GGBS). Flexural strength also showed a noticeable improvement, increasing from 9.8 MPa (0% SF) to 10.3 MPa (5% SF), and reaching 10.4 MPa at 10% SF. Although the 5% SF level improved the strength, the difference compared to the control mix was not significant. In contrast, at 10% SF, the pozzolanic reaction became more pronounced, generating additional hydration products such as secondary C-S-H and C-A-S-H gels, which contributed substantially to the increase in compressive strength. SF also played a crucial role in enhancing the mortar's microstructure. Due to its ultrafine particle size, SF effectively filled voids within the cement matrix, reducing porosity and increasing overall compactness. This refinement not only improved compressive and flexural strength but also reduced water permeability and enhanced the long-term durability of the mortar.

Regarding flowability, the slump (flow diameter) increased from 13 cm to 13.75 cm at 5% SF and further to 16 cm as SF content rose from 0% to 10%. At 5% SF, the improvement in flowability was primarily due to void filling within the cement paste structure. However, at 10% SF, in addition to filling microvoids, the silica fume also contributed to a more continuous particle size distribution. In this distribution, the ultrafine SF particles acted as micro-fillers, facilitating particle movement and allowing the mix to flow more easily by reducing internal resistance and enabling better flow under vibration or self-weight.

Based on experimental data, the combination of 10% SF and 20% GGBS proved to be the most suitable for achieving high flowability, compressive strength, and flexural strength.

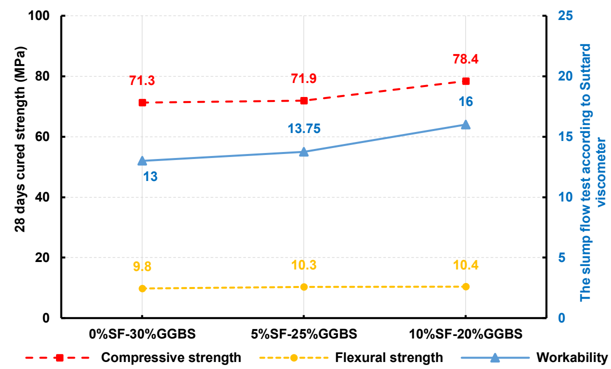

Figure 5. *Effect of Silica Fume (SF) and GGBS content on the workability and strength of mortar*

3.3. Influence of Superplasticizer Dosage

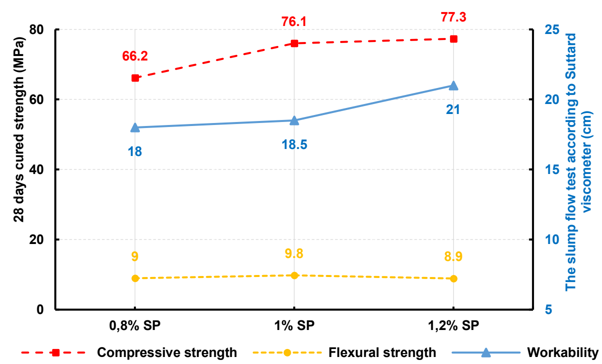

Figure 6. *Effect of Superplasticizer (SP) content on the workability and strength of mortar*

The dosage range of superplasticizer (SP) in this study was selected to evaluate the responsiveness of white cement to chemical admixtures. As shown in Figure 6, increasing the SP content from 0.8% to 1.0% led to a significant improvement in compressive strength, with an increase of 9.9 MPa-approximately a 15% gain compared to the 0.8% SP mix. Flexural strength also increased by 0.8 MPa, representing about a 9% improvement, while the flowability showed only a slight increase. However, when the SP content was raised to 1.2%, the improvement in compressive strength became marginal, and flexural strength even tended to decrease, although the flowability increased substantially.

The performance enhancement observed when increasing SP from 0.8% to 1.0% can be attributed to the admixture's superplasticizing effect, which improves cement particle dispersion, minimizes agglomeration, and enhances the hydration process. Additionally, SP reduces the amount of capillary water, thereby lowering the overall porosity of the mortar and leading to a denser microstructure and better mechanical strength. However, at 1.2% SP, the excess dosage may result in a surplus of surface-active agents, weakening the interfacial bonding between cement particles and aggregates. Another contributing factor is the pronounced increase in flowability. hen workability becomes too high, segregation or bleeding may occur, disrupting the mortar's internal structure and negatively impacting its tensile and flexural strength.

Therefore, a dosage of 1.0% SP appears to provide the best balance, offering optimal compressive and flexural strength while maintaining sufficient flowability for convenient placement.

3.4. Influence of Polypropylene Fiber Content on workability and strength of mortar

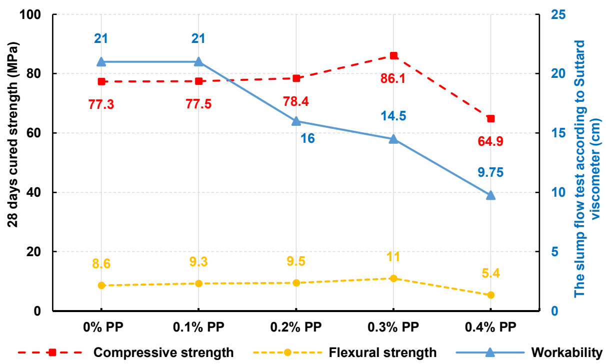

Figure 7. *Effect of polypropylene fiber content on the workability and strength of mortar.*

The results in Figure 7 indicate a clear inverse relationship between polypropylene (PP) fiber content and mortar flowability. As the fiber volume fraction increased from 0% to 0.4%, the flow diameter steadily decreased from 21 cm to 9.75 cm. This reduction in flowability can be attributed primarily to the increase in specific surface area introduced by the addition of fine PP fibers. Since the mixing water must coat the surfaces of all constituent particles, a higher surface area means more water is needed to maintain workability. However, in these tests, the water content was held constant across all mixtures, leading to an effective water shortage as fiber content increased. Another important factor is the ability of the PP fibers to trap air during mixing, further disrupting particle cohesion and reducing the mixture's fluidity. Together, these effects explain the observed continuous decline in flowability with increasing fiber content.

In terms of mechanical performance, the compressive strength remained relatively stable with fiber content up to 0.2%, but a notable increase of more than 7 MPa was observed when the fiber content reached 0.3%. Flexural strength exhibited a steady upward trend, peaking at the 0.3% fiber dosage. These improvements can be explained by the reinforcing action of the PP fibers. Once the mortar hardened, the fibers formed an internal micro-reinforcement network that enhanced resistance to lateral expansion and shear under compressive loads. This bridging mechanism also helped to delay crack propagation and maintain structural integrity under flexural stress. The fibers not only resisted tensile forces but also held opposing crack faces together, leading to enhanced flexural strength. However, a further increase in fiber content to 0.4% resulted in a significant decline in both compressive and flexural strength. This drop is likely due to the excessively low flowability at that fiber dosage, which impaired the uniform distribution and packing of particles during casting.

From the results, a fiber dosage of 0.3% by volume appears to be the optimal threshold, achieving the highest mechanical performance without compromising workability to a critical extent.

3.5. Effect of fiber content on flowability in L-box test

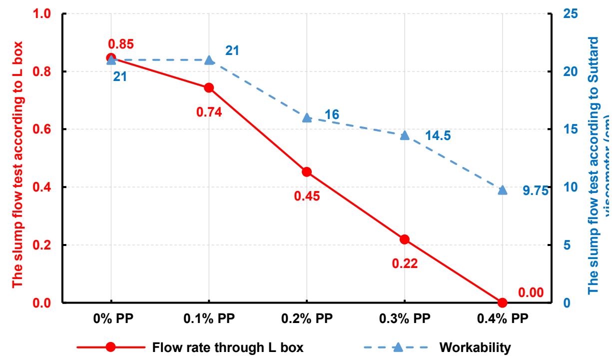

Figure 8. *Flowability of the mortar mixture by the L-box Test*

The L-box test was used to evaluate the impact of fiber content on the flowability of the fiber-reinforced mortar mix through the gap between two bars spaced 20 mm apart. Figure 8 indicates a significant reduction in flowability as the fiber content increased. Specifically, the flowability of the mix decreased from 0.85 (for the sample without fiber) to 0.74 with the addition of 0.3% PP fiber. This shows that adding fiber to the mix increases the surface area of the components, resulting in higher internal friction. The increased surface area of the fibers also reduces the sliding ability of the particles within the mix, limiting the flow of the mortar through the L-box. This explains why, at a fiber content of 0.4%, the mix becomes too viscous to move through the L-box.

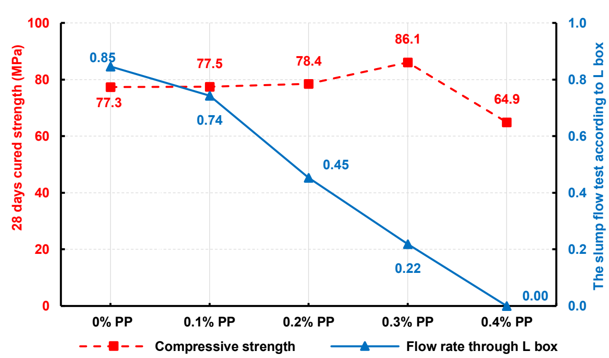

Figure 9. *Mortar flowability (L-box Test) and compressive strength (R28) at various PP content*

However, the mix with 0.1% fiber maintained the best flowability among all fiber-containing mixes, while the compressive strength at 28 days did not differ significantly from the sample without fibers, as shown in Figure 9. This suggests that 0.1% fiber content maintains workability while ensuring mechanical properties close to the non-fiber mix. Therefore, 0.1% fiber content is suitable for applications requiring high workability, such as translucent mortar, without compromising its workability.

3.6. Effect of fiber content on abrasion

Abrasion is a crucial property for mortar, particularly in applications subjected to heavy load or frequent mechanical impact. The research results indicate that incorporating PP fibers into the mortar mix significantly reduces its abrasion. Specifically, the mix without fibers exhibited an abrasion of 0.335 g/cm², while the mix with 0.1% PP fibers demonstrated a significantly lower abrasion of 0.285 g/cm². As the fiber content increased, the abrasion continued to decrease, reaching 0.285 g/cm² at a fiber content of 0.2%. However, when the fiber content was further increased to 0.3%, the abrasion began to rise again to 0.29 g/cm², and continued to increase as the fiber content reached 0.4%. The compressive strength exhibited a corresponding trend, gradually increasing from 77.3 MPa (no fiber) to a peak of 86.1 MPa at 0.3% fiber content, before sharply decreasing to 64.9 MPa at 0.4% fiber content.

The improved compressive strength of the mortar contributes to reduced abrasion, as the denser microstructure formed at higher strength reduces the formation of voids and capillaries, both of which can weaken the surface and make it more prone to abrasion. High compressive strength is typically associated with improved resistance to surface forces. When added in optimal amounts, the PP fibers improve the bond between the cement particles and aggregates, enhancing the mortar's resistance to mechanical impacts. This results in greater durability against chipping and wear under friction or repetitive forces. However, this beneficial effect only occurs when the fiber content is within the optimal range (such as 0.2–0.3% in this study). Excessive fiber content may disrupt the homogeneity of the structure, leading to a reduction in both strength and abrasion.

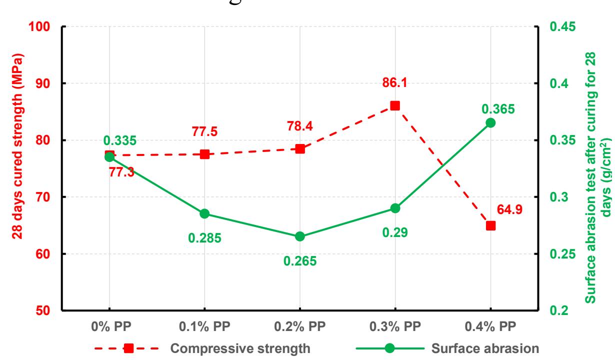

Figure 10. *Abrasion and strength of fiber-reinforced mortar at various fiber contents*

The correlation between compressive strength and abrasion is further confirmed by this study. The compressive strength increased from 77.3 MPa (no fiber) to 86.1 MPa with 0.3% fiber, leading to improved abrasion. However, beyond the optimal fiber content (0.3%), both compressive strength and abrasion started to decline. These findings highlight the importance of controlling fiber content in the mortar mix. The optimal fiber content (0.2%–0.3%) ensures high strength, low abrasion, and good workability. Exceeding the optimal fiber content may cause structural inhomogeneity, negatively impacting both mechanical properties and abrasion.

4. Conclusions

This study focuses on the design of high-strength polypropylene fiber-reinforced mortar, based on experimental analysis of key properties including flowability, compressive strength, and abrasion resistance. The main findings, along with the optimal proportions of each mix component using locally sourced materials, can be summarized as follows:

- Increasing binder content significantly enhanced flowability, compressive, and flexural strength. Mixes containing 740–820 kg/m³ of binder proved optimal for producing high-quality fiber-reinforced mortar (compressive strength is higher than 70 MPa), offering a balanced combination of workability, density, and mechanical performance.

- A superplasticizer (SP) dosage of 1% is recommended for translucent PP fiber-reinforced mortar using white cement and 740 kg/m³ binder. This dosage maximizes strength while preserving adequate flowability.

- Silica fume (SF) additions ranging from 5% to 10% consistently improved flowability, compressive strength, and flexural strength. The combination of 10% SF and 20% GGBS was found to be most effective, achieving superior performance in both mechanical properties and workability while keeping the total binder content constant.

- Varying the PP fiber volume had distinct impacts. Strength increased up to an optimal fiber content of 0.3%, while abrasion resistance peaked at 0.2%. However, flowability dropped sharply at 0.4%, indicating that a 0.1% fiber content strikes the best balance between performance and workability.

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