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Performance of Grouting Mixtures Incorporating Silica Fume, Slag, and Polypropylene Fibers

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ABSTRACT

Grouting is a frequently employed ground enhancement process boosts rigidity, lowers permeability, and hardens soil. The research studies mechanical and rheological characteristics of cement-based grouts for usage in geotechnical and civil engineering projects that have been supplemented with Polypropylene Fibers (PPF), chemical additives, and supplemental cementitious materials (SCMs). The aim of this study was to determine the impacts of ten grout combinations with various percentages of silica fume (SF), ground granulated blast furnace slag (GGBFS), and PPF on setting time, compressive strength, flexural strength, and splitting tensile strength at 28 and 90 days. The results indicated that applying 10% SF substantially benefited each mechanical property, and Mix M2 exhibited best performance among all mixtures. Fiber-reinforced composites improved tensile and flexural properties by enhancing internal cohesion and resistance to cracking, but GGBFS-containing combinations demonstrated retarded growth in strength attributed to slower hydration kinetics. The fibers raised porosity and lowered flowability, nevertheless, slightly reduction in compressive strength. Mechanical performance was assessed by evaluating setting time, compressive, flexural, and splitting tensile strength at both 28 and 90-day. The results underscore how essential it is to strike the right equilibrium of workability, long-term viability, and mechanical properties when optimizing grout formulation. These findings offered credibility to the generation of long-lasting, efficient, and sustainable grouts for purposes like subsurface building, stabilizing soil, and structural restoration.

1. INTRODUCTION

Grouting is a comprehensive ground change process commonly used for geotechnical and civil engineering purposes [1] and is considered one of the most effective ways to strengthen and seal the ground. It is required to fill inaccessible spaces to enhance the stability of the Earth, enhance its bearing capacity, and reduce soil permeability for the construction of embankments, foundations, and buildings [2-4], tunnels, highways, ground fractures, and other locations where grouting is required [5]. Although it utilizes various procedures and technology, it serves the same primary functions in both soil and rock contexts. Permeation grouting is among the most widely used and involves injecting grout into the soil's voids to close them and foster cohesiveness among the soil molecules [6]. It is anticipated that the grouts will spread regularly in various directions through the grouting procedure, which will contribute to a consistent and long-lasting enhancement to the structure [7]. Soil reinforcement techniques aim to enhance the strength and durability of soil and rock masses. Among the most prominent of these techniques, the injection of grout ingredients is used as an effective means to modify the mechanical and physical qualities of the earth. By enhancing load-bearing capacity, reducing settlement, decreasing permeability, and improving cohesion, shear, and uniaxial compressive strength [8, 9], all of which assist numerous engineering tasks in keeping their structural integrity and long-term durability. This procedure is used especially in the construction of dams, where liquids are injected under pressure into cracks and voids to reduce permeability and improve the mechanical stability of the structure. To facilitate the injection process, sufficient flowability of grouting is required. In addition to flowability, grouting must possess sufficient mechanical qualities, including compressive and tensile strength, fluidity, impermeability, and sulfate resistance [10], to ensure its effective fixation.

Due to there being very few applicable mix design techniques for cement-based grouting, grout mix design is typically done by trial and error. In that time, several grout mixes are required to provide the necessary mechanical and physical requirements [11]. The performance of cement-based grouts can be enhanced by incorporating admixtures such as fly ash (FA), bentonite (B), and silica fume (SF). The decision about the type of grouting substances in the grouting design ought to be based on specific circumstances and a thorough assessment of several parameters, like the nature of the soil, the reason for grouting, and even economic considerations. Additives are frequently utilized to improve the grout efficiency. For example, accelerators may accelerate the procedure of hydration, retarders may postpone it, and water reducers lower the quantity of water utilized [11]. The key variable influencing grout strength is the water-to-cement (w/c) ratio; therefore, for grouts that have minimal w/c ratios, a superplasticizer must be included in order to attain suitable rheological features. This helps guarantee that grouts can move properly in rock joints and ensures grouting efficiency [12]. Many studies have looked into how certain admixtures affect the different qualities of grouts [13]. Studies have shown that some waste products can be used as supplementary cement additives (SCMs) due to their multiple benefits in improving the performance of cement mixtures. For example, slag and silica fume were characterized by a stronger pozzolanic reaction than fly ash and pumice, which led to a rise in compressive strength in the mixture. Nevertheless, in the initial phases, the impact of adding components to grout mixes was negligible. As time went on, their effect became obvious: the cement particles' C-S-H gel expanded toward the outside, reducing the porosity and improving density [14]. However, numerous studies have demonstrated the distinct effects of various SCMs on mechanical properties over different curing periods. For instance, the incorporation of FA tends to enhance long-term compressive strength (e.g., at 90 days), whereas the inclusion of 16% SF by weight of cement contributes to both early-age (1 and 3 days) and long-term (90 days) strength development [15].

Silica fume (SF), also known as micro silica or compressed silica fume, is a byproduct of the silicon metal industry and is frequently regarded for its high silica content and ultrafine particle size. Its incorporation into cement-based composites is among the most common strategies to improve microstructural density and, consequently, mechanical strength [16-18]. Further proved that silica fume substantially raises compressive strength and lowers porosity and permeability. According to the reference [19], SF can be partially substituted for cement in the formulation of highly efficient, environmentally friendly, and long-lasting grouts. These groups are applicable in sectors such as soil stabilization and rock grouting. The combination of silica fume and superplasticizers has also been researched for enhancing grout features. Their findings revealed that a combination of 10% SF and 1% superplasticizer accomplishes the aim of making a strong, flowable grout with no bleeding an optimal balance of workability and stability [20]. In the pursuit of more sustainable construction materials, GGBFS is used as an effective replacement for ordinary Portland cement (OPC). GGBFS exhibits cementitious properties similar to those of Portland cement and contributes to significant decreases in carbon dioxide emissions. From a practical standpoint, GGBFS can be utilized effectively in place of conventional cement on a weight-to-weight basis, with substitution percentages typically ranging from 30% to 85% [21].

To further enhance the performance and durability of grouts, multiple searches have examined the influence of including fibers and chemical additives on the mechanical qualities and durability of cementitious grouts. PP fiber, in particular, has been adopted for many studies due to its exceptional resistance to chemical assault and capacity to decrease the likelihood of cracking in grout barriers, especially those used in burial trenches [22]. In light of the extending requirements for successful ground enhancement methods and rising demand for environmentally friendly building methods, grouting has become known to be a crucial solution for civil engineering programs. The incorporation of supplementary cementitious materials in addition to chemical admixtures and fibers has significantly improved the efficacy, dependability, and environmental effect of cement-based grouts. Consequently, this study concentrates on measuring the influence of numerous additions on the mechanical and rheological qualities of cementitious grouts for the purpose of developing successful, high-performance formulas suitable for satisfying current engineering demands.

2. EXPERIMENTAL PROGRAM

2.. Materials

2.1.1 Cement sulphate-resistant cement

Sulphate-resistant cement (SRC) with a specific gravity of 3.125 and a Blaine surface area of 3174 cm²/g was used in the present research. The Mass Cement Company in Sulaymaniyah, Iraq, manufactured it. This kind of cement meets the Iraqi specification No.5/1984 [23], and its chemical features are listed in Table 1.

Table 1. The chemical composition of sulfate resistant cement (SRC)

Chemical Composition	Content (%)	Iraqi Specification No.5/1984 [23]
SiO_2	22.66	-
Al_2O_3	4.14	-
Fe_2O_3	5.01	-
CaO	60.64	-
Sulfur trioxide, SO_3	2.11	≤ 2.5%
Magnesium oxide, MgO	2.03	≤ 5%
Loss of ignition (LOI)	1.76	≤ 4%
Insoluble residue (Ins. Res.)	0.67	≤ 1.5%
C3S	33.59	-
C2S	39.67	-
C3A	2.50	≤ 3.5%
C4AF	15.23	-

2.1.2 Silica fume (SF)

A very reactive SCM compound with a specific gravity of 2.11, SF is a by-product of the manufacture of silicon metal or ferrosilicon alloy. This material fulfills the requirements of ASTM C1240-15 [24], and its chemical features are listed in Table 2.

Table 2. Chemical composition of silica fume

Oxides	Oxide Content (%)
SiO_2	89
Al_2O_3	0.4
Fe_2O_3	1.2
MgO	2.5
CaO	1.4
SO_3	1
Na_2O	1.2
LOI	0.371

2.1.3 Ground granulated blast furnace slag

GGBFS Grade 80 was produced by the Nawroz metal manufacturing coMPany in Zakho, Iraq. In this research, it was sifted through No.325 (0.045 µm) to ensure uniform fineness. The specific surface area and specific gravity were 550 m²/kg and 2.8, respectively, and the material seemed like a dark black powder. In Table 3, the chemical structure of

GGBFS can be seen in line with ASTM C989 [25].

Table 3. Chemical compositions of GGBFS

Element	Content
MgO (%)	2.3807
Al_2O_3(%)	12.9636
SiO_2(%)	62.2782
P_2O_5(%)	0.0480
Sulfur (%)	0.0172
K_2O (%)	1.2555
CaO (%)	3.8790
Manganese (%)	0.0577
Fe_2O_3(%)	16.9709

2.1.4 Polypropylene fiber

In this study, polypropylene fiber, a widely available and low-cost plastic waste material, was used to improve soil properties. Its physical features and specifications are shown in Table 4. It enhances shear strength and reduces volumetric changes, contributing to better soil stability. Due to its high tensile strength and abundance as waste, it is considered a sustainable option for enhancing the mechanical properties of soil.

Table 4. Properties of polypropylene fibers

Fiber Properties	Values
Fiber type	single fiber
Length (mm)	6
Diameter (mm)	0.034
Density (g/cm^3)	0.91
Tensile strength (MPa)	350
Young’s modulus (MPa)	3500
Fusion point (℃)	165
Burning point (℃)	590
Surface area (m^2/kg)	250
Elongation (%)	24.4
Water absorption	nil

2.1.5 Superplasticizer (SP)

Hyperplastic PC600 SP was utilized in various quantities by binder weight with the aim to decrease the quantity of water required. Enhanced flowability, workability, and optimal cohesiveness can be obtained by the usage of SP. The suggested dose of Hyperplastic PC600 is 0.5 to 2.5 liters per 100 kg of cementitious components, such as SF or GGBFS, in the combination. ASTM C494/C494M-24 [26] Classes A and G list the physical and chemical features in Table 5.

Table 5. Properties of superplasticizer

Properties	Value
Color	yellowish to brownish liquid
Freezing point	-1℃
Specific gravity	1.07 ± 0.03
Chloride content: BS5075	Nil
Air entrainment	less than 2% at normal dosages

2.1.6 Fine aggregate

The present research utilized natural river sand from the Kanhash area of Mosul, Iraq. With several water washes, the sand was thoroughly cleaned in order to get free of pollutants and clumps of clay. It was subsequently spread out and left to air dry till the surface was saturated and dry. The sand was then sieved in order to make certain it could go through a 1.18 mm No. sieve. According to BS: 882: 1992 [27], the sand's physical features were characterized by an uncompressed unit weight of 1735 kg/m³, ability to absorb of 2.9%, and a dehydrated specific gravity of 2.66.

3. RESEARCH METHODOLOGY

A total of 10 grout mixtures were made to find out the impact of supplementary cementitious materials (SCMs) on the qualities of grout. Each of these mixes had different ratios of PPF, GGBFS, cement, and SF. The precise conjunction amounts are illustrated in Table 6. In all combinations, the water-to-binder ratio stayed similar. Cement was partially substituted by SF at substitution amounts of 5%, 10%, and 15%, while GGBFS was employed at 15%, 25%, and 40% substitution amounts. Also, PPF were incorporated at 0.10%, 0.15%, and 0.25% of the binder's weight. A power mixer was used to for three minutes in mixing process to insure the homogeneity the grout. A determining code (M1 to M10) was issued to every grout mix in line with the precise SCM and fiber dose ratio that it included. The specimens were cured in water bath at 20 ± 3℃ till 28 and 90 days. Three specimens of each mix were tested. The grout specimens' design is shown in Figure 1, and the study's production and testing techniques are explained in Figure 2.

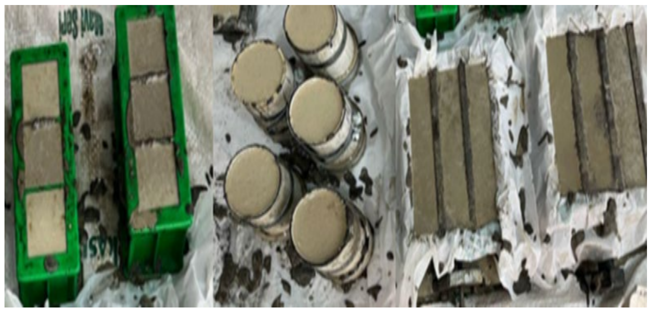

Figure 1. Grouting specimens

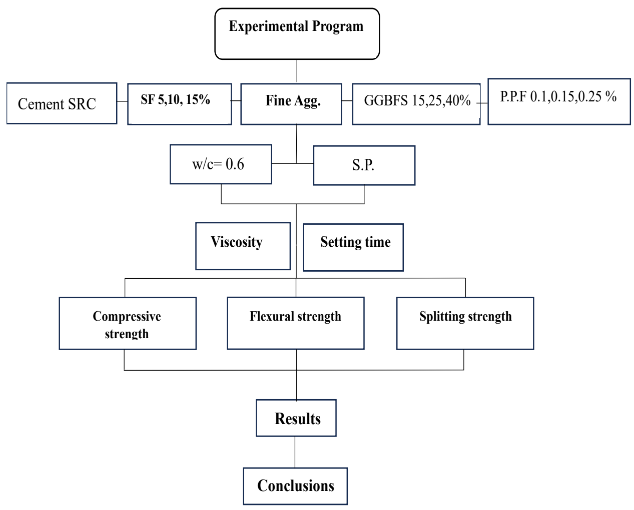

Figure 2. Procedure for preparing grouting mixtures

4. MIX PROPORTIONS

Grouting mixes were prepared manually. Dry materials, including sulfate-resisting cement (SRC), sand, SF, and GGBFS, were first blended thoroughly by hand for 1 minute.

Tap water and superplasticizer were then gradually added and mixed for 2 minutes. PPF were introduced last and hand-mixed for another 3 minutes to ensure even distribution. The detailed mix proportions are summarized in Table 6, which shows that all mixtures maintained a fixed water-to-binder ratio of 0.5. SF replaced cement at levels of 5%, 10%, and 15% by weight of cement, while GGBFS was used at 15%, 25%, and 40% by weight of cement. PPF was added at 0.1%, 0.15%, and 0.25% (by grout volume) based on the weight of the cement. A control mix with 100% SRC and no SCMs or fibers was also prepared. All mixes exhibited excellent workability without signs of bleeding or segregation. The mixing process followed ASTM C938 [28] and ASTM C939 [29] standards to ensure consistency and accuracy, as illustrated in Figure 2. The prepared specimens included cubes, prisms, and cylinders as shown in Figure 1, which displays the casting process and the various mold types used: 50 × 50 × 50 mm cubes, 40 × 40 × 160 mm prisms, and 50 × 100 mm cylinders.

Table 6. Mix proportions of grouting

Mix	Cement (kg/m³)	Sand (kg/m³)	SF (by weight %)	GGBFS (by weight %)	PPF (by volume %)	w/c Ratio	SP (%)
Mix0	825.8	792.77	----	----	----	0.6	---
Mix1	784.51	792.77	5	----	----	0.6	0.5
Mix2	743.22	792.77	10	----	----	0.6	0.5
Mix3	701.93	792.77	15	----	----	0.6	0.5
Mix4	701.93	792.77	----	15	----	0.6	0.7
Mix5	619.35	792.77	----	25	----	0.6	0.7
Mix6	495.48	792.77	----	40	----	0.6	0.7
Mix7	825.8	792.77	----	----	0.1	0.6	0.5
Mix8	825.8	792.77	----	----	0.15	0.6	0.5
Mix9	825.8	792.77	----	----	0.25	0.6	0.5

5. TEST METHODS

5.1 Compressive strength

Compressive strength tests were conducted using 50 mm cubic grouting mortar specimens. In accordance with ASTM C109 [30], the average result of six specimens was recorded. Testing was performed using a uniaxial compression machine under a constant loading rate of 0.3 N/mm²/s, as shown in Figure 3. Specimens were tested after curing for 28 and 90 days under both tap water and sulfate exposure conditions. The compressive strength of each specimen was found utilizing Eq. (1).

$$fm = \frac{P}{A} \tag{1}$$

where,
fm = compressive strength in (MPa).
P = total maximum load in (N).
A = area of loaded surface (mm²).

Figure 3. Compressive strength test machine

5.2 Flexural strength test

According to ASTM C348 [31], the prism sample, which possessed measurements of 40 × 40 × 160 mm, was employed to find the flexural strength, as shown in Figure 4. This is how the modulus of rupture is determined from Eq. (2):

$$Sf = \frac{3PL}{2bd^2} S \tag{2}$$

where,
Sf = Flexural strength, MPa.
P = Total maximum load, N.
L = Distance between two supports of specimens (mm).
b = the width of specimens (mm).
d = the high of specimen (mm).

Figure 4. Flexural strength test machine

5.3 Splitting strength

Following ASTM C496 [32] Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens were accompanied in the test. This approach may also be employed for mortar if the samples are created with the proper dimensions (50 mm in diameter and 100 mm in height) and treated under typical laboratory circumstances. A pressure testing machine's platens maintain the specimen horizontally as the force builds up till splitting takes place. Applying the typical Eq. (3), the splitting tensile strength is identified.

$$ft = \frac{2P}{\pi LD} \tag{3}$$

ft = splitting tensile strength (MPa).
P = maximum applied load (N).
L = length of the specimen (mm).
D = diameter of the specimen (mm).

5.4 Setting time

The setting time can be identified by utilizing the Vicat gadget in line with ASTM C191 [33]. The Vicat apparatus mould has an approximate height of 40 ± 1 mm, a top internal diameter of 70 ± 3 mm, and a bottom internal diameter of 60 ± 3 mm, and it features a needle with a diameter of 1 ± 0.05 mm connected to an adaptable rod weighing 300 ± 0.5 g. The mould was set on the non-adsorptive plate, which had been packed with paste. The amount of water and binder that was added to the mortar mixtures was the same as that of the paste mix. One of the key variables affecting the grouting pastes' setting time was the laboratory climate in which the test took place. A certain amount of the created grout was extracted and inserted into the setting time devices once blended according to the needed percentage. In order to precisely determine the beginning and end times in line with the typical testing regulations, the mould was packed with the mix slowly until it was totally full.

5.5 Viscosity

The viscosity test evaluates the duration it needs for grout to go through a typical cone for the purpose of measuring the workability and fluidity of grouting mixtures. ASTM C939 [29], Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method), is applied when carrying out this test. The standard flow cone's parameters are listed below, in accordance with ASTM C939. For optimal precision for following evaluations, the test requires to be carried out in a controlled atmosphere, and the instrumentation must be washed shortly after every test.

6. RESULTS AND DISCUSSIONS

6.1 Compressive strength

The compressive strength results for mixes M0 through M9 at 28 and 90 days are shown in Figure 5. The type and proportion of chemical admixtures and supplementary cementitious materials (SCMs) used in each blend strongly influenced strength development over time. Particle size, pozzolanic activity, and the way additives interacted with the cementitious matrix all shaped the outcomes. At both 28 and 90 days, the highest strength values were observed in mixes M1 through M3, each exceeding 40 MPa at 90 days. These mixtures likely contained the optimal ratios of highly reactive pozzolanic materials GGBFS and SF. When calcium hydroxide (CH), generated during cement hydration, reacts with the fine amorphous silica in SF, additional calcium silicate hydrate (C-S-H) is produced. This secondary reaction densifies the matrix and lowers porosity. Yet, at higher replacement levels, particle agglomeration may offset these benefits, hindering hydration efficiency and compaction [34].

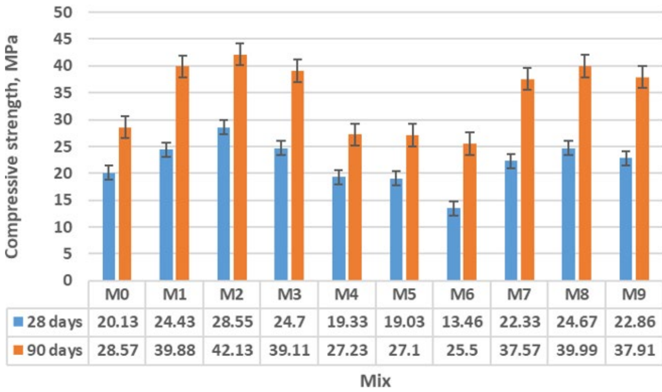

Figure 5. Compressive strength of grouting mixtures at 28 days and 90 days

These findings are consistent with Badalyan et al. [35], who demonstrated the efficiency of SF in improving grout performance. Their work showed that replacing 8% of cement with SF, combined with a 0.4 water-to-cement ratio and a high-range water reducer HRWR, significantly enhanced compressive strength, reduced bleeding, and improved long-term resistance to corrosion. They also reported gains in electrical resistance, workability, and overall stability when SF was paired with HRWR. Such outcomes align closely with the patterns observed in the present study, reinforcing the central role of finely reactive SCMs in boosting both mechanical strength and durability. By contrast, mixes M4 through M6, which contained GGBFS, showed weak early-age strength due to the slow hydraulic reactivity of slag. However, by 90 days especially in mix M6 strength gains became evident. The gradual reaction of slag with CH produced additional C-S-H, progressively refining the microstructure. These delayed improvements echo the observations of Ahmad et al. [36] and Mohammed et al. [37], who highlighted the long-term benefits of slag in creating sustainable and durable cementitious systems.

The performance of mixes M7 through M9, which incorporated polypropylene fibers (PPF), was more modest. The limited strength gains align with prior studies [38-41]. While fibers help control microcracking and improve internal cohesion, they do not chemically contribute to hydration. One cited investigation into cement-ash slurry with PP fibers and a superplasticizer (SP) found that fibers enhanced resistance to volumetric changes, sulfate attack, and degradation. At the same time, however, they increased viscosity and permeability, compromising workability. Fiber clustering and void formation may also explain the slight reductions in compressive strength observed in several fiber-reinforced mixes. This reinforces the view that fibers primarily improve crack resistance and tensile behavior rather than significantly boosting compressive strength.

Overall, the compressive strength results reveal how strongly admixture type and dosage influence the long-term performance of grouting materials. Mix M2 emerged as the best-performing blend, reflecting the synergy between silica fume and other constituents in promoting hydration and matrix densification. Slag-based mixes showed weaker initial strength but clear long-term gains, while fiber-reinforced grouts offered only minor compressive benefits, functioning more effectively as crack-control agents. These results underscore the importance of optimizing SCMs for strength and durability, with fibers serving a complementary role in enhancing structural integrity.

6.2 Flexural strength

The flexural resistance of combinations of grouting (M0-M9) exhibited substantial variations between 28 and 90 days, as displayed in Figure 6, with the kind of additive utilized in every mix having a noticeable effect on the values. Following 28 days, the additive-free M0 control mix demonstrated a resistance of approximately 3.1 MPa, which elevated to approximately 4.7 MPa by 90 days. In contrast to M0, combinations of M1, M2, and M3, which comprise varying amounts of silica fume, fared better. The M1 mixture's flexural resistance was roughly 3.8 MPa at 28 days and 5.1 MPa at 90 days; nevertheless, the M2 resistance did better than any of the other blends, measuring 4.2 MPa and 6.2 MPa at 28 and 90 days, correspondingly. Pozzolan silica fume's significant activity, which helps in the generation of other C-S-H components and enhances density and longevity, was the reason for this outstanding efficiency. Although M3 contained the greatest amount of silica fume, its resistance varied between 4.0 and 5.3 MPa, which could be an indication of microcracks brought on by low functionality or saturation with tiny particles. Bending resistance dropped at 28 days in M4-M6 blends once blast furnace slag was substituted for cement, with values of 2.6, 2.4, and 2.5 MPa, correspondingly. The reduction comes from the slags' early, late hydraulic response. The resistance climbed to 4.7 MPa in M4, 4.5 in M5, and 4.4 in M6, showing the initial phase of the slag, the interaction with CH, and the creation of secondary cement ingredients that slowly boost the mixture's strength. Yet, an important increase was noticed at the age of 90 days.

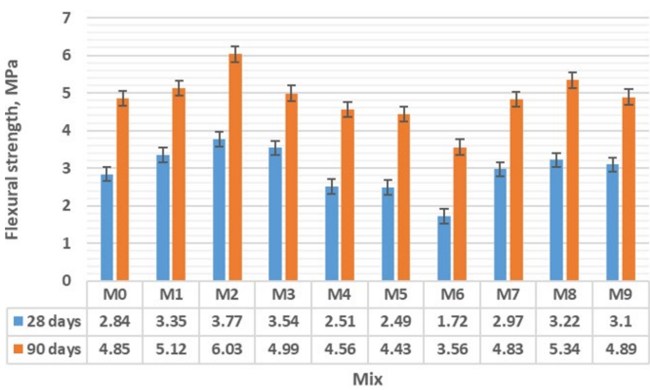

Figure 6. Flexural strength of grouting mixtures at 28 and 90 days

The polypropylene fiber-containing blends M7, M8, and M9 had fairly acceptable resistance across the two ages; M7 got resistances of approximately 3.3 and 4.9 MPa, M8 got resistances of 3.5 and 5.2 MPa, and M9 got resistances of approximately 3.4 and 4.9 MPa. Given the advantage of M8, the findings demonstrate that the fibers' long term flexural resistance by minimizing microcracks and strengthening interior connections without having a direct chemical impact. The fiber proportion possibly established a perfect equilibrium between performance and clogging avoidance. In general, the M2 combination with 10% silica fume surpassed all other combinations in regard to flexural resistance across all ages because of enhanced grouting microstructure and enhanced pozzolan responses. Conversely, the mixtures with GPS demonstrated an unexpected delay in efficiency, and the fibers generated slight enhancements in the mixture's physical characteristics. These findings indicate that the nature and dosage of additives have an essential part in regulating the bending properties of grout-based mixes. Different substances, such as slag and fibers, demonstrate slower or slight increases in strength, whereas extremely reactive pozzolanic compounds, like silica fume, substantially boost strength because of matrix density and secondary C-S-H generation, especially at perfect doses. For flexural effectiveness modification, additive optimization of material is consequently crucial, and M2 is the ideal formulation for long-term structural development.

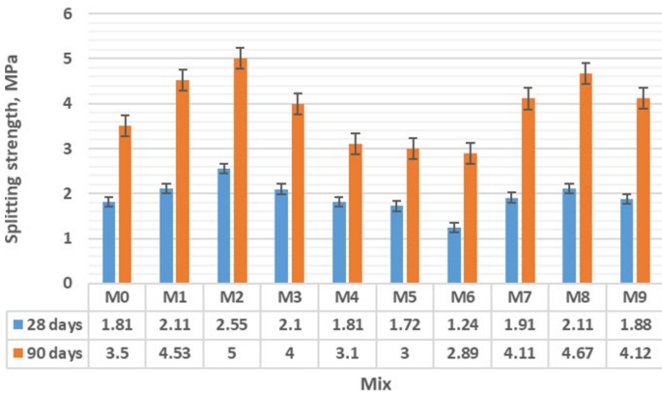

Figure 7. Splitting tensile strength of grouting mixtures at 28 and 90 days

6.3 Splitting tensile strength

The data of the splitting tensile strength at 28 and 90 days are displayed in Figure 7, indicating a substantial difference throughout the blends (M0-M9), according to the nature and content of the extra components. The reference mix M0 reported an initial strength of about 1.9 MPa at 28 days, which increased to 3.3 MPa at 90 days because of the usual rate of cement hydration. Mixes including silica fume (M1-M3) demonstrated substantial enhancements in tensile strength, with Mix M2 (including 10% silica fume) attaining the greatest strength of roughly 4.9 MPa at 90 days. This enhancement is attributed to the elevated pozzolanic response of silica fume, which stimulates more C-S-H manufacturing and decreases porosity. On the other hand, the tensile strength of mixes that included GGBFS (M4-M6) was considerably smaller. Mix M6 had the smallest value (3.0 MPa) at 90 days. The weak hydraulic responsiveness of the slag and inadequate initial production of bonding components are the root causes of this behavior. In contrast, the inclusion of PPF into mixes M7-M9 successfully improved the splitting tensile strength through minimizing microcracks while boosting interior cohesiveness. Mix M8 had a significant tensile strength of 4.5 MPa; nevertheless, Mix M9 had a slight decrease in strength, which could have been caused by elevated inner voids or fiber clumping. The outcomes show that while large substitution or extra material may have negative consequences, introducing highly reactive pozzolanic substances and fibers in proper amounts may substantially enhance tensile strength.

7. CONCLUSIONS

Based on the findings of the study, the following specific conclusions can be drawn:

1. The inclusion of extremely reactive pozzolanic materials, specifically SF, markedly raised the grout mixtures' compressive, flexural, and splitting tensile strengths. Due to its improved matrix density, long term C-S-H creation of gels, and decreased porosity, Mix M2, comprising 10% silica fume, behaved exceptionally well for every mechanical variable and time.

2. Slag-based combinations (M4-M6) exhibited a retarded strength advancement result from the sluggish hydraulic reaction of GGBFS.

3. Fiber-reinforced mixes M7-M9 had a negligible or no improvement in compressive strength due to potential void formation and limited workability. Still, they produced substantial boosts to tensile and flexural resistance via optimized crack management and internal cohesiveness.

4. The optimum SCM for improving strength without losing grout workability was determined to be silica fume in proper quantities, specifically when mixed with high-range water reducers. When used properly, GGBFS and fibers helped achieve environmental responsibility and durability goals.

5. The research indicated that modifying the kind and quantity of additives may result in grout compositions that are permanent, efficient, and ecologically friendly. To be able to solve both present and potential technical issues, these optimal grouts are ideal for specialized uses such as soil stabilization and subterranean building.

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