



Development and Performance Evaluation of Metakaolin–GGBS-Based Sustainable Grouts for Semi-Flexible Pavement Applications

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DOI: <https://www.doi.org/10.29194/NJES.29030473>

Received: Nov. 15, 2025

Revised: Nov. 28, 2025

Accepted: Jan. 12, 2026

Published: Sep. 20, 2026

Abstract

The present research aims to develop a sustainable, high-performance grout mix for semi-flexible pavement applications by partially replacing Ordinary Portland Cement (OPC) with Metakaolin (MK) and Ground Granulated Blast Furnace Slag (GGBS). The experiments were carried out in two steps: Portland cement was partially replaced with MK (10%, 20%, and 30%) to determine the optimum mix proportions for rheological and mechanical behavior. The selected optimal MK content was mixed with GGBS at 50%, 60%, and 70% replacement levels. Flowability was evaluated using flow time tests, and DIOs assessed mechanical performance through compressive, tensile, and flexural strength testing. The results showed that a 20% MK replacement level achieved a balance between workability and strength, with an optimum flow time of 14.03 s and a compressive strength of approximately 32.2 kN at 7 days of age. However, incorporating GGBS with a 20% MK blend enhanced the sustainability of these blended grouts without sacrificing their mechanical properties. The MK-GGBS grout-60% GGBS (60% GGBS) showed the highest compressive and flexural strengths, which can be considered for semi-flexible pavement applications. The incorporation of MK and GGBS reduces energy consumption during cement production, which is widely known as a significant contributor to global warming. It increases the durability of grouting materials under traffic loading.

Keywords: Sustainable Grouting, Metakaolin (MK), Ground Granulated Blast Furnace Slag (GGBS).

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1. Introduction

There are mainly two types of road pavement commonly used: flexible and rigid pavements. However, it is possible to make a road a composite of the two by changing the application technique. Semi-flexible pavement (SFP) represents an alternative between flexible and rigid pavements [1]. In general, road paving in road construction is mostly done by flexible pavement [2], [3], as rigid pavement is less common to be utilized because it takes a longer time for construction, uncomfortable road riding quality, noise issues in the surface of slab and its joints that are needed to expand shrinkage of service condition during placing work stage and more expensive application [4], [5]. However, it has better durability compared with flexible pavement. Flexible pavements are very sensitive to the combined effects of load and temperature; they are incapable of withstanding heavy traffic loads, which can lead to structural failure [6]. In flexible pavements, rutting and cracking are critical problems caused by heavy traffic and poor durability.

Multiple deficiencies in the two commonly used pavement types partially justify SFP as an alternative. SFP, developed in the 1950s [7], can be used to construct an open-graded asphalt skeleton with air voids of approximately 25–35% [8], [9], surrounded by a

cement-based grouting material. This hybrid combination ensures that the resultant layering has the best attributes of bituminous (flexibility) and concrete pavements (rigidity) [10]. As a result, SFP has several remarkable merits, such as overload capacity, wear resistance, shear strength, and water stability, providing comfort driving [11]. As such, SFP could be utilized at facilities that would experience heavy or low volume usage, including industrial areas, harbors and docks, warehouses and distribution centers, road crossings, bus terminals, parking lots, cargo yards, pavements near airports and airfields, and holding bays/ hangar pavement [7], [12]. Asphalt pavement has become one of the most widely used pavement types in road engineering owing to its exceptional performance and driving comfort. However, the continual rise in highway traffic volume results in the early development of rutting in asphalt pavement [13]. Investigations have shown that the use of anti-rutting agents, high-modulus agents, and other additives in hot-mixed asphalt may substantially reduce rutting [14], [15]. At elevated temperatures, the viscosity of asphalt decreases, reducing the ability of asphalt pavement with additives to maintain significant resistance to deformation [16]. Conversely, the SFP favors elastic materials by including certain cementitious substances into the OGA mixture, which has a porosity of 20–30% [17]. Increased porosity of the OGA necessitates greater amounts

of grouting material, and the "stiffening impact" of cement-based substances enhances the resistance to rutting and modulus of elasticity of SFP [18], [19]. Driving comfort, fatigue life, and durability are simultaneously improved, making the SFP advantageous for traffic and the environment throughout its life cycle [20]. Nonetheless, the already used OPC-based grouts exhibit problems, including inadequate early strength, extended initial setting time, and significant production contamination. Annually, 5–10% of global carbon emissions result from OPC production. In contrast, the production of Ultra-High-Performance Concrete (UHPC) generates 33% more greenhouse gases than geopolymers [20], [21], [22], potentially hindering the future applications of Sustainable SFP [23], [24].

Yang et al. [17] studied the influence of cyclic wheel loading on the durability of SFPs of various porosities and found a relation between the time of loading and damage factors. Setyawan et al. [25] studied the compressive performance of various pozzolanic grouts and bitumen- and aggregate-kind grouted macadam composites, and compared material properties between porous asphalt and grouted macadam. Cai et al. [3] found that the contributive rate and contributive effect of an asphalt mixture matrix were less than those of a grouting material. Zhang et al. [2] investigated the effect of composition and preparation on two common grouting materials. They found that if cement paste were prepared correctly, it would be more suitable for use as a grouting material. Zhang et al. [26] studied the effect of three main factors (water–binder proportion, sodium oxide amount, powder quality proportion) and their interactions on four dependent variables for composite grouting materials. The response surface and orthogonal test design techniques can be used to determine the optimal mix proportions for the geopolymer grouting material. Ding et al. [27] compared the durability and mechanical performance of SFP specimens with those of traditional AC pavements at various porosity levels. They found that SFP had better high-temp stability and low-temp relaxation capabilities, and that a higher mineral aggregate matrix porosity was beneficial for performance.

Supplementary cementitious materials (SCMs) play an important role in improving the performance and durability of cementitious grouts used in semi-rigid pavements [28]. Its incorporation significantly improved mechanical strength, reduced shrinkage, and enhanced water repellence by optimizing the pore structure and promoting a secondary hydration reaction. SCMs like MK [29] and GGBS [30] enhance early-age strength through pozzolanic and latent hydraulic activity, while also reducing the heat of hydration and improving long-term stability.

The uniqueness of this work lies in the fact that research was conducted for the first time on the systematic preparation and optimization of a hybrid MK–GGBS cementitious grout for its application in SFP, with a special emphasis on achieving superior penetration characteristics, robust mechanical performance, and sustainability. Unlike most previous research, which isolated metakaolin or GGBS, this paper explores the synergistic interplay between highly reactive metakaolin and latent-hydraulic GGBS to achieve early-age strength development, long-term performance, and reduced dependence on Portland cement.

A significant original contribution is the two-step optimization (2-OP) procedure, which first determines the optimal MK replacement level in the fresh and mechanical states based solely on MK content, followed by selective replacement of MK with different GGBS proportions. Such a staged approach helps provide clear mechanistic insight into how the pozzolanic and hydraulic reactions compete in grouting systems for SFP, for which previous studies offer limited understanding. The contribution also quantifies the specific role of PCE-based superplasticizer in hybrid MK–GGBS grouts, highlighting its key role in delivering a thin or narrow flow time window required for efficient filling of open-graded asphalt skeletons that have been largely neglected, or empirically addressed in previous research.

In all cases, the novel grout formulation is assessed not only for its strength performance but also for its rheological potential for field grouting and penetration extent, as well as for sustainability gains, whereby the design of materials is connected with practical SFP performance criteria. This new hybrid binder (20% MK + 60% GGBS + 1.5% SP), which achieves advanced mechanical properties while significantly reducing OPC content, is a clear improvement over conventional cement-based or single-SCM grout systems. Taken together, this investigation demonstrates a new, application-driven strategy for materials design to develop sustainable SFPs that link laboratory grout formulations with real pavement performance requirements.

2. Experimental Procedure and Materials

2.1. Utilized Materials

Blending Materials

In this study, Ordinary Portland Cement (OPC), Ground Granulated Blast-Furnace Slag (GGBS), Metakaolin (MK), shown in Figure 1, and a polycarboxylate ether (PCE)-based superplasticizer (SP) were employed as blending materials to develop high-performance grouting systems for semi-flexible pavements. The OPC, supplied by AL-JESR/Lafarge Cement Factory in Sulaymaniyah City, conformed to the Iraqi Standard No. 5/1984, ensuring consistent chemical composition and mechanical quality suitable for cementitious grout applications. To ensure adequate workability at low water-to-binder ratios, a high-range water-reducing admixture (Sika® ViscoCrete® 905 S Hi Tech) was incorporated. Tables 1 and 2 show the physical features and chemical analysis for all selected materials.

Table 1. Physical features of utilized materials.

OPC			
Physical features	Unit	Result	IQS 5/1984
Finesse (Blaine)	m ² /k	350	≥ 300
Soundness (expansion) - Le Chatle	g mm	0	≤ 10
Initial setting time	Min.	61	≥ 45
Final setting time	Min.	233	≤ 600
Compressive strength	3days	MPa	≥ 15
	7days	MPa	≥ 23
GGBS			
Property	Requirement		Results
Specific surface area (m ² /kg)	≥ 400		418
Relative fluidity (%)	≥ 95		106
Activity index at 7 days (%)	≥ 75		77

Activity index at 28 days (%)	≥ 95	107
Density (g/cm ³)	≥ 2.8	2.9
Moisture content (%)	≤ 1.0	0.1
SO ₃ content (%)	≤ 4.0	0.3
Chloride ion content (%)	≤ 0.06	0.02
Loss on ignition (%)	≤ 3.0	0.2
Vitreous content (%)	≥ 85	93
Radioactivity	—	Conforms
MK		
Property	Results	
Whiteness	90-91%	
Particle Size	325 mesh	
Moisture	≤0.5	
PH Value	6.0-8.0	

Table 2. Chemical composition and main compounds of utilized materials.

OPC		
Oxide	% by weight	Limits of IQS No.5/1984 (63)
SiO ₂	20.7	-
CaO	61	-
Al ₂ O ₃	4.1	-
Fe ₂ O ₃	5.5	-
Lime Saturation Factor	0.89	0.66-1.02
MgO	3.1	≤ 5%
SO ₃	2.3	≤ 2.5%
Loss on Ignition	3.5	≤ 4%
Insoluble Residue	0.4	≤ 1.5
MK		
Oxide	% by weight	
SiO ₂	53 ± 2	
Al ₂ O ₃	45 ± 2	
Fe ₂ O ₃	0.268	
TiO ₂	0.76	
K ₂ O	0.071	
Na ₂ O	0.08	
CaO	0.193	
MgO	0.151	



Figure 1. a) GGBS; b) MK.

Aggregates

Semi-flexible pavement should have a voids ratio ranging from 25% to 35%, and, based on research by Saboo et al. [31], a hierarchical ranking approach was developed to rank several kinds of porous asphalt skeletons for SFP. Table 3 presents the specifics of seven distinct porous asphalt mixtures. A bitumen percentage of 2% to 4.5% was used for all grades (M1 to M7). In the current study, Anderton [9] was selected due to achieving a suitable voids ratio.

Table 3. Grading implemented by Saboo et al. [31].

Sieve Size (mm)	Anderton (2000)
19	100
12.5	62.8
9.5	51.5
6.3	35
4.75	17.6
2.36	11.1
1.18	7.3
0.6	6.6
0.3	2.4
0.15	1.2
0.075	1.1
Air Voids	27-31%
Binder Content range, % (Optimum, %)	2-4.5% (3.5%)
ITS (kPa)	116.52

Mixing Procedure

Grout mixing followed ASTM C939 [32], but with monitored sequencing to ensure uniformity and repeatability. At first, the dry binder ingredients (OPC, MK, and GGBS) were weighed according to specific mix blends and dry-mixed in a mechanical mixer at low speed for 2 minutes to achieve uniform particle dispersion. Afterwards, the mixing water was premixed with a dosage of polycarboxylate ether (PCE)-based superplasticizer, and it was slowly added to the dry mix within 30–45 s by a mixing forerunner at a medium rate. Mixing was then conducted for a further 3–4 minutes. During that time, the mixer was briefly stopped once to clean down the bowl side, prevent material agglomeration, and achieve complete incorporation of fines. A visual examination of the placed grout was performed to verify that there was no segregation, bleeding, or clumping in the fresh grout. The freshly mixed grout was immediately checked for workability using the flow cone, then cast in the moulds for mechanical testing without any external compaction. All mixing and testing were conducted at a constant laboratory temperature of 23 ± 2 °C to minimize variability in the rheological response.

Design Mix Proportions

To identify the optimal grout composition, multiple mix designs were investigated by varying the ratios of MK, GGBS, cement, and SP while maintaining a water-to-cement ratio (w/c) of 0.58-40. The experimental matrix included:

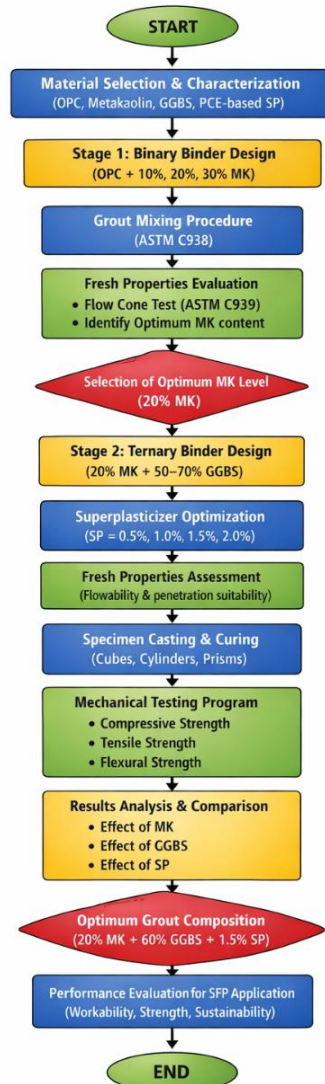
- MK replacement levels: 10%, 20%, and 30% (by weight of cement)
- GGBS (G) replacement levels: 50%, 60%, and 70% (by weight of cement)
- SP dosages: 0.5%, 1.0%, 1.5%, and 2.0% (by weight of cement)

The mix design table for each mixture is presented in Table 4.

Table 4. Mix design of grout mixtures (binder basis = 100%)

Mix ID	OPC (%)	MK (%)	GGBS (%)	SP (%)
MK10	90	10	0	0
MK20	80	20	0	0
MK30	70	30	0	0
MK20+50G	30	20	50	0
MK20+60G	20	20	60	0
MK20+70G	10	20	70	0
MK20+60G+0.5SP	20	20	60	0.5
MK20+60G+1SP	20	20	60	1
MK20+60G+1.5SP	20	20	60	1.5
MK20+60G+2SP	20	20	60	2

The workflow diagram for experimental work is shown in Figure 2.

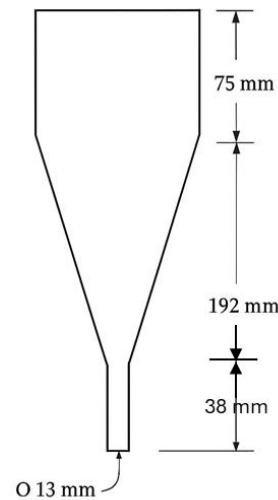
**Figure 2.** Flowchart for working methodology.

2.2. Tests of Grouting Materials

Flow Time Test

Grout flow characteristics were identified utilizing an efflux time calibration flow cone in accordance with ASTM C939 [32], a key parameter for grout fluidity and stability required for penetrating the asphalt skeleton. The cone (shown in Figure 3) was pre-wetted before testing to reduce friction, and 1725 mL of grout was discharged, and the ex-dating time was recorded. The best balance between workability and viscosity for homogeneous infiltration without splitting was observed with mixtures having an efflux time

of 10–14 s. All flow cone tests were conducted at a controlled laboratory temperature of 23 ± 2 °C, as specified in ASTM C939 [32].

**Figure 3.** Flow time test mold (flow cone).

Compressive Strength Test

The compressive strength was assessed to assess the load-bearing capacity and structural soundness of the grout mixes for semi-flexible pavement. This test assesses a material's resistance to axial loading and is an indicator of binder hydration and microstructural packing. Pure specimens were molded in 50 mm cubes according to standard ASTM C109/C109M [33] as shown in Figure 4, under controlled curing, and analyzed at days 7, 14, and 28 on a calibrated device under compression (Equation (1)) to find the ultimate compressive strength:

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

where:

f_c = compressive strength (MPa)

P = maximum applied load at failure (N)

A = loaded cross-sectional area of the cube (mm²)

**Figure 4.** Preparation of 50 mm grout cubes in molds for compressive strength testing (ASTM C109/C109M).

Tensile Strength Test

ASTM C307 [34] was used to determine the tensile strength of the grout mixtures under direct tension, which was indicative of the cohesive resistance and crack-propagation behavior of the hard matrix. Cylindrical samples were fabricated, cured in the laboratory under controlled conditions, and tested to failure in axial tension in a universal testing machine. Ultimate tensile strength is defined as the maximum load divided by the neck area and accurately reflects the mechanical behavior and structural integrity of grout. The tensile strength (f_t) was identified as per Equation (2):

$$f_t = \frac{P}{A} \quad (2)$$

Whereas:

P is the max applied load at failure (N),

A is the sample's cross-sectional area (mm²).

Flexural Strength Test

The grouts developed for semi-flexible pavements were further tested using a flexural strength test to measure their resistance to bending and their ability to tolerate cracking. Such a parameter, called the modulus of rupture (MOR), characterizes the grout's resistance to tensile stress under flexural loading and can be directly related to fatigue life and load capacity performance in composite pavements. Tests were conducted according to ASTM C348 [35] and standards on 50 × 50 × 150 mm prisms, under controlled curing, using three-point bending to determine MOR with accuracy and repeatability. The flexural strength (f^f) was determined using Equation (3).

$$f^f = \frac{3PL}{2bh^2} \quad (3)$$

Whereas:

f^f = flexural strength (MPa)

P = max applied load at failure (N)

L = span length between supports (mm)

b = width of the sample (mm)

h = the height of the sample (mm).

3. Results and Discussion

3.1. Flow Time

The relationship of flow time versus (W/C %) in the blended systems, which included MK, GGBS, and various SP content, is demonstrated in Figure 5 (a-b). Without SP, when W/C increased from 40 to 55 %, the flow time decreased significantly, demonstrating decreased viscosity and improved workability due to intensified mixing in a 10–20 % MK partially substituted blend, where the improved fluidity resulted in more refined particle packing and increased pozzolanic reactivity, leading to reduced particle-to-particle voids [36]. At 30 % MK, on the other hand, higher water and surface area demand led to an increased internal friction, which in turn caused (to some extent) workability decrease [36]. Flow time also decreased with the use of GGBS (50–70 %) together with 20 % MK due to the smooth, glassy structure and reduced reactivity of GGBS, which reduced their tendency for particle-to-particle friction; hence, it helps improve dispersion in the cement matrices [37]. The hybrid 20 % MK + 60 % GGBS paste showed an ideal rheology, with a flow time ≈ 9–11 s at W/C ≥ 50 %, indicating its high grouting penetration ability. The presence of PCE-based SP can induce strong electrostatic and

steric repulsion among MP particles, leading to effective dispersion and reduced viscosity [38]. At higher levels of SP (up to 2 %), flow time was considerably reduced (≈ 8–10 s), and low dosages and/or low W/C mixes remained more viscous due to poor lubrication [39].

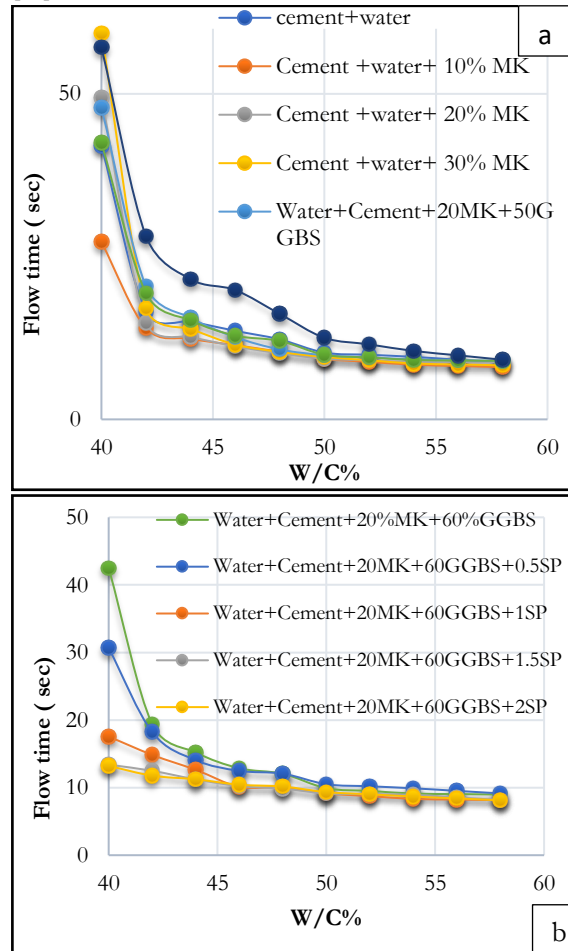


Figure 5. Flow time results in various mixtures: a) without SP and B) with (0.5, 1, 1.5, and 2)% SP.

3.2. Compressive Strength

The compressive strength development of cementitious mixes with various MK and GGBS percentages and SP dosages is shown in Figure 6 (a-b). When 20 % MK was used as an alternative material for cement, it yielded the maximum compressive strength (22.48 MPa) at 28-day curing age, indicating the maximum pozzolanic reactivity of MK and the minimum water demand for hydration in this binary system. The reason is that MK contains high levels of silica and alumina, which can promote the consumption of calcium hydroxide and the formation of secondary C-S-H phases, thereby forming a denser pore structure and better relieving the load [21]. A further increase in MK above 25 % reduced the advantage due to too-fine particles and lower reactivity [21, 22]. The early strength was reduced when MK was mixed with GGBS due to the latent hydraulic property of slag; however, sufficient long-term strength could be maintained through the collective activation effect produced by the two binders in a composition of 20 % MK + 60% GGBS [22]. Mechanical performance was dramatically improved by adding SP, mainly due to enhanced particle dispersion and more uniform hydration. The maximum compressive strength was gained with an

SP dosage of 1.5 % (≈ 30 MPa), and less than this amount, the decrease occurred because of overdispersion and hydration retardation [23, 24].

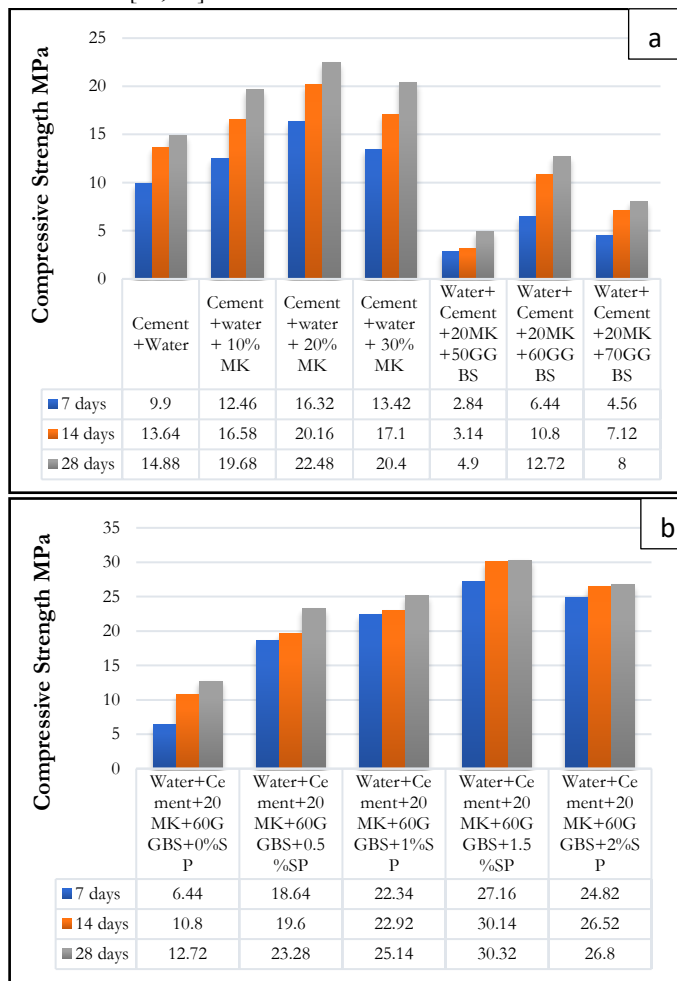


Figure 6. Compressive strength results in various mixtures: a) without SP and B) with (0.5, 1, 1.5, and 2)% SP.

3.3. Flexural Strength

Figure 7 (a-b) shows the evolution of flexural strength for MK-, GGBS-, and various SP dosage-containing cementitious blends. The inclusion of MK significantly increased the strength compared to that of plain cement paste, in which the application of 20 % MK led to the highest 28-day strength as 3.56 MPa due to its pozzolanic effect, which induced further C-S-H and C-A-S-H production and prevented microcrack growth [21]. While 30 % MK worked well, the increased fineness and water requirement impaired the hydration reaction to some extent [22]. The early-age strength of the blended cement with GGBS for the partial replacement of cement was lower than that of pure C at an early stage because GGBS had a low hydration rate; however, at 28 days, the mixture with 20 % MK was characterized by a continuous increase to 2.67 MPa, which suggested that MK could complement slag activation when it is utilized together into our blend [22,23]. The incorporation of SP resulted in a significant increase in flexural strength, due to improved particle dispersion and pore refinement. The strength increased significantly, from 2.67 MPa for the case without SP to 4.13 MPa at 1.5 % SP, corresponding to an approximately 55 % increase via uniform hydration and a dense microstructure without cracks. At higher doses (2 %), the strength

was slightly reduced by over-dispersion and delayed gel formation [24].

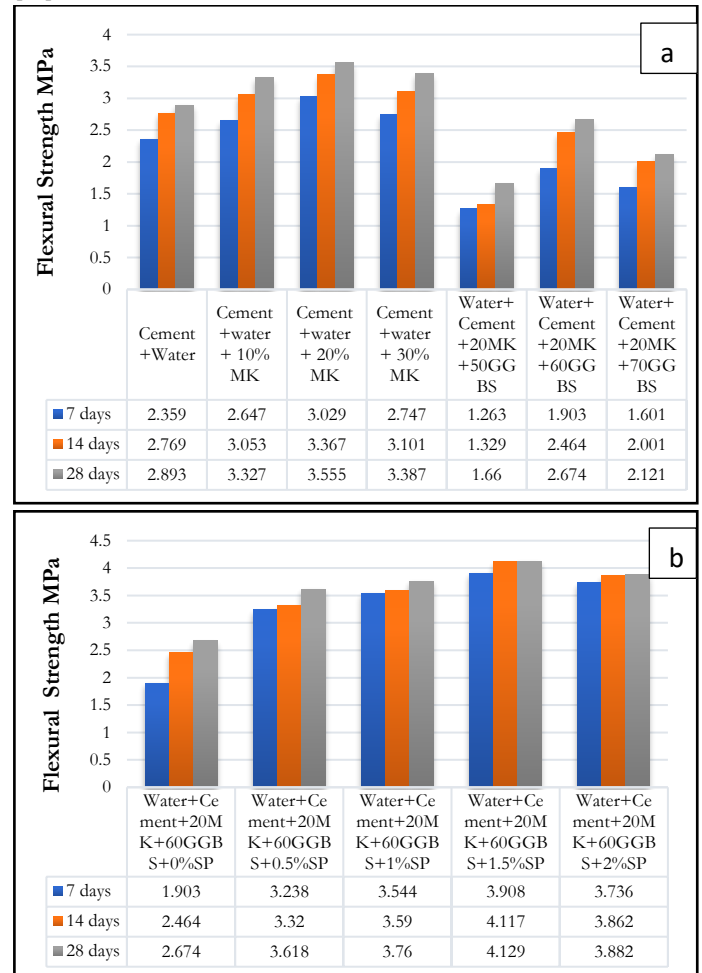


Figure 7. Flexural strength results in various mixtures: a) without SP and B) with (0.5, 1, 1.5, and 2)% SP.

3.4. Tensile Strength

Figure 8 (a-b) shows the evolution of tensile strength with respect to various curing ages and SP dosages of MK/GGBS blends. The addition of MK significantly improved tensile strength compared to that of the control mix, and the maximum 28 d value (3.53 MPa) was achieved in the case of 20 % MK due to its pozzolanic reactivity and supply of additional C-S-H/C-A-S-H phase, which contributed to densification of the matrix structure as well as enhancing interfacial transition zone (ITZ) [21]. At 30 % MK strength loss, even though high fineness particles would require more water and less hydration activity [22]. The incorporation of GGBS reduced early strength due to its relatively sluggish hydration kinetics, but the 20 % MK + 60 % GGBS system showed continuous improvement through late slag activation and secondary gel formation [23]. The introduction of SP improved tensile performance by enhancing dispersion, reducing porosity, and promoting uniform hydration. For example, Benaicha et al. [24] demonstrated that the addition of 1.5 % SP to the SCM resulted in a significant improvement in strength from 2.37 MPa (without SP) to 4.36 MPa, an increase of $\sim 84\%$, indicating the complementary action of SCMs and chemical admixtures when used together optimally. Minor strength decrease with high SP (2 %) has occurred due to overdispersion and retarded setting. The

optimum hybrid combination of 20 % MK + 60 % GGBS + 1.5 % SP achieved the optimal trade-off between microstructural densification, hydration kinetics, and mechanical integrity, substantiating its appropriateness as a sustainable, high-performance grout for semi-flexible pavement applications.

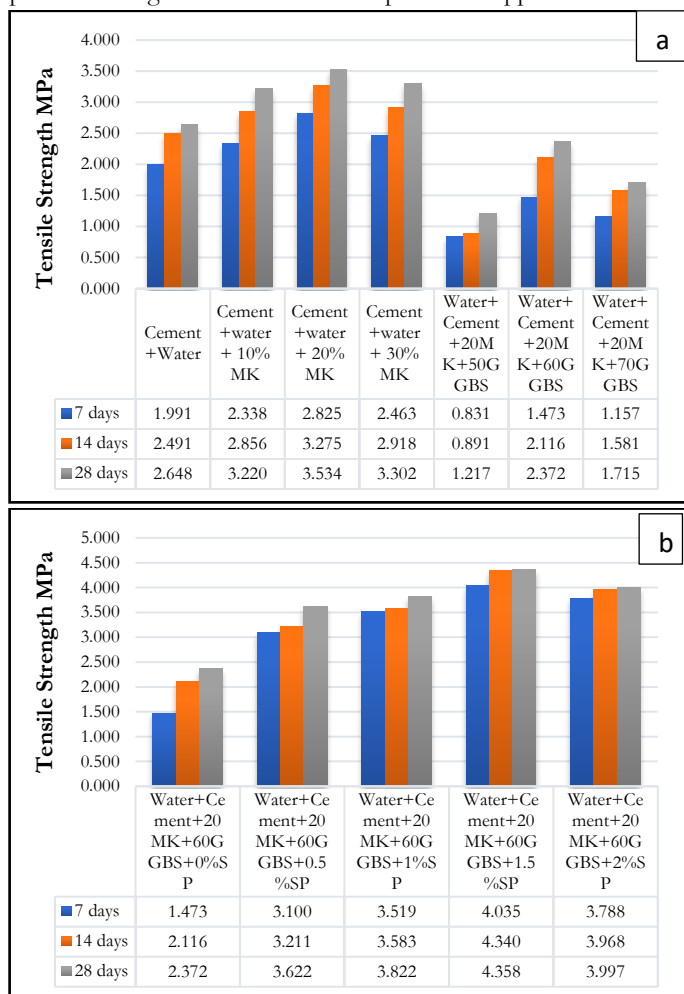


Figure 8. Tensile strength results in various mixtures: a) without SP and B) with (0.5, 1, 1.5, and 2)% SP.

Metakaolin is a highly reactive pozzolanic material containing amorphous aluminosilicate that comes readily into reaction with calcium hydroxide emanating from the hydration of OPC to give C–A–S–H and C–S–H gels, which contribute significantly to early-age strength development, pore structure refinement, and interfacial transition zone densification. On the contrary, GGBS behaves as a latent hydraulic cement, providing long-term strength development, lower heat of hydration, and higher durability, especially under sustained traffic loading and environmental conditions [30], [40]. The hybrid MK–GGBS pathway thus affords balanced strength development by leveraging the early reactivity of MK and the long-term stability of GGBS, with substantial OPC savings and embodied carbon credits, making it a key sustainability target in this study.

4. Conclusion

This study demonstrated the successful development of sustainable grouting materials for semi-flexible pavements by partially replacing OPC with MK and GGBS, with a polycarboxylate-based superplasticizer (SP) enhancing

performance. The experimental findings revealed that the optimal binder composition of 20% MK + 60% GGBS + 1.5% SP provided the most balanced performance across all tested parameters.

In terms of flow time, the hybrid mix achieved an efflux time of approximately 8–10 seconds, indicating excellent fluidity and stability, essential for efficient grout penetration into the porous asphalt skeleton. For compressive strength, the same mixture recorded the highest value of about 30.32 MPa at 28 days, signifying superior microstructural densification and enhanced hydration efficiency. Regarding flexural strength, the optimized blend achieved 4.13 MPa, reflecting improved load transfer capacity and resistance to bending stresses resulting from the synergistic pozzolanic–hydraulic reaction between MK and GGBS. Similarly, tensile strength reached 4.36 MPa, representing an 84% improvement over the control mix, attributed to refined pore structure, reduced microcracking, and enhanced interfacial transition zone integrity.

Ultimately, the results confirm that integrating 20% MK, 60% GGBS, and 1.5% SP yields a high-performance, environmentally sustainable grout with optimal rheological, mechanical, and durability characteristics, suitable for heavy-duty semi-flexible pavement applications.

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