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Experimental investigation of ecological semi-flexible pavement with silica sand as a partial substitution of cement

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ABSTRACT

The exploitation of locally available and abundant natural resources such as silica sand and its use as a supplementary cementitious material in the production of grout used in semi-flexible pavement (SFP) surfaces is of paramount importance in reducing transportation costs and emissions, contributing to more sustainable development practices, and reducing the overall environmental impact of cement plants. SFP or injected pavement, is a porous asphalt structure with 25–35% voids, filled with cementitious grout. SFP is distinguished by its robustness, resistance to deformation, and exceptional longevity, enabling it to endure substantial traffic loads and extreme weather conditions, hence offering a strong and dependable road surface that is comparatively simpler to maintain than other road construction types. This study focuses on developing a novel sustainable cementitious grout for SFP by partially substituting traditional cement with quartz silica sand powder (QSP) in different proportions (10%, 20%, and 30%). The grout mixtures were evaluated for flow and mechanical properties. Also, SFP samples were made by adding a 5% SBS modifier to a hot mix porous asphalt (HMPA) and then filling the holes with a predesigned cement-based grout then these samples were assessed for Marshall stability and moisture damage resistance tests. The results demonstrated that replacing cement with more than 10% of QSP reduces compressive strength and stability. This is due to the reduction in workability caused by water absorption in the grout mixture. This, in turn, increases the water-to-cement ratio to achieve the required fluidity, as well as increasing the porosity and decreasing the volume of hydration products. Therefore, this study suggests that 10% of QSP is the optimum replacement ratio as it achieves the required fluidity and increases the compressive strength, stability, and tensile strength ratio by 20.7%, 13.4%, and 12.0% respectively at 28 days of curing compared to the reference grout mixture. This mixture is considered suitable as it combines the properties of durability and environmental objectives by reducing the grinding energy and its use in severe conditions.

1. Introduction

In recent decades, semi-flexible pavement (SFP) has been established as an innovative pavement design and construction method. SFP is usually built up with a porous asphalt mixture with air voids of (25- 35)%, filled with cementitious grout material[1, 2]. A cementitious grout layer adds stiffness, increases skid resistance, and distributes stresses to the subgrade layer; a porous asphalt layer offers smoothness and flexibility, accommodating some of the traffic's dynamic loads. SFP can withstand harsh weather conditions and heavy traffic loads because of its strength, resistance to deformation, and excellent durability. This kind of pavement

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is often used in places where conventional asphalt or concrete roads are not feasible or economical, such as industrial zones and airports[3].

SFP has superior stability at higher temperatures than hot mix asphalt (HMA). The rutting resistance and dynamic stability of SFP were determined to be 2.5 times more than those of HMA[4]. The characteristics of the grout substantially affect the performance, stiffness, durability, and general behavior of the pavement. The cementitious grout's flowability is essential to the complete penetration of grout into the porous asphalt mixture [5, 6]. Grout's components, including the water-to-cement ratio, superplasticizer (SP), and other cementitious additives, significantly influence its workability and strength [7, 8]. The asphalt skeleton is a crucial element of SFP and indicates grouted porous pavement effectiveness. The optimal asphalt binder content is essential for enveloping aggregate in asphaltic structures. Numerous research papers have used binder concentrations between 2% and 4.5% by mass of the mixture [9]. The aggregate structure of SFP must be sufficiently porous to allow cementitious grout to infiltrate and demonstrate the necessary tensile strength. Achieving adequate porosity in mixes may be accomplished by using a uniform aggregate single-size of 10–14 mm combined with a minimal quantity of fines. This will allow grouting materials to be easily inserted into voids. By reducing the quantity of fine aggregates, higher air voids have been achieved satisfying to open-grade asphalt-OGA mixes[10-12] . Although limited studies have dealt with permanent deformation in SFP, their results demonstrated remarkable resilience to rutting, exhibiting no observable deformation. SFPs did not experience any irreversible deformation throughout their intended usage and that can be attributed to their high stiffness [13-15].SFP is a versatile pavement solution that can be tailored to enhance performance attributes, provide joint-free surfaces, and accommodate severely loaded areas, making it an appealing choice for improving the resilience and lifespan of highways under heavily loaded areas. These benefits of SFP may decrease maintenance expenses and enhance overall road conditions [16]. These benefits of SFP may decrease maintenance expenses and enhance overall road conditions [16]. An important negative aspect of SFP surface production is the increased construction cost due to the extensive use of cementitious grout. Moreover, the use of cement in SFP composites results in CO_2 emissions. Emissions from cement plants are detrimental to the environment since they include carbon dioxide, sulfur oxides, nitrogen oxides, methane, and heavy metals like cobalt, nickel, mercury, chromium, and lead, among others [17]. Besides contributing to climate change and global warming, these emissions adversely affect health, leading to symptoms such as ocular irritation, respiratory inflammation, breathing difficulties, central nervous system damage, and liver impairment [18]. These emissions may lead to hazy air and acid rain, directly contributing to the acidification of lakes and streams, and adversely affecting aquatic life, especially fish populations [19, 20]. Many studies attempt to replace some of the ordinary Portland cement (OPC) that is usually used as grouts in SFP with pozzolanic natural materials or recycled waste to minimize CO_2 emissions from cement plants and their usage in SFP construction. Recently, the utilization of some natural or by-product pozzolanic materials such as blast furnace slag, fly ash, silica fume, kaolin, and pozzolana has declined. This decline has been driven by environmental concerns related to energy use, steel recycling, and the depletion of natural deposits. For this purpose, detecting plentiful and alternative pozzolanic materials comparable to those already adopted is strategically important[21]. Worldwide, silica sand is among the most accessible resources. Its SiO_2 composition originates in nature. Silica sand from a quartz source physically interacts with cement during the hydration process, including diluting cement grains, nucleating cement hydrates, and space-filling [22] . Figures 1 and 2 summarize findings from literature studies on the use of silica sand as a replacement material or mineral additive in the field of construction. According to the Iraqi Geological

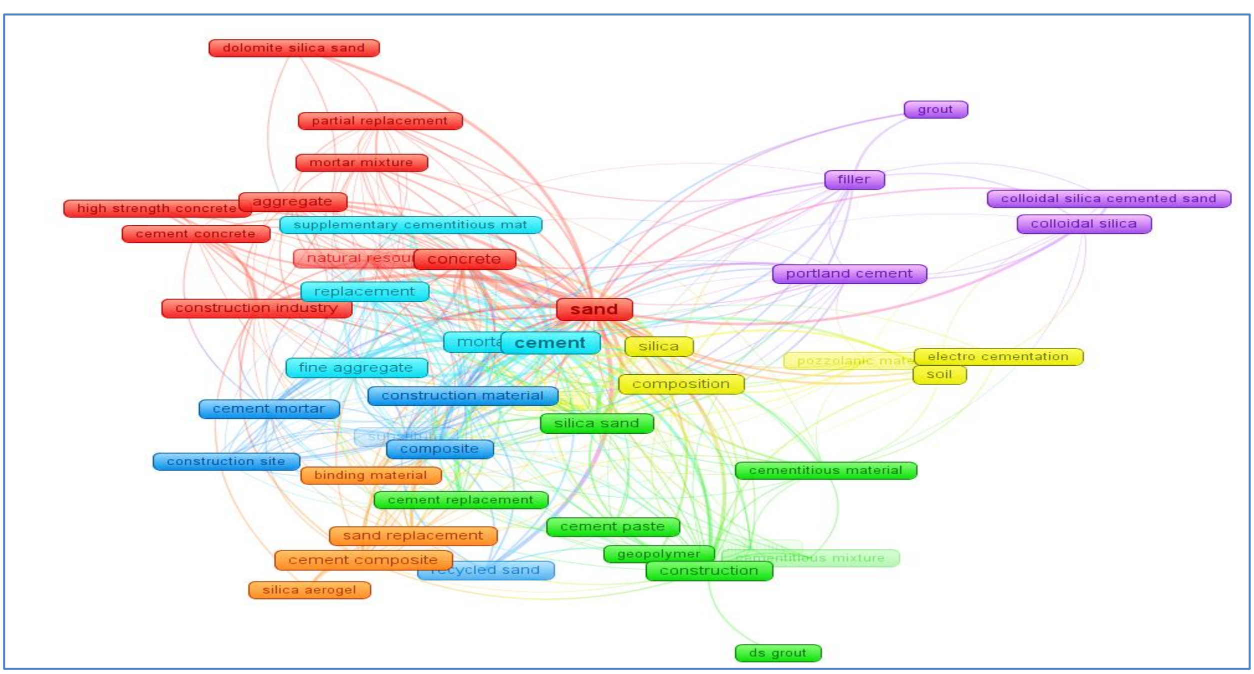

Figure 1. The network representation of using silica sand in construction materials in the literature from 2014 to 2024

Survey, the provinces of Najaf and Anbar contain reserves exceeding one billion cubic meters of silica sand (quartz sand).

to silica sand, which has a lower hardness and a milky white color that is less shiny from quartz sand [24].

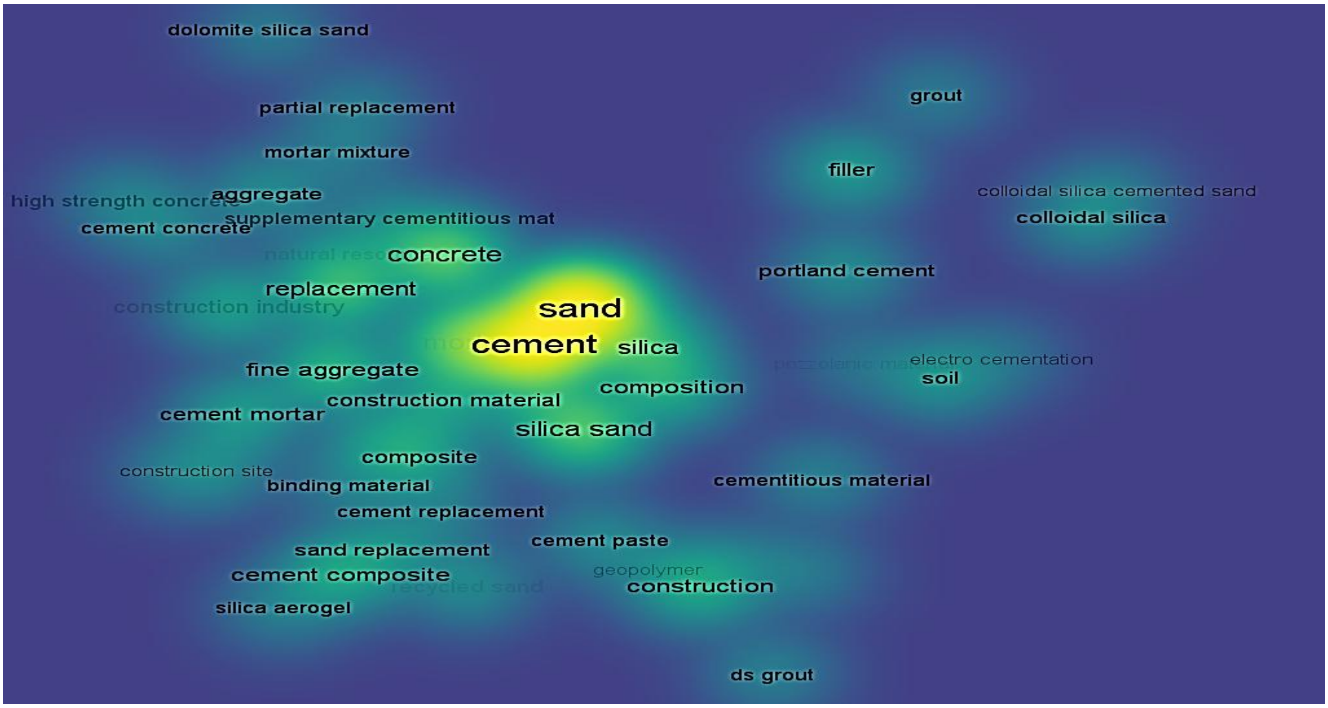

Figure 2 .Density validation networks map of using silica sand in literature

Table 1. Summary for using silica sand as a supplementary cementitious material or mineral additive.

Silica Sand Sources	Cement Replacement	Conclusion	Ref.
Desert sand	0-60 %	At the age of 28 days, the mixed cement showed 75% stronger than pure cement, indicating that replacing cement with 15% silica sand was the optimal amount.	[25]
Desert sand	0-20%	A mixture containing 10% pozzolan and dune sand powder ensures the best potential resistance. Above this proportion, strength begins to decline.	[26]
Desert sand	15-25%	Mortars composed of 20% desert sand are cost-effective and sustainable.	[27]
Desert sand	0-25%	Adding desert sand at a ratio of up to 25% as cement replacement promotes the workability of mortar in the fresh state and its mechanical strength.	[28]
Quartz	0-20%	The compressive strength and carbonation effectiveness of cement mortars are both enhanced by quartz.	[29]
Quartz	0-20%	Quartz lowers the hydration heat.	[30]
Quartz	0-40%	Increasing the replacement ratio from 10% to 40% leads to decreased compressive strength as well as rising water absorption by 25% in the cement mortar.	[31]
Desert and river sand	0-20%	Binary sand mixtures significantly improved the compactness of the high-performance self-compacting concrete. The study results indicate that a substitution rate of less than 20% leads to combinations that yield high mechanical properties and economic environmental advantages.	[32]

One of the most important sites that contain large quantities of high-quality silica sand is the Ardma area west of Anbar, where the purity of silicon sand reaches 99%[23]. Quartz sand differs from pure silica sand according to its silica content (SiO_2). When the SiO_2 content is above 98.5%, it is quartz sand, and when it is less than this percentage, it is silica sand. The hardness of quartz sand is very high, and its color is pure white and shiny compared

Based on the previous literature presented and illustrated in Table 1 and Figure 1, silica sand has been adopted as a mineral additive or supplementary cementitious material or partial replacement for cement and fine aggregate in various construction materials applications, including cement paste, mortar, geopolymer, ordinary concrete, high-strength concrete, and self-compact concrete. However, the use of silica sand to partially replaced cement in the production of grout to inject porous pavement voids remains unexplored extensively by researchers. Therefore, this research is carried out to explore the adoption of silica sand as a partial replacement for cement in SFP surface grout, with the primary goal of reducing cement costs, utilizing abundant natural resources such as quartz sand, particularly in Iraq, and reducing the CO_2 emissions that result from the high consumption of cement in factories for building and infrastructure construction. Portland cement was replaced by 10% to 30% with quartz silica sand powder (QSP) in the grouts, and the mixtures were evaluated for flowability and compressive strength. Moreover, an open-graded asphalt skeleton was prepared using SBS-modified asphalt and injected with pre-designed cement grouts. The obtained SFP was evaluated according to several standard tests such as Marshall stability and moisture damage.

2. Materials and methodology

The materials incorporated in laboratory programs that are locally available. This study assesses the potential of using QSP in cementitious grout for SFP applications as a partial substitution for OPC. The study uses flow cone and compressive strength tests to assess the grout in both its fresh and hard state. Figure 3 shows the flowchart of experimental work adopted in this investigation.

2.1. Sustainable cementitious grout

The components used in the production of sustainable cementitious grout are superplasticizer (SP), water, quartz silica sand powder (QSP), and ordinary Portland cement (OPC). The specific gravity of OPC I 42.5 N is 3.14, and its surface area is 327 m²/kg (Table 2). Silica sand powder is obtained from natural quartz sand hills abundantly available in Najaf Governorate (see Figure 4), Iraq, where it is ground by a mechanical mill to become powder and then sifted by a sieve No. 200 (size 75 µm). The current research utilized CONMIX SP 1030 to improve grout mixture fluidity and strength. This SP, derived from modified polycarboxylate ether, has exceptional performance in grout. Its distinctive carboxylic ether polymer, characterized by elongated lateral chains, differentiates it from other SP. As a result, it is an exceptional high-range water reducer and cement dispersant. ASTM C494 [33] Specifies SP dosage between 0.5% and 2% by weight of cementitious material. Similarly, filtered water was used as the liquid component in the formulation of the grout combination. Table 3 lists the properties of typical cementitious grout components. Figure 5 displays the stages of preparing quartz silica powder

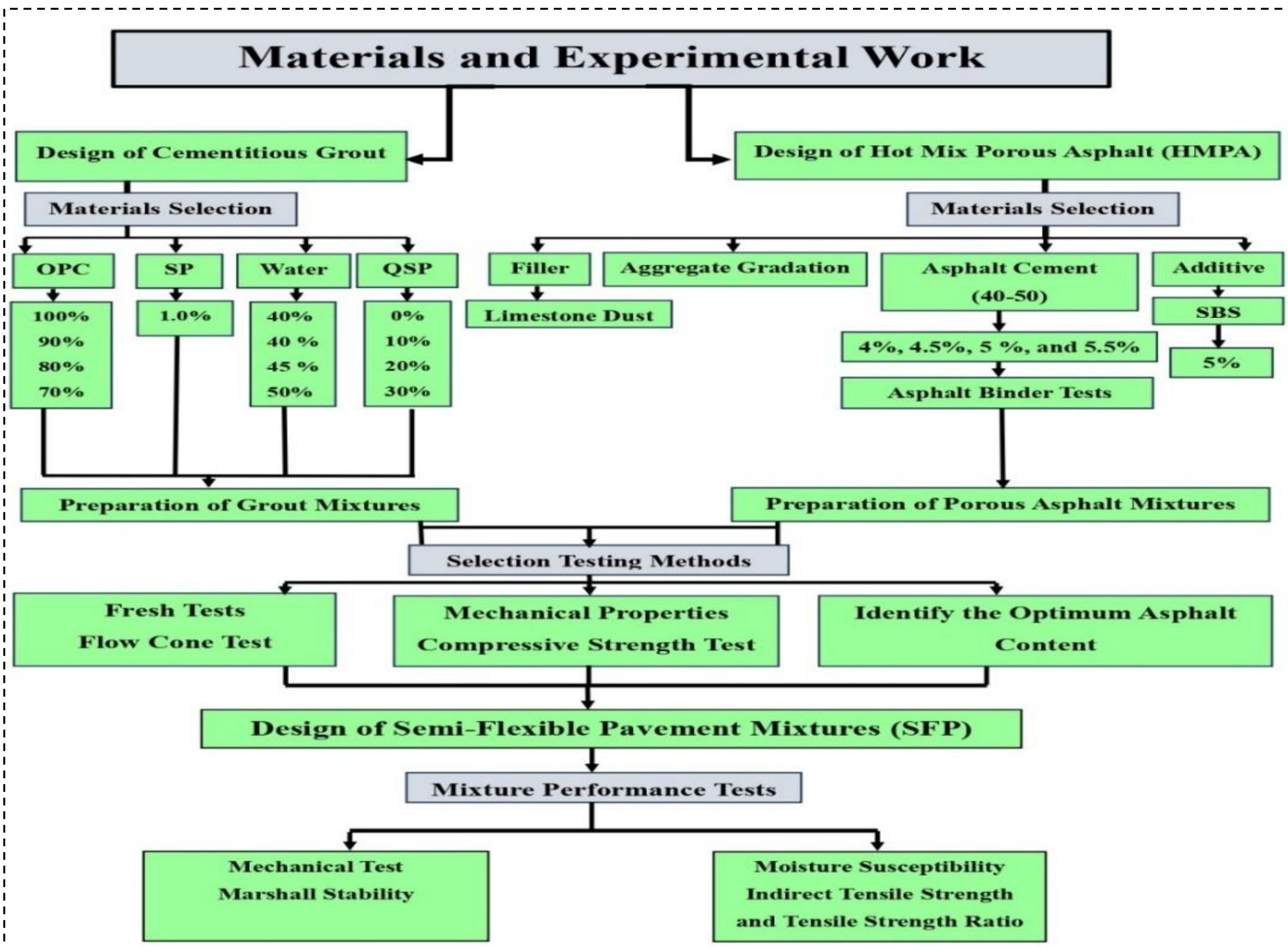

Figure 3. Experimental program flow chart.

Figure 4. Quartz silica sand particles.

Figure 5. Schematic of QSP preparation.

Table 2. Grout materials' physical and chemical properties.

Characteristic	Type of Materials	
Physical properties		
	QSP	**OPC**
Surface area (m^2/kg)	445	0327
Specific gravity(g/cm^3)	2.70	3.14
Loss of Ignition (%)	0.06	3.20
Chemical properties		
SiO_2 (%)	99.02	19.53
Al_2O_3 (%)	0.769	3.637
SO_3 (%)	1.601	2.269
Fe_2O_3(%)	0.215	4.480
CaO (%)	3.020	60.10
MgO (%)	0.080	2.460
K_2O (%)	0.140	0.510
Na_2O (%)	0.010	0.20

2.2. Hot mix porous asphalt (HMPA)

The hot porous asphalt mixture consists of asphalt (PEN40-50) and crushed aggregate, which were prepared from the Al-Hafar plant in Al-Diwaniyah, Iraq. Table 3 presents the physical test of aggregate. The current investigation used ASTM D7064 [34] to select the aggregate gradation for an open-graded porous asphalt mixture, as shown in Figure 6. This study involved an asphalt binder modification using styrene butadiene styrene (SBS) Kraton type D1192 (see Table 4). The control asphalt binder was heated in an oven at 160 °C for one hour to facilitate the mixing with SBS. Subsequently, it is placed in a high-shear mixer, where SBS is incrementally introduced in the specified quantities (5% by weight of the pure asphalt; this ratio was chosen based on the result of previous research [35]), then blended for 3 hours at 3000 rpm and 180 °C to guarantee thorough homogeneity and prevent separating and agglomerating (see Figure 7). Table 5 displays the rheological engineering characteristics of pure and polymerized asphalt with SBS additive.

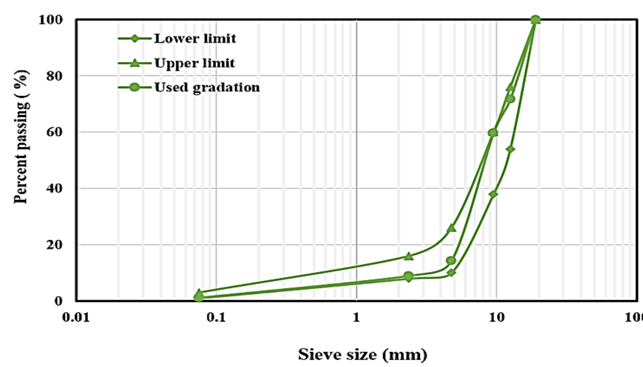

Figure 6. The open-graded HMPA according to ASTM D7064 [34]

Table 3. The aggregate's physical characteristics.

Property	Standard	Result
Coarse Aggregate		
Bulk specific gravity, (g/cm^3)	ASTM C127[36]	2.620
Apparent specific gravity, (g/cm^3)	ASTM C127[36]	2.649
Saturated surface dry, (g/cm^3)	ASTM C127[36]	2.610
Water absorption, (%)	ASTM C127[36]	1.400
The proportion of fractured surfaces of coarse aggregate particles, (%)	ASTM D5821[37]	97.0
Los Angeles abrasion value, (%)	ASTM C131 [38]	26.00
Flakiness indexes, (%)	ASTM D4791[39]	1.300
Clay lumps, (%)	ASTM C142[40]	1.420
Fine Aggregate		
Bulk specific gravity, (g/cm^3)	ASTM C128[41]	2.610
Apparent specific gravity, (g/cm^3)	ASTM C128[41]	2.870
Saturated surface dry, (g/cm^3)	ASTM C128[41]	2.670
Water absorption, (%)	ASTM C128[41]	3.950
Clay lumps, (%)	ASTM C142[40]	0.960

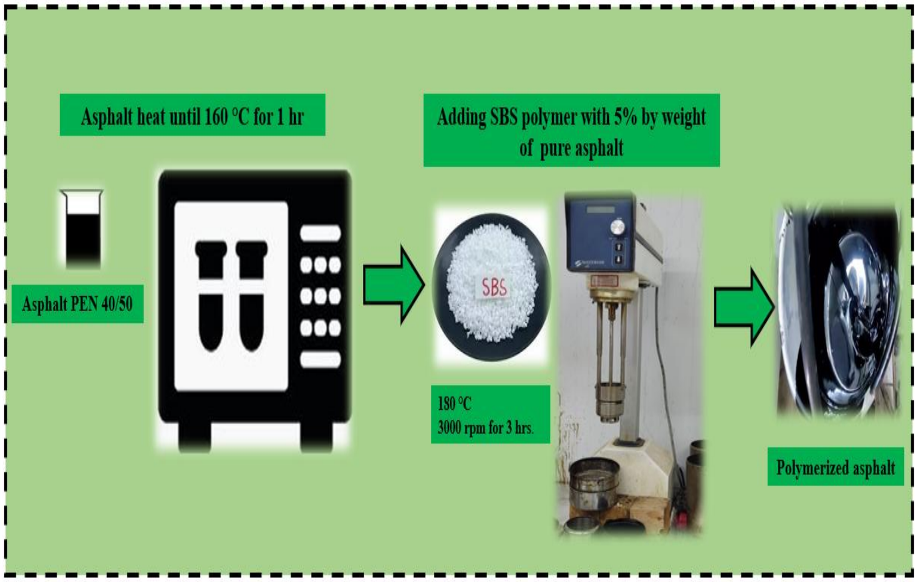

Figure 7. Schematic of the preparation of SBS-modified asphalt in this study.

2.3. Compositions and grout preparation

A flow cone test was performed on all grout mixes to assess their flowability, using the ASTM cone with a mixed volume of 1725 ml, as seen in Figure 8 [42]. Initially, six grout formulations were produced. The first combination is the reference mixture (RM), comprising 29% water and 71% cement with a w/c of 0.4 with 1.0% SP. Subsequently, the remaining five mixtures were formulated by substituting cement with QSP in proportions of 10%, 20%, and 30%, incorporating 1.0% SP (w/c 0.40-0.5) to achieve the desired consistency, exhibiting fluidity ranging from 11 to 16 seconds, as per previous research [3],ensuring the grouting material adequately occupies all voids within the porous asphalt matrix. Similarly, the grout mixture is prepared by mixing water and SP in a mechanical mixer for five minutes. To avert the separation process, the dry components are first integrated manually before being gradually incorporated into the water and SP mixture, which is then blended for 2 minutes at medium speed. Figure 9 illustrates the procedures for producing cementitious grout material. According to ASTM C942 [43], the compressive strength of the cementitious grout was measured using (50 × 50 × 50) mm cubes that had been cured for 7 and 28 days (see Figure 10). Table 6 illustrates the mix design for cementitious grout mixtures.

Table 4. Characteristics of SBS-Kraton type D1192.

Property	Result
Color	White
Specific Gravity	0.88
Elongation (%)	86
Bulk Density (Kg/cm^3)	0. 39
Melting Point (°C)	180

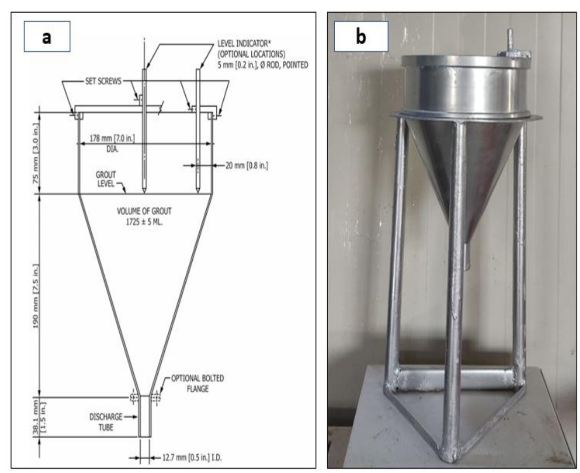

Figure 8. Flow cone test setup :(a) flow cone device measurement schematic [42], and (b) ASTM flow cone.

2.4. Semi-flexible pavement (SFP) mix design

In compliance with the ASTM D1559 standards [44] , the hot mix porous asphalt (HMPA) is produced and cast in Marshall mold. Several blows (18, 20, 25, and 30) were adopted in the HMPA design procedure, and it was found that 20 blows for each face of specimens is optimal as it achieves the required percentage of voids for the porous asphalt skeleton of the SFP surface. Samples with different amounts of asphalt binder (between 4% and 5.5% of the total weight) are subject to the Marshall stability test, an air void content analysis, a bulk density measurement, and a drain-down test to find the best binder concentration [45]. The results of these trials led to the decision to use 4% asphalt as the optimal composition for the HMPA mixture design, ensuring the required air void ratio, satisfactory drain-down, and superior stability, according to the previous literature [3] .

Table 5. The engineering characteristics for pure and SBS-modified asphalt binder.

Test type	Pure asphalt	Modified asphalt	Standard
Penetration, 25 °C	46.00	027	ASTM D5[46]
Ring and ball softening point, °C	54.00	068	ASTM D36[47]
Ductility,25 °C	130.0	110	ASTM D113[48]
Flashpoint, °C	292.0	352	ASTM D92[49]
Toughness (N.m)	13.40	33.2	ASTM D88[50]
Tenacity (N.m)	03.00	17.9	ASTM D88[50]
Mass change (%)	00.49	0.08	AASHTOT240[51]
Elastic recovery,25°C	022.0	078	AASHTOT301[52]

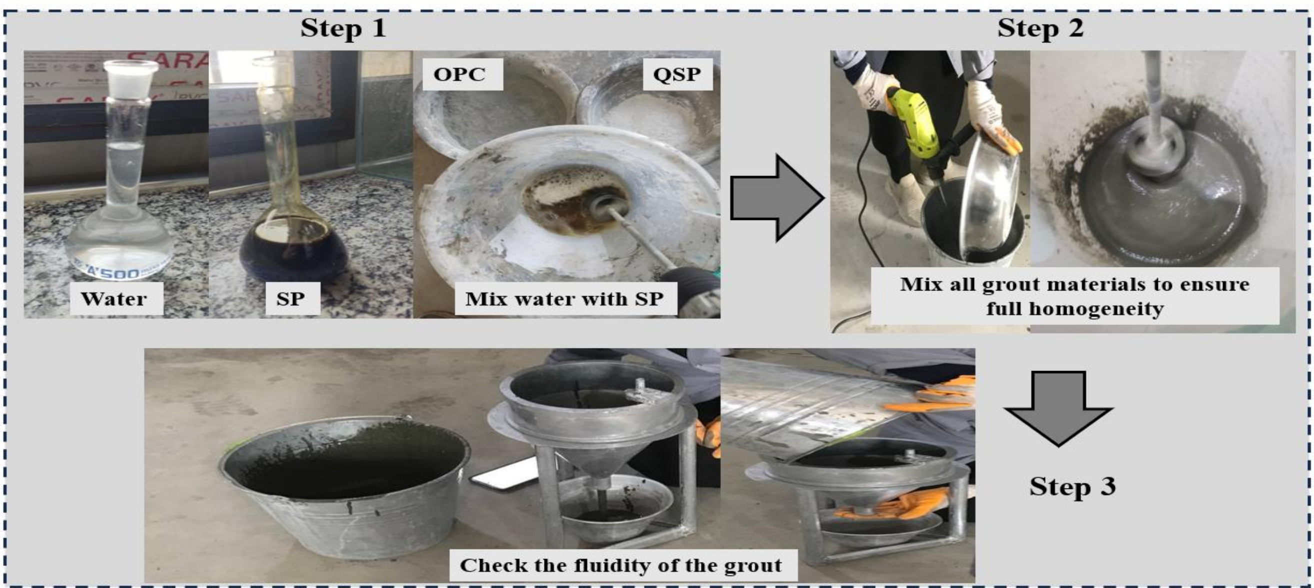

Figure 9. Steps of formulation of sustainable cementitious grout

Figure 10. The compressive strength device with its specimens.

Table 6. Mix design of cement-based grouts

Mixture No.	OPC, (%)	W/C, (%)	QSP, (%)	SP, (%)
Mix0	100	40	0	1.0
Mix1	90	40	10	1.0
Mix2	80	45	20	1.0
Mix3	70	50	30	1.0

Table 7. Mix design of SFP mixtures

Composition of HMPA		Composition of cementitious grout	
Asphalt binder	04.0%	Reference mixture (cement, SP, and water)	40% w/c
Additive (SBS)	05.0% by weight of pure asphalt		1.0 % SP
Aggregate (coarse and fine)	91.2 %	Modified mixtures with QSP by partially replacing cement with 10%, 20%, and 30% of QSP. These ratios are based on the weight of cement.	(40-50) % w/c
Filler (limestone dust)	04.8 %		1.0 % SP
Voids content	25-35 %		

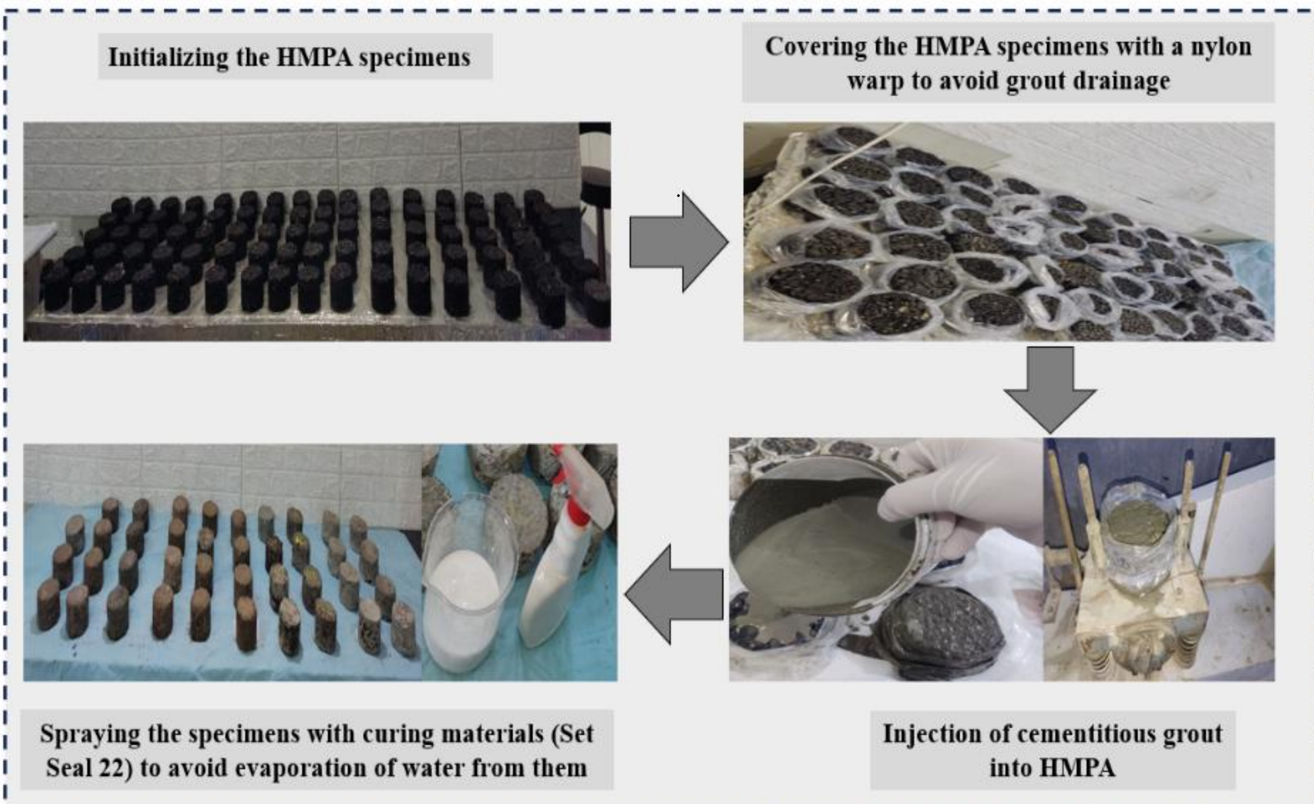

Figure 11. Steps of formulation of SFP specimens.

After selecting the ideal asphalt binder concentration, Marshall samples are used to attain a void percentage between 25 and 35%. This specified proportion of air spaces allows the grout ingredients to fill the voids in the HMPA. SFP samples are prepared by encasing the HMPA molds with a plastic cover, followed by injection of the cementitious grout material and placement on a vibrating apparatus for one minute, after which they are allowed to rest in the laboratory for 24 to 48 hours before curing. A curing agent named "Set Seal 22" is applied to the surfaces of the specimens after the hardening of the cementitious grout components. This curing substance inhibits the evaporation of internal moisture from the specimen caused by heat generated during hydration and environmental conditions, hence facilitating the formation of cement hydration products. The specimens were maintained at 25 °C in the laboratory until the requisite tests were performed. Table 7 shows the mix design of SFP mixtures. Figure 11 depicts the process of injecting grouting material into the HMPA specimens to produce the SFP specimens.

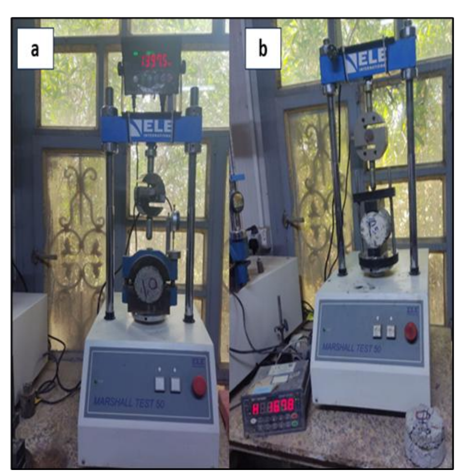

Figure 12. Methods of testing setup: (a) Marshall stability device, and (b) ITS device.

2.5. Testing Methods

2.5.1. Marshall stability test

Based on ASTM D6927 [45], HMPA and SFP mixtures were subjected to a Marshall test to ascertain their flow characteristics and stability, using standard procedure. The SFP specimens were tested at 7 and 28 days after curing. Figure 12-a illustrates the general setup of the testing equipment.

2.5.2. Moisture susceptibility tests

The term "resistances to moisture damage failure" indicates the ability of a compacted SFP to withstand the harmful effects of water, temperature, humidity, air, and vehicle traffic during the pavement's lifetime [53] .It may also be defined as the pavement's ability to function effectively without requiring premature repairs over the expected service life. The indirect tensile strength (ITS) test was implemented to evaluate the moisture susceptibility of SFP and PA mixtures in accordance with ASTM D 4867 [54] .Six mixtures with target air voids of 3% to 9% were categorized into two groups. The first group of specimens was placed in a room at 25°C for 2 hours to assess tensile strength in dry conditions. The second group of specimens was immersed in a water bath at 60°C for 24 hours. Equation (1) is used for calculating ITS, which is then utilized for the greatest load that the sample has previously experienced.

$$ITS = \frac{2000 \times p}{\pi \times t \times d} \tag{1}$$

Where P represents the height load (N), d denotes the specimen's diameter (mm), and t represents the specimen's height (mm) before the test. Most studies aimed at assessing asphalt mixes' moisture susceptibility have relied on the value of tensile strength ratio (TSR) specified by ASTM D4867 [54] and can be determined using Eq. (2) in accordance with ASTM D4867 [54]. The TSR should be higher than 80%, according to the majority of pavement agencies. Figure 12-b shows the general setup of the test apparatus.

$$TSR = \frac{\text{ITS wet}}{\text{ITS dry}} \tag{2}$$

3. Results and discussions

3.1. Flow time of cementitious grouts

The fluidity of cement-based grouts was evaluated by utilizing a standard flow cone. Figure 13 shows the flowability results of cement-based grout with different percentages of QSP. Figure 13 demonstrates that the partial substitution of OPC with QSP in the cementitious grout blend resulted in a significant reduction in flow values. The flowability decreases compared to the reference mix (RM) when cement is replaced with 10% QSP by 5.7%, then the flowability decreases when cement is replaced by 20%-30% by 14.6%-28%. This decrease is expected to occur due to the increase in w/c from 0.4 to 0.5, as the increase in water in the grout mixture increases its flowability. Furthermore, as the QSP concentration increases from 10% to 30%, the flow values tend to increase, indicating a decrease in flowability. Replacing cement up to 10% with QSP reduces workability, so the grout needs to be increased in water consumption to achieve the required fluidity. Higher QSP contents result in less fluid cement grout, as shown by the upward trend of fluidity values with increasing cement replacement by fine silica sand powder, consistent with findings from other studies [31, 55].

Literature indicates that grouting material suitable for SFP surfacing should preferably have flow values between 11 and 16 seconds [3, 56]. This range guarantees that the cement grouts may readily permeate the voids of open-graded asphalt mixes. The results of Figure 13 reveal that the specified combinations of QSP content and water-to-cement ratios satisfy the approval requirements for grouted pavement. Cement grout with 10% QSP at a 0.4 w/c ratio is the optimum replacement. This combination not only meets the required flow values but also maintains a balance between fluidity and strength, making it suitable for injection into the voids of hot porous asphalt-graded mixes for the SFP skeleton. Furthermore, the flow cone test reveals that the QSP concentration and w/c ratio have a significant impact on cement grout flowability. Increases in w/c content improve flowability, whereas increases in QSP content decrease it. In order to choose the best cement grout formulations for grouted pavement applications, it is helpful to refer to the chosen combinations that fulfill the specifications. Particularly encouraging are cement grouts containing 10% QSP at a 0.4 w/c ratio, which exhibit ideal flow values that fall within the specified range. Finally, Figure 13 results offer crucial insights into the flow characteristics of the evaluated cement grouts. Finally, these results highlight the need for further research on the mechanical properties and long-term durability of the selected grout formulations to develop efficient and effective cement grouts for SFP applications.

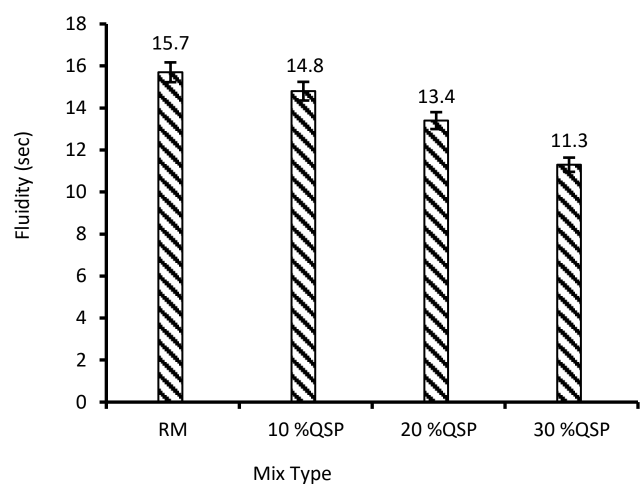

Figure 13. Fluidity results of conventional and modified cementitious grout with QSP.3.

3.2. Compressive strength of cementitious grouts

Compression tests were performed on the 50 mm × 50 mm ×50 mm hardened cementitious grout cubes after they had cured for 7 and 28 days. Figure 14 displays the compressive strength results of cement grouts modified with QSP. The results in Figure 14 reveal that replacing cement in the grout mixture with 10% QSP resulted in a significant increase in mechanical performance, as the compressive strength at 7 and 28 days of curing increased by 33.2% and 20.7%, respectively, compared to the grout mixture without silica sand powder (reference mixture "RM"). This clear rise is because silica sand naturally has pozzolanic activity. Chemical tests on the silica sand particles in Table 2 show that SiO_2 + Al_2O_3 + Fe_2O_3 = 100%, which is higher than the minimum requirement of 70% set by ASTM C618-19[57]. This activity is responsible for the material's high silicon

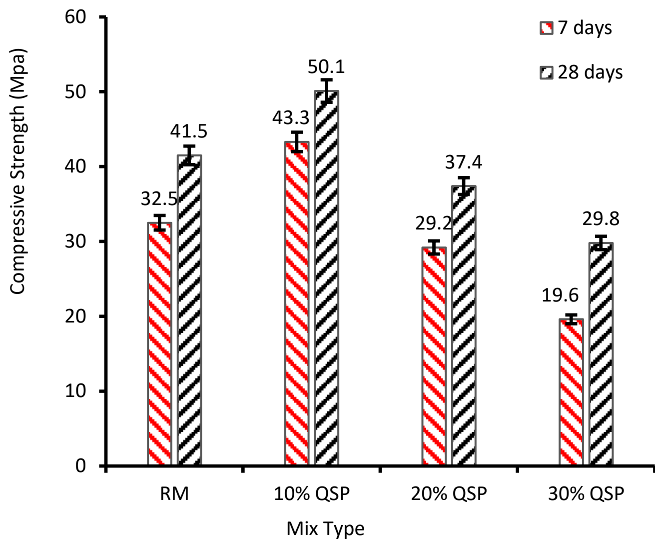

Figure 14. Compressive strength results for conventional and modified cementitious grout with QSP at 7 and 28 days of curing.

purity, with a silica content of 99.02%. The presence of silica in the material facilitates its reaction with portlandite, resulting in the production of more calcium silicate hydrate gel (C-S-H). This process improves the pores, reduces porosity, and creates a denser microstructure for the formulation of gelatinous C-S-H paste. This, in turn, increases the paste's resistance and tolerance to applied loads, thereby forming a strong structure. After 28 days of curing, this paste's concentration increases until it reaches its maximum density relative to the grout mixture. Thus, it can be concluded that the grouts' strength growth was favorably affected by the addition of QSP within this range. This clearly shows that QSP can enhance the strength characteristics of the grouts. Previous literature [58-60] has observed similar behavior.

Figure 14 shows that increasing the cement replacement ratio with QSP by more than 10% lowers compressive strength when compared to the RM. The compressive strength of cement-based grout mixtures with 20% to 30% QSP decreased by 10.2% to 39.7% after 7 days of curing and by 9.9% to 28.2% after 28 days. The explanation for these declines is that the w/c ratio increased by more than 0.4% since these mixes acquired the requisite fluidity at a w/c ratio of 0.45% to 0.5%. This is due to the capacity of the QSP to absorb water from the cement grout mixture. As the QSP percentage goes above 10%, the mixture becomes more porous and absorbs more water. This lowers the amount of cement that hydrates and stops the formation of C-S-H gel, which creates a weak microstructure and thus reduces the compressive strength in these grout mixtures. These results indicate that increasing the silica sand content with w/c content has a detrimental effect on the compressive strength and reduces the C-S-H gel. As a result, this study suggests that cementitious grout containing 10% silica sand powder is the ideal grout for SFP surfaces because it balances mechanical, durability, and environmental objectives in terms of high compressive strength and ideal water content to achieve sufficient fluidity for injection into the voids of the porous asphalt mixture, as well as low grinding energy.

3.3. Marshall stability of SFP mixtures

This study assessed the stability of SFP specimens using conventional cement grout mixtures and silica sand powder (QSP) modified grout mixtures. Figure 15 illustrates the results. The findings indicate that the Marshall stability of all SFP specimens increases as the curing time increases. The SFP mixture with 10% cement replaced by QSP was more stable than the SFP mixture without QSP, as per the stability findings in Figure 15. In comparison to the reference SFP mixture, the stability of this QSP-modified grout mixture increased by 15.6% and 13.4%, respectively, at 7 and 28 days of curing. The initial pozzolanic reaction of QSP generates substantial amounts of C-S-H gelatinous gel, which contributes to this rise in stability. The pozzolanic reaction of silica sand, which aids in the development of thick and amorphous calcium silicate hydrate gel, provides a mechanical justification for its use [61, 62]. According to the results of physical tests shown in Table 2, QSP has a larger surface area (445 m^2/kg) than cement (327 m^2/kg). This means that QSP is easier to flow and fills in all the gaps in hot mix porous asphalt, making it stick better to asphaltic aggregate.

As a consequence, the structure becomes more robust and able to handle the stresses that are applied by the Marshall device. This improves the structure's strength and stability. The presence of silica sand powder in the grout mixture helps to prolong the duration of hydration reactions by consuming portlandite $Ca(OH)_2$ resulting from the OPC hydration; the presence of it in large quantities weakens the resistance and thus increases the formation of calcium silicate hydrates that swell in the form of a colloidal gel, which in turn works to increase the compressive resistance. This behavior illustrates the advantages of silica sand as a supplementary cementitious material and natural pozzolanic substance, as agreed with previous literature [63-66]. As for the rest of the SFP specimens, it was noted from the results of Figure 15 that the Marshall stability of SFP specimens decreased as the replacement ratio increased above 10% at all curing ages. The stability values in the mixtures containing 20–30% cement replacement with QSP decreased by 11.6–17.5% at 7 days of curing and 9.2-24.1% at 28 days of curing compared with reference SFP specimens. This drop in stability is due to a similar phenomenon found in compressive strength. Increasing the w/c ratio from 0.45 to 0.5 caused a decrease in stability in these mixtures due to the increased water consumption of QSP, as agreed with previous literature [67, 68].

3.4. Moisture sensitivity of SFP mixtures

ITS and TSR were used to assess the impact of moisture failure on SFP mixes. In addition to the assessment of moisture failure, ITS and TSR were used to assess the cohesiveness between the HMPA and the cement-based grout material. These tests were conducted according to ASTM D4867 [54].The results show that the strength gained during curing is responsible for the large rise in ITS values seen in all SFP combinations for all curing ages. The literature [69-71] has observed a similar response. Additionally, the findings indicate that all combinations using silica sand materials exhibited superior ITS values compared to the reference SFP mixture under both dry and wet conditions. The results of the moisture sensitivity tests of the SFP mixtures shown in Figure 16 reveal that all SFP mixtures modified with QSP at ratios of 10–30% recorded an increase in ITS values in all conditions compared to the reference SFP mixture. This is considered an important indicator of the effectiveness of silica sand compared to cement, as well as its effective ability to penetrate inside the porous asphalt mixture.

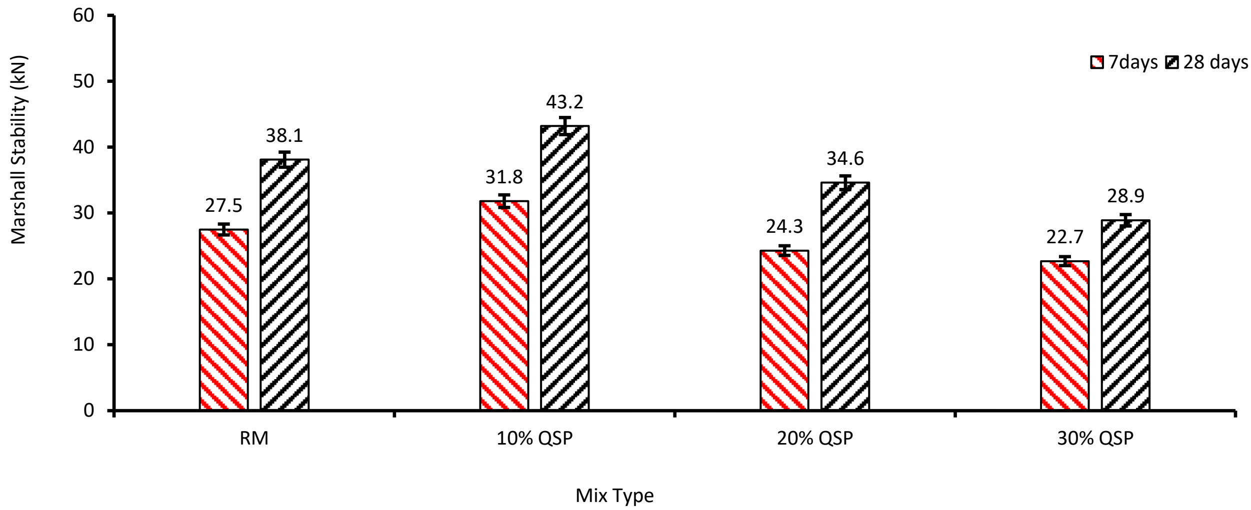

Figure 15. The Marshall stability findings for conventional and modified SFP specimens with various content of QSP at 7 and 28 days of curing.

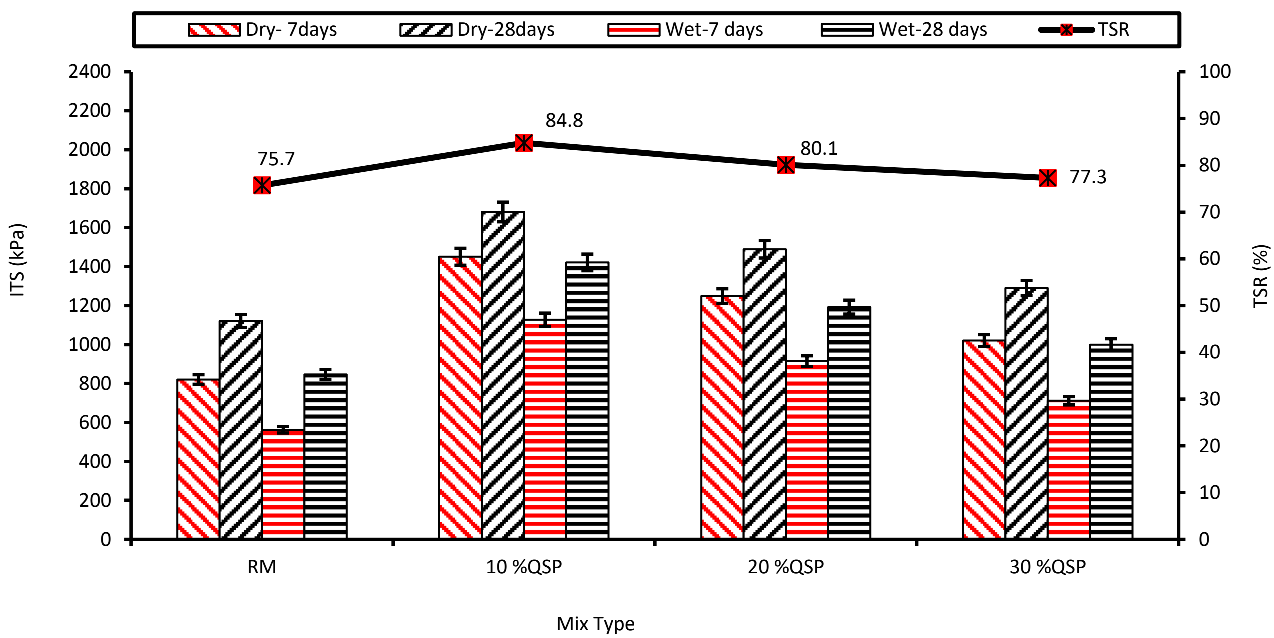

Figure 16. The results of ITS and TSR for conventional and modified SFP mixtures with QSP at 7 and 28 days of curing

This is due to the fineness and smoothness of its granules, as well as its angular shape, which facilitates easy adherence to the asphalt-covered aggregate. The previous literature reported the same trend [31, 55].The more interlocking there is between the cement grout mixture and the porous asphalt mixture, the greater the tensile strength, resulting in a strong structure that can withstand loads without deformation. The mixtures with 10%, 20%, and 30% cement replacement by QSP exhibited notable increases in strength after 7 days of curing, achieving 76.7%, 52.1%, and 24.2% enhancements, respectively, under dry conditions. In wet conditions, the same mixtures demonstrated even greater increases of 100.2%, 62.5%, and 26.3% compared to the reference SFP mix. Similarly, the same QSP-modified SFP mixes at 28 days of curing also recorded significant increases compared to the reference SFP mix by 49.9%, 32.8%, and 15.1% in dry conditions and 68.1%, 40.9%, and 18.2% in wet conditions. The ITS test results of the conventional and QSP-modified SFP mixtures also reveal three important trends: the ITS values of all mixtures in dry conditions are greater than in wet conditions. This indicates that the SFP mixture samples are sensitive to temperature increases from 25°C to 60°C when immersed in water, which may cause loss of bonding between the grout and the porous asphalt mixture structure.

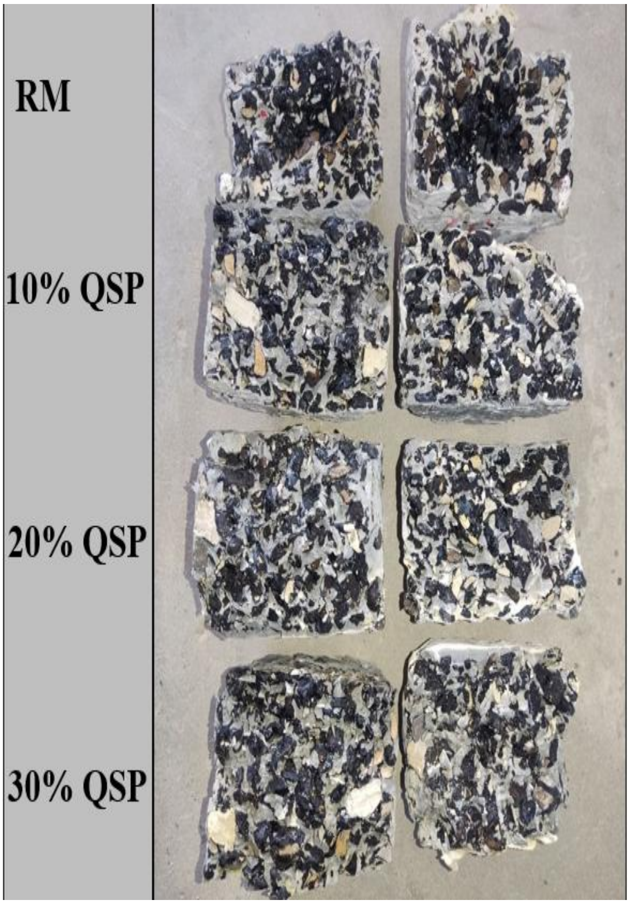

Figure 17. The difference between control and QSP-modified SFP mixtures after the ITS test.

The second trend shows that the reference SFP mixture recorded the lowest ITS value due to its high void ratio. This is due to the cement's large surface area, which prevents it from penetrating to the farthest point in the HMPA structure when mixed with water and SP. This may result in a gap where grout cannot be injected, potentially creating a weak point (see Figure 17). When the sample is immersed in water, the cement grout may separate at the HMPA structure, allowing water to enter it. Upon examination, it collapses and fails quickly when exposed to the loads applied by the ITS device. The results reveal a third trend: the ITS values decrease when the cement replacement ratio increases from 10% to 30% with QSP for the SFP mixtures in dry and wet conditions. This is due to the calcium silicate hydrates C-S-H, which mitigate the increase in the silica sand powder content due to its absorption by $Ca(OH)_2$ ions that are produced during the development of the hydration process, which reduces the cement hydrate volume and works to increase porosity and increased water consumption by the grout mixture and thus decreased tensile strength of the SFP mixture. The previous literature revealed the same phenomenon[25, 72]. As for TSR results in Figure 16, all SFP mixtures modified with QSP gave the same behavior as that of ITS. SFP mixes containing 10%, 20%, and 30% cement substitution with QSP showed increases of 12.0%, 5.8%, and 2.1% compared with reference specimens after 28 days of curing.

4. Conclusions

This research aims to examine the effects of partially substituting ordinary Portland cement (OPC) with quartz silica sand powder (QSP) in a cementitious grout mixture for the construction of sustainable semi-flexible pavement (SFP) surfaces. Laboratory assessments were carried out, encompassing mechanical, functional, and moisture susceptibility tests to evaluate the characteristics and performance of SFP specimens. The following points outline the key findings from this investigation:

- Using QSP as a partial replacement for cement in the production of cement grout at a rate of more than 10% leads to a reduction in workability and an increase in water consumption as it increases flow values of the grout due to increasing of w/c.
- The compressive strength results showed that replacing cement with QSP by more than 10% leads to a decrease in compressive strength by 39.7% to 28.2% at 28 days of curing. This is due to the increased water consumption which would weaken the strength and lead to increased porosity and reduced volume of hydration products represented by calcium silicate hydrates which would reduce compressive strength.
- The QSP-modified SFP mixtures showed better stability than the reference SFP mixtures without QSP. Marshall stability increased by 15.6% and 13.4% at 7 and 28 days of curing. This is attributed to the early pozzolanic reaction of silica sand and its ability to form C-S-H gel.
- Compared with reference mixture (RM), using QSP with 10% replacement grout to produce SFP specimens increases their ITS and TSR by 68% and 12.0%, respectively. This is due to its superior ability to adhere to bituminous aggregate, which improves its adhesion properties and forms a strong gelatinous skeleton. In addition to the active pozzolanic reaction caused by the high amount of silica (SiO_2), chemical test analysis indicates that the presence of silica also contributes to the formulation of C-S-H gel, thereby increasing its tensile strength.
- According to the test findings, which include fluidity, compressive strength, Marshall stability, and moisture susceptibility, the optimum cement replacement ratio is 10% QSP. These resulted in a denser microstructure, high flowability, high stability, and high compressive strength, eventually leading to improvement in the overall performance
- Using QSP as supplementary cementitious material can contribute to reducing carbon dioxide emissions resulting from cement factory consumption and represents an effective solution in providing industrial resources by employing natural resources and using it as a promising option in constructing buildings and infrastructure.

Declaration of competing interest

The authors declare no competing interests.

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