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Article

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Influence of Sustainable Grout Material on the Moisture Damage of Semi-flexible Pavement

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Abstract

Semi-flexible pavement (SFP), also known as grouted pavement, is a type of pavement structure consisting of a porous asphalt skeleton with air voids between 25 and 35% injected with cementitious grout materials. The special skeleton of SFP provided enhanced durability and resilience, making it a promising option for the construction of road surfaces in high-traffic areas and severe conditions. The main aim of the current research is to investigate the rutting behavior and moisture resilience of SFP-containing sustainable grout using ceramic waste powder (CWP). This research introduced the use of CWP as a replacement for conventional grout (cement) in SFP for the first time. CWP partially replaced cement at ratios of 15, 20, 30, 40, and 50% of the cement weight. Indirect Tensile Strength (ITS) and Hamburg Wheel Tracking Tests (HWTT) were used to evaluate the performance of SFP to reduce the detrimental effect of moisture. The grout modified with CWP shows excellent results in the ITS and Tensile Strength Ratio (TSR), and all modified SFP mixtures give higher values in these tests compared with Control Mix (CM). In the HWTT, the minimum rut depth of the modified SFP was 2.8 mm and 3.10 mm. Compared to CM, rutting decreased by 73%–76% for CWP mixes with 20% and 30% replacement. This indicates the high fluidity of CWP, which enabled it to penetrate all voids in the porous pavement (PA) and form a dense microstructure due to its excellent pozzolanic interaction, making it a strong structure capable of bearing rutting.

Keywords

semi-flexible pavement, ceramic waste powder, polymer-modified bitumen, sustainable grout, SEM/EDX

1 Introduction

Environmental hazards are raised as a result of the huge amounts of solid waste being dumped directly into the environment. Several countries now actively promote recycling and other forms of trash reuse to reduce environmental damage from waste materials. To save energy and materials and prevent pollution, waste items may be recycled into new products or used as additives. A rise in the demand for cement plants leads to increased carbon dioxide (CO_2) emissions, causing the present global warming [1]. Solid wastes in Iraq mainly cover urban areas as a result of urban development, and the process of managing these wastes is very primitive. In 2012, Iraq produced 119,425 tons of hazardous solid industrial wastes (unit production rate: 0.01 kg/capita/day) [2]. Construction and demolition waste constitute 75% of the world's solid waste, while ceramic tile waste makes up 54% of this waste [3]. The use of moderate quantities of ceramic tiles in the subway and infrastructure may facilitate the ecologically acceptable disposal of such waste.

Using ceramic waste dust in cement grout to dispose of such waste can be preferable because it preserves natural resources, valorizes industrial waste products, offers a solution for waste disposal, avoids using landfill spaces, and contributes to lessening the need for cement [4]. The physical and chemical properties of ceramic waste are superior to those of other types of waste due to its durability, high resistance, and pozzolanic activities, even at advanced ages. Increasing the specific surface area of the pozzolans is one way to boost their pozzolanic characteristics [5]. As previously mentioned, using ceramic dust has the benefits of being a durable, long-lasting material in highway construction facilities as well as a practical, environmentally friendly method of collection and processing [6]. The use of municipal waste materials (such as solid wastes)

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and/or other industrial by-products as a partial replacement for Portland cement is one strategy for drastically lowering emissions of CO_2 and greenhouse gases.

Semi-flexible pavement (SFP) also known as grouted pavement, is a hybrid pavement that combines the properties of flexible and rigid pavement and is commonly used in various transportation infrastructure projects [7]. It consists of a porous asphalt mixture (PAM) with a 25–35% void ratio injected with cementitious grout material [8]. Grouting materials serve a significant role in filling and stiffening the asphalt mixture when pouring SFP, resulting in high-performance pavement [9]. SFP is designed to exhibit a combination of flexible and rigid characteristics. It has higher structural strength and stiffness compared to flexible pavement, making it better able to withstand heavy traffic loads and reduce rutting and deformation. The cement grout design was intended to achieve a compromise between fluidity and strength. Cementitious grout materials are often developed in response to the need to quickly form a highly flowable substance in the porous asphalt skeleton [10]. The optimum fluidity of cement grout should be in the 11–16 second's range. Therefore, flow intervals of less than 11 s may not allow the grout material to enter the spaces in the SFP mixture, while flow periods longer than 16 s may cause more voids to remain unfilled [11].

Several factors affect the performance behavior of SFP mixtures. It includes indirect tensile strength, moisture resistance, tensile strength ratio, fatigue life, and rutting. Moisture is one of the environmental factors that decrease the durability of pavement. The performance of semi-flexible pavement surface materials has shown notable superiority in mitigating rutting with low levels of deformation. As a result of having a greater rigidity modulus, semi-flexible pavements did not undergo any irreversible deformation during the whole of their design life [12]. The geographical location of Iraq affects its climate, making it semi-continental, as it is located within the northern temperate zone with high, almost constant atmospheric pressure. The climate is characterized by very hot summers and short, cold winters. High temperatures are a result of hot, humid winds that affect Iraq in the summer, especially in the southern and central regions. The hotter weather makes summer rutting susceptibility a major concern in pavement design [13]. German engineers developed the Hamburg wheel-track Test (HWT) device in the 1970s as a well-established test to assess the performance of hot mix asphalt under the most severe conditions [14]. The HWTT is an excellent technique for evaluating the moisture susceptibility of SFP mixes. Xu et al. [15] found that when different grouts were used to make semi-flexible mixes, the rut depth was almost few and the dynamic stability was over 13,000 times/mm at a temperature of 60 °C. Semi-flexible mixes have superior thermal stability in comparison to hot mix asphalt (HMA) mixes.

Several cement-based products, including mortar and concrete, have been reported to use ceramic waste as either a mineral addition or as fine and coarse aggregate.

Serin et al. [16] studied the effect of using ceramic waste powder (CWP) and concrete waste powder (COW) as mineral fillers in the production of hot mix asphalt (HMA). The findings of their study indicate that including CWP and COW as filler materials in HMA increases its stability and may provide a more environmentally friendly option compared to the use of conventional limestone. Kara and Karacasu [17] examined the utilization of ceramic waste in HMA. It was concluded that the utilization of ceramic waste in HMA meets the Turkish Highway Construction Specifications. The binder course may incorporate up to 30% ceramic waste, while the wearing course can use up to 20% ceramic waste in HMA. Kofteci and Nazary [18] used crushed ceramic waste with red brick waste as fine aggregate in HMA. The results of their study indicated that the aggregate used from recycled brick was superior to other mixtures in terms of stability, while the aggregate from ceramic waste gave superior performance in terms of high and low-temperature properties. Muniandy et al. [19] examined the usability of partial replacement of granite aggregate with 0, 20, 40, 60, 80, and 100% of ceramic tile waste. The result of their investigation proved that the optimum percent of replacement was 20%. At this percentage, the samples show greater stability and resilience compared with the control sample. Shamsaei et al. [20] investigated the effect of replacing CWP with limestone powder (LS) as filler in the production of HMA. The experimental work of the study included partial replacement of LS with 25%, 50%, 75%, and 100% CWP by weight. The results conclude that all replacement ratios improved Marshall's stability and fatigue life. It also concluded that the CWP increased the rutting resistance by reducing the rutting depth by 31% compared with the control sample. Based on the available literature, limited studies investigated the effect of replacing cement partially with CWP in the development of SFP. Therefore, the primary objective of the present research is to investigate the effect of partially replacing cement with CWP in the cementitious grouts used for semi-flexible pavement (SFP) surfaces.

2 Materials

2.1 Cementitious grout

The grout's components consist of ordinary Portland cement (OPC), ceramic waste powder (CWP), water, and superplasticizer (SP). The OPC that has been used for this study is CEM I 42.5 R with a specific gravity (SG) of 3.16 and a specific surface area (SSA) of 322 m^2/kg Table 1.

Ceramic tiles were collected from the remains of the shops as well as from the waste left behind from building and demolition projects. Broken waste tiles were collected, cleaned with a brush to remove any other polluted suspended minerals or dust, and then hammered into little pieces with a hammer. The pieces were then put in a Los Angeles abrasion test machine to decrease their size even more. The waste was then taken from the machine and sieved using sieve No. 200 (0.075 mm). In order to enhance the fluidity and effectiveness of grout mixtures, a superplasticizer was used in this investigation under the name "Mega Flow 2000" from CONMIX Company. It is a modified polycarboxylate ether-based superplasticizer that provides superior performance in grout. Compared to other types of superplasticizers, it has a distinctive carboxylic ether polymer that is characterized by long lateral chains. As a result, it functions exceptionally well as a cement dispersion and high-range water reducer. The recommended dosage of SP is between 0.5 and 2% by weight of cementitious material, according to ASTM C494/C494M-17 [21]. Table 1 illustrates the essential properties of CWP and OPC. In Fig. 1, the scanning electron microscopy (SEM) image of CWP is presented, which shows irregularly shaped CWP particles with smooth surfaces and sharp edges. Energy-dispersive X-ray (EDX) analysis was utilized to identify the CWP's chemical composition, and the findings are shown in Fig. 2. As can be observed in Figs. 2 and 3, the CWP comprises high amounts of silicon and aluminum elements. In addition to smaller percentages of calcium, iron, and antimony elements.

Table 1 The characteristics of CWP and OPC

Property	Materials type	
	CWP	OPC
Physical properties		
Surface area (m^2/kg)	555	322
Specific gravity (g/cm^3)	2.68	3.15
Passing from sieve size No.200 (0.075 mm), %	95	97
Loss of ignition, %	0.9625	3.485
Chemical properties		
SiO_2 (%)	57.36	22.24
Al_2O_3 (%)	14.87	3.637
SO_3 (%)	0.06	2.269
Fe_2O_3(%)	16.82	4.150
CaO (%)	0.39	61.10
MgO (%)	3.45	2.661
K_2O (%)	4.20	0.51
Na_2O (%)	2.01	0.2

(a)

(b)

Fig. 1 (a) CWP and (b) SEM image

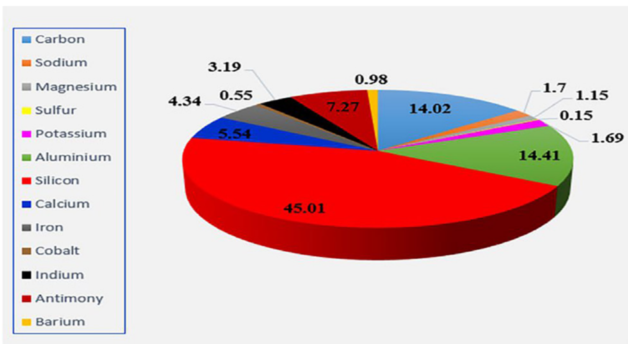


Fig. 2 The proportion of chemical elements constituting CWP by EDX

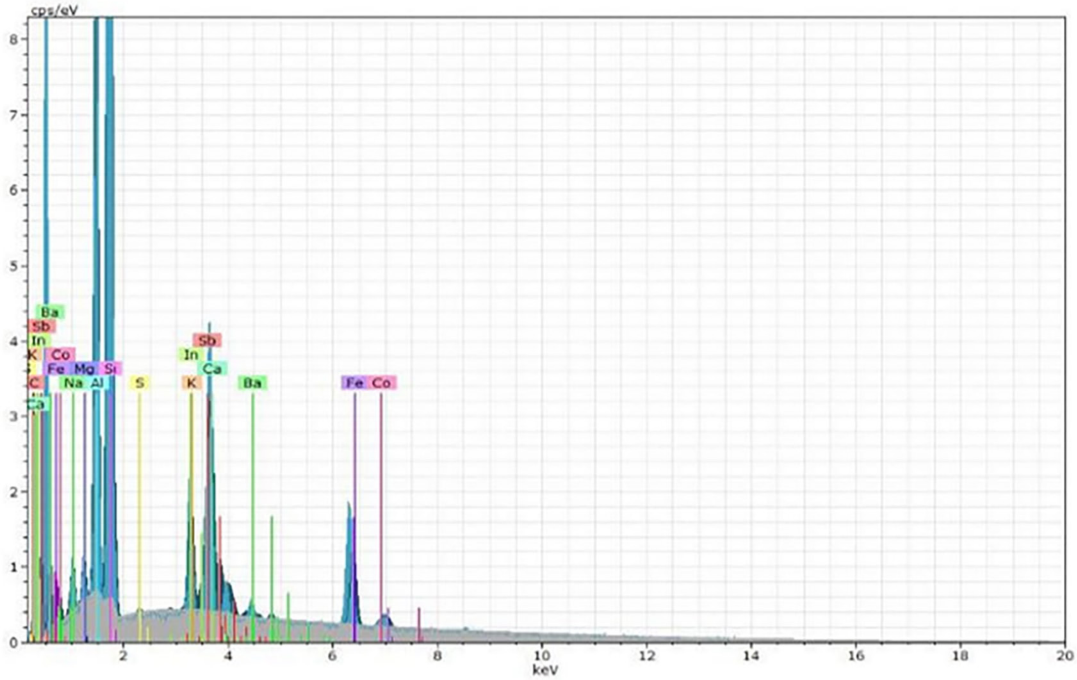


Fig. 3 The results of the energy-dispersive X-ray (EDX) analysis performed on CWP

Table 2 Physical properties of limestone aggregate

The property	Standard (ASTM)	Test value
	Crushed coarse aggregate	
Bulk specific gravity, (g/cm^3)	ASTM C127-12 [22]	2.621
Apparent specific gravity, (g/cm^3)	ASTM C127-12 [22]	2.650
SSD specific gravity, (g/cm^3)	ASTM C127-12 [22]	2.603
Water absorption, (%)	ASTM C127-12 [22]	1.4
Percent of crushed surfaces in coarse aggregate particles, (%)	ASTM D5821-13 [23]	93
Los Angeles abrasion value, (%)	ASTM C131-06 [24]	21
Flakiness indexes, (%)	ASTM D4791-19 [25]	1.3
Clay lumps, (%)	ASTM C142/C142M-17 [26]	1.353
	Crushed fine aggregate	
Bulk specific gravity, (g/cm^3)	ASTM C128-01 [27]	2.61
Apparent specific gravity, (g/cm^3)	ASTM C128-01 [27]	2.87
SSD specific gravity, (g/cm^3)	ASTM C128-01 [27]	2.67
Water absorption, (%)	ASTM C128-01 [27]	3.954
Clay lumps, (%)	ASTM C142/C142M-17 [26]	0.963

2.2 Aggregate and asphalt binder

Limestone aggregates and asphalt binders that were sourced locally were utilized in this research to produce porous pavement (PA) mixtures. Table 2 describes the physical properties of the aggregate used in this study [22–27]. Fig. 4 shows the gradation of the aggregates utilized in this study according to the mean limits of ASTM D7064/D7064M-08 [28] requirements for open-graded gradation of surface courses. The aggregate gradation's nominal maximum size is 12.50 mm. To evaluate the characteristics of the control asphalt binder,

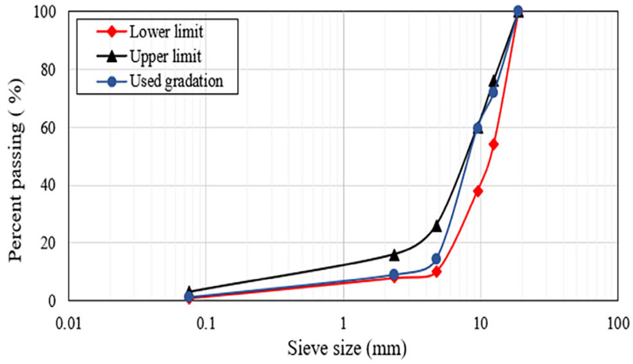


Fig. 4 Gradation of the aggregates utilized for this investigation

conventional asphalt binder testing methods such as penetration, flashpoint, Saybolt point, and ductility test were used. Table 3 shows the engineering characteristics of the asphalt binder [29–34].

2.3 Additive

Styrene Butadiene Styrene (SBS) is one of the most popular elastomer polymers used worldwide. It is one of the polymers that are commonly used to improve the rheological properties of asphalt around the world, where it makes asphalt binder more rigid, stable, and elastic. SBS Kraton type D1192 was used as a modifier for bitumen in this study, which is supplied by a Kraton polymer company. To blend control asphalt cement with SBS, first heat the asphalt in an oven at 160 °C for 1 hour. Second, it is placed in a high-shear mixer, and SBS is progressively added in the necessary quantities (5% by weight of the pure asphalt) to prevent agglomeration. Third, it is mixed using a high-shear mixer at 3000 revolutions per minute and 180 °C. Finally, it is placed in an oven for 4 hours at 160 °C to finish the curing process, complete the homogeneity of the mixture, and prevent separation. The mixture is then reintroduced to the mixer and stirred for an hour at a temperature of 180 °C.

3 Experimental setup and procedure

3.1 Mix design

The SFP design process is summarized in three steps: designing the cementitious grout composition with a flow time of 11–16 seconds using CWP; designing the porous hot mix asphalt (PHMA) with 25–35% air voids; and characterizing the SFP mix properties after grout injection into porous asphalt mixture.

Firstly, the typical Marshal mix design was used to produce the porous asphalt mixes. Marshall specimens were created in two series. To find the optimum asphalt binder content, the first set of specimens included a variety of asphalt binder compositions (4, 4.5, 5, 5.5, and 6%). The second series was at the optimum concentration of asphalt binder to assess the mechanical characteristics of PHMA. The mix design's optimal asphalt binder content was calculated by using the drain-down test at 175 °C. The drain down must not exceed 0.3% according to standard of ASTM D7064/D7064M-08 [28] standards. The optimum asphalt concentration is 4% (Fig. 5) to achieve the required air void ratio, adequate drain down, and higher stability. Table 4 displays details of the mix design for the PA mixture.

In this study, two types of grout mixtures were used. The first mixture is control grout, which consists of 69% OPC and 31% water. In the second mixture, the CWP was used as a supplementary cementitious material, where cement was partially replaced by 15, 10, 20, 30, 40, and 50% of CWP by the weight of the cement with the addition of an SP at a rate of 2% and a W/B ratio of 40%. The flow cone test, also known as the fluidity test, is used to evaluate the flow time of grout by using a standard flow cone mold that is in accordance with ASTM C939-10 specifications [35]. Table 5 shows the grout combinations.

The W/B ratio for the reference mixture (Mix 0) and the other mixtures (Mixes 1–5) modified with CWP was determined through trial and error using a Marshall flow cone device (Fig. 6) to achieve an optimum standard flow time of 11–16 seconds. According to ASTM standard C939-10 [35], it is sufficient for the cementitious grout material to penetrate all the voids in the PA mixture.

Table 3 The physical characteristics of base asphalt bitumen

Test type	Standard (ASTM)	Result
Penetration at 25 °C (0.1 mm)	ASTM D5/D5M-13 [29]	42
Softening point (R&B°C)	ASTM D36/D36M-14 [30]	53
Ductility at 25 °C (cm)	ASTM D113/D113M-17 [31]	117
Flashpoint (°C)	ASTM D92-02b [32]	350
Solubility in trichloroethylene (%)	ASTM D2042-15 [33]	99.8
Dynamic viscosity at 60 °C (Pa s)	ASTM D88/D88M-07 [34]	486
Kinematic viscosity at 60 °C (Cs)	ASTM D88/D88M-07 [34]	477

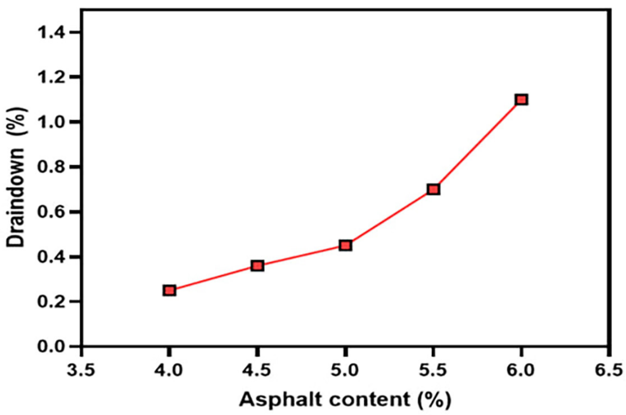


Fig. 5 The drain-down amount for various asphalt concentrations

Table 4 Mixing ratios for porous asphalt

Material	Value (%)
Optimum binder content	4.0
Aggregate (coarse and fine)	91.22
Filler (lime dust powder)	4.78

Table 5 The grout combination mixtures

Mix No.	OPC, (%)	W/B, (%)	CWP, (%)	SP, (%)	Fluidity, (s)
Mix0	100	45	0	0	15.8
Mix1	85	40	15	2	14.5
Mix2	80	40	20	2	13.4
Mix3	70	40	30	2	13.1
Mix4	60	40	40	2	12.2
Mix5	50	40	50	2	11.0

Fig. 6 Flow cone test

The PA mixture molds are prepared by covering them with plastic wrap and then placing them in a plastic mold of the same size as the Marshall mold in order to maintain the sample size and prevent leakage of the cementitious grouting materials. After that, the mold is placed on a vibrator device in a slow circular motion for two minutes in order to ensure that the grout penetrates all the voids in the porous sample and fully fills it, as well as to avoid the separation of the grout materials as a result of the rapid vibrational movement. Then the samples were removed from the plastic mold after two days to ensure their hardening was completed. The injection process for the PA samples utilizing cementitious grout materials is shown in Fig. 7.

Following the hardening of the cementitious grout materials, the surface of the sample is sprayed with a curing substance called "Set Seal 22". This curing substance works to moisturize the cement hydration products and keeps the internal water of the sample from evaporating as a result of the heat emitted from the hydration process. The specimens were kept in the laboratory at 25 °C until the required tests were performed. Fig. 8 shows the maturation process of the SFP samples.

Fig. 7 Preparation of SFP specimens

Fig. 8 Curing of SFP specimens

3.2 Test methods

3.2.1 Indirect tensile strength test (ITS)

The ITS test is a measure of the tensile strength of HMA as well as an excellent predictor of mixture cohesiveness. The ITS is also able to measure the moisture effect on asphalt concrete paving mixes. In the case of the grouted macadam, it is anticipated that the asphalt matrix will, in the majority of cases, be the component responsible for providing the tensile qualities to the mix [36]. The ITS test demonstrates the asphalt mixture's resistance to fatigue and thermal cracking. A mixture with greater tensile strength is more resistant to fatigue and thermal cracking. The stripping resistance (moisture sensitivity) of PA and SFP mixes was determined by measuring the amount of loss in ITS that occurred after being submerged in water for 24 hours at a temperature of 60 °C by following the procedure for testing outlined in ASTM D4867/D4867M-09 [37]. ITS is determined by Eq. (1) and applied to the highest load experienced by the sample

$$\mathrm{ITS} = 2000 \times P / \pi \times t \times D \quad (1)$$

where ITS represents to indirect tensile strength (KPa), P, maximum load (N), t, the height of the specimen before the test (mm), and d, the diameter of the specimen (mm).

3.2.2 Tensile Strength Ratio (TSR)

One of the most significant problems that might occur with asphalt pavements is the deterioration of asphalt mixes caused by moisture. Moisture-related damage is the result of two different failure mechanisms: one is the loss of cohesive bonding within the asphalt binder, and the other is the loss of adhesive bonding between the aggregate and the binder [38]. The deterioration of an asphalt concrete pavement's strength contributes to the development of many types of failure, including rutting, raveling, fracturing, and fatigue cracking [39]. Since it is a quick and simple test to conduct, the TSR value established by ASTM D4867/D4867M-09 [37] has been the basis for the majority of research to determine how susceptible asphalt mixtures are to moisture. According to Eq. (2) listed in ASTM D4867/D4867M-09 [37], the TSR value for SFP may be calculated by dividing the ITS value of conditioned specimens after 24 hours in a water bath at 60 °C by the ITS value of unconditioned specimens. Most pavement agencies recommend that the TSR be greater than 80%.

$$\mathrm{TSR} = Stm / Std \quad (2)$$

where TSR represents to tensile strength ratio, *Stm*, the average tensile strength of the moisture-conditioned subset (kPa), *Std*, and the average tensile strength of the dry subset (kPa).

3.2.3 The Hamburg Wheel Tracking Test (HWTT)

The HWTT is an experimental laboratory test technique for gauging the depth of ruts produced in an asphalt mixture with increasing load cycles by repeated loading in the presence of water [40]. Asphalt mixtures are tested for their sensitivity to moisture and rutting, respectively, and the results are evaluated [41]. The HWTT is based on the AASHTO T324-11 [42] specification. The standard allows for testing with either a rectangular slab or a cylindrical specimen. An asphalt concrete sample was tested by submerging it in hot water at 50 °C, 55 °C, and 60 °C and then rolling a steel wheel over its surface to simulate the effects of vehicle loads [43]. The performance of rutting is assessed in this research using the rut depth after 10,000 wheel passes with a total load on the arm equal to 700 N. Testing was done on slab specimens with dimensions of 340 × 180 × 50 mm. The test temperature for HWTT in this study was chosen to be 60 °C. Fig. 9 shows the Hamburg wheel track device.

4 Results and discussions

4.1 Indirect Tensile Strength and Tensile Strength Ratio

The ITS determines the tensile strength of PA and SFP mixtures. At the bottom of bituminous layers, the ITS measures the mixture's ability to withstand a horizontal tensile strain. To evaluate the long-term deformation of SFA mixtures, ITS is performed at 25 °C and 60 °C according to ASTM D4867/D4867M-09 [37]. The results of the ITS in an unconditioned state are shown in Fig. 10. The results demonstrate that the significant increase in ITS values

Fig. 9 The Hamburg wheel tracking test

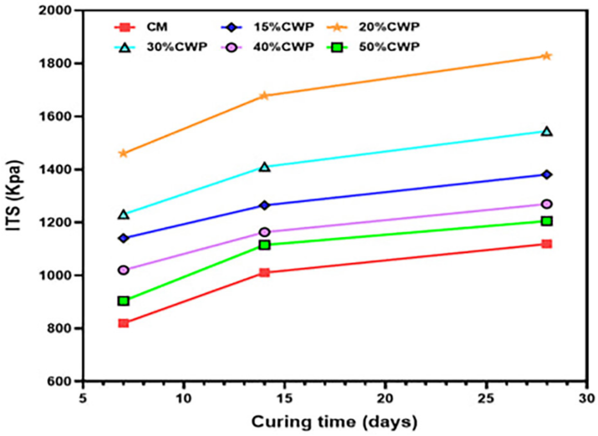


Fig. 10 The indirect tensile strength of unconditioned specimens at different curing ages

observed in all mixtures can be attributed to the strength obtained as a result of the curing process. It is noted from Figs. 10 and 11 that the lowest values of ITS in the porous asphalt mix are because it is a weak mixture and not injected with grout material. It is also noted that there is a significant improvement in the ITS values compared to the CM, and this significant improvement is attributed to the high fluidity of the modified grout mixes with CWP. Ceramic waste is used to minimize early-age shrinkage and temperature increases caused by the heat of hydration. CWP allows cementitious grouting materials to achieve the requisite fluidity with a lower water content. Cementitious grouting materials' flowability was shown to be positively associated with their surface area, in which more surface area resulted in greater flowability. The ceramic material has a surface area of 555 m^2/kg, which is higher than that of cement (322 m^2/kg), therefore, the ability of ceramic waste to penetrate the PA is very high, consequently filling all voids and strengthening the mixture by increasing the adhesion between its components. The mixtures with 20% and 30% CWP replacement have a higher ITS value of 1827.9 kPa and 1544.70 kPa, respectively, which is 63% and 38% higher than the CM. The strength gain is attributed to the higher tensile strength exhibited by the PMB binder and the higher fluidity of modified grout with Mega flow SP. In addition, both ratios produced a dense microstructure. As can be seen from Fig. 12, the SEM image for 20% and 30% replacement showed a high amount of CSH gel due to a high pozzolanic reaction of CWP and increasing the concentration of CSH gel, resulting in a rise in the strength of CWP-modified mixes. The low fluidity of grout in CM results in a lower ITS value because many voids were formed that were not filled with grout material, which caused water to enter them and thus caused the premature failure of the mixture Fig. 11 (b). Fig. 13 indicates that ITS values at 25 °C are greater than those at 60 °C, illustrating the temperature susceptibility of SFP mixes. It might be related to the loss of aggregate bonding caused by the softening of coated bitumen [44].

Regarding the TSR values, the results showed in Fig. 14 that all SFP mixtures modified with solid waste and SP are higher than the CM containing only water and cement, and

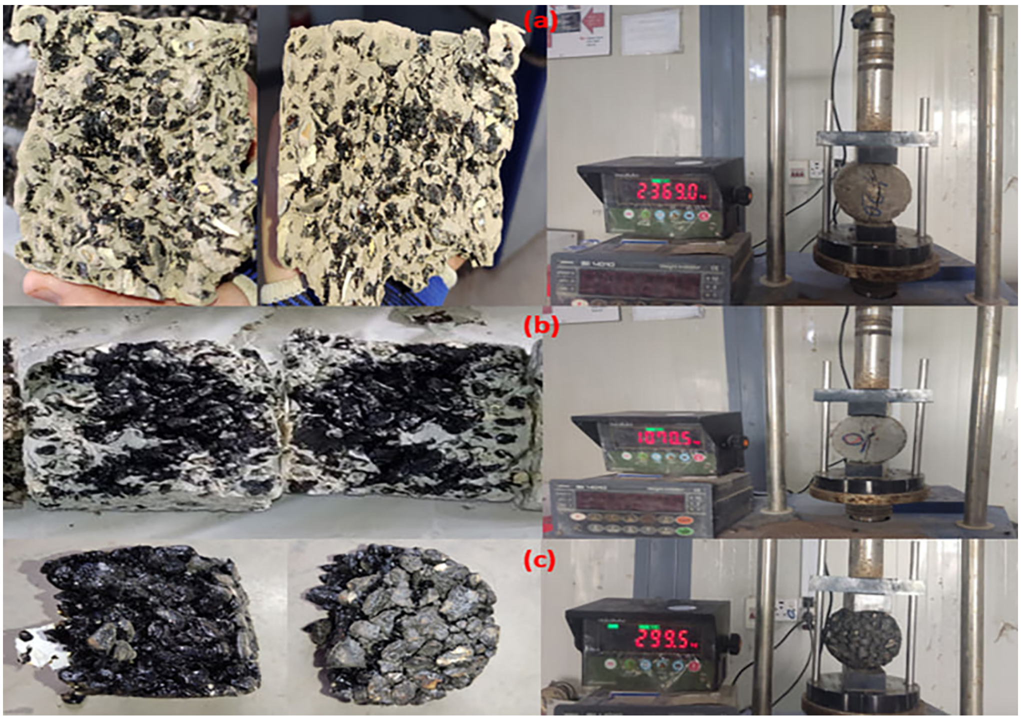
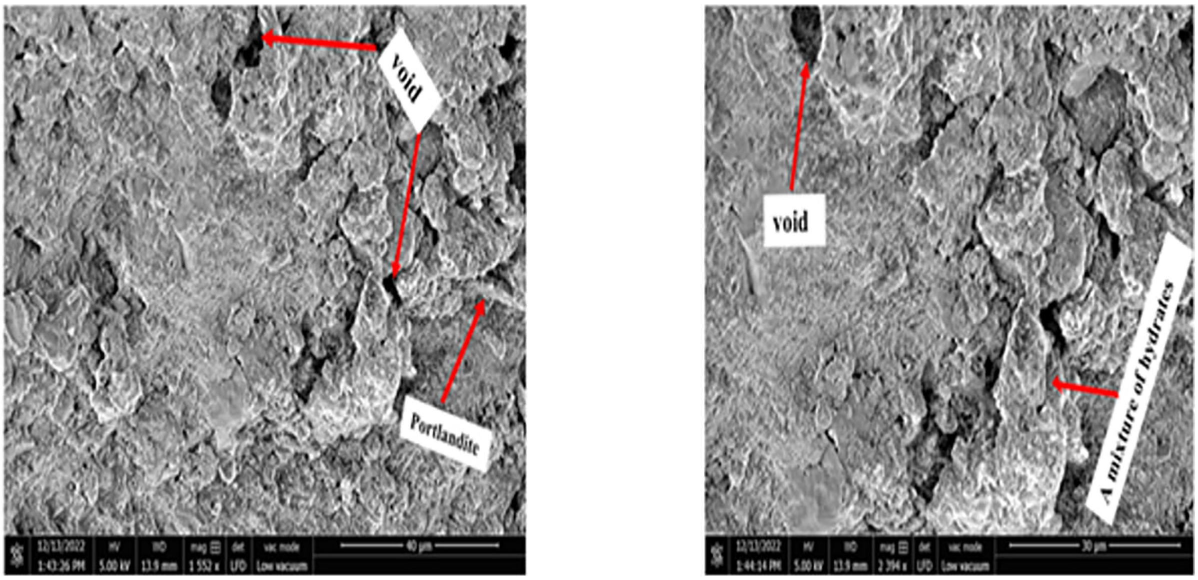


Fig. 11 Samples of the ITS test in unconditional state at 28 days for the mixtures: (a) 20% CWP, (b) CM, (c) PA



(a) (b)

Fig. 12 SEM image for SFP samples containing varying percent of CWP (a) 20% CWP, (b) 30% CWP

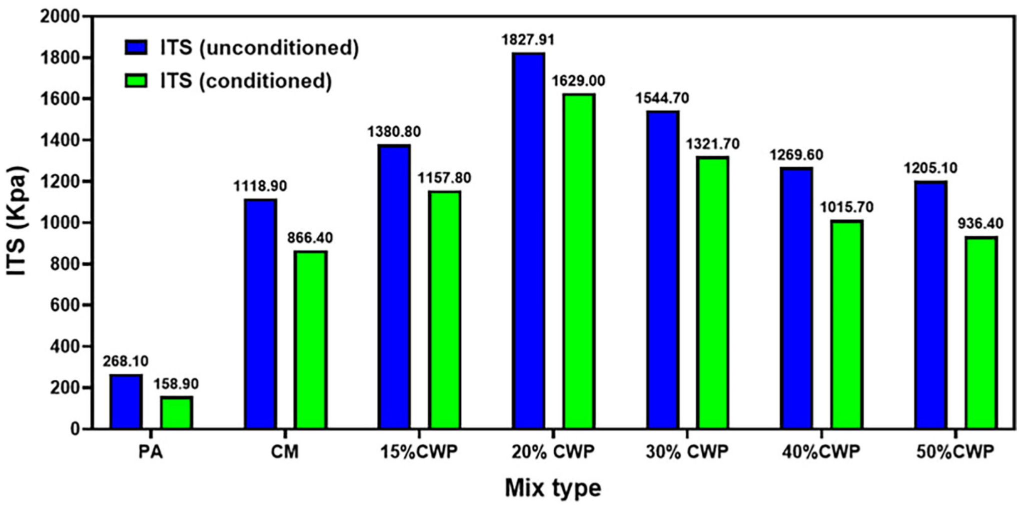


Fig. 13 The indirect tensile strength of aged and unaged specimens at 28 curing days

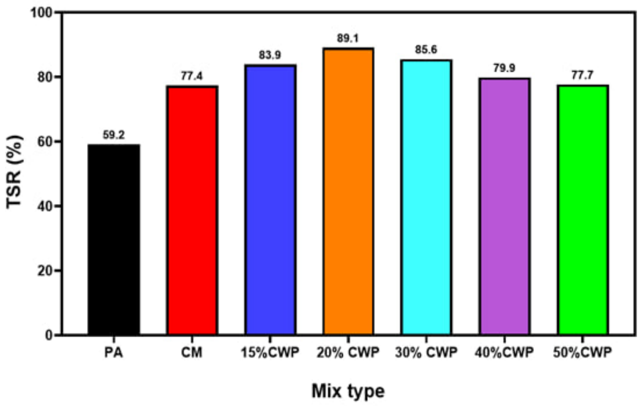


Fig. 14 Tensile strength ratio for various mixtures at 28 days of age

the explanation for this is the high flowability of CWP and the higher effectiveness of SP. Fig. 14 shows that the maximum TSR value was found for a mixture of 20% cement replacement with CWP, resulting in a 15.4% increase compared to the control mix at 28 days of curing. The mixture with 30% replacement also recorded a 10.6% increase at the same curing period due to the denser microstructure of these two mixtures. Additionally, the mixture with 15% replacement showed an increase of about 8.4% compared to the control mix. The 40% and 50% mixtures recorded increases in TSR values by approximately 2.9% and 0.38%, respectively. This decrease in TSR value with the increasing ratio of replacement is due to the dilution of the CSH components, as previously explained.

4.2 The Hamburg Wheel Tracking Test (HWTT)

Fig. 15 displays the result of HWTT. The results indicate that the highest value of rutting is in the un-injected

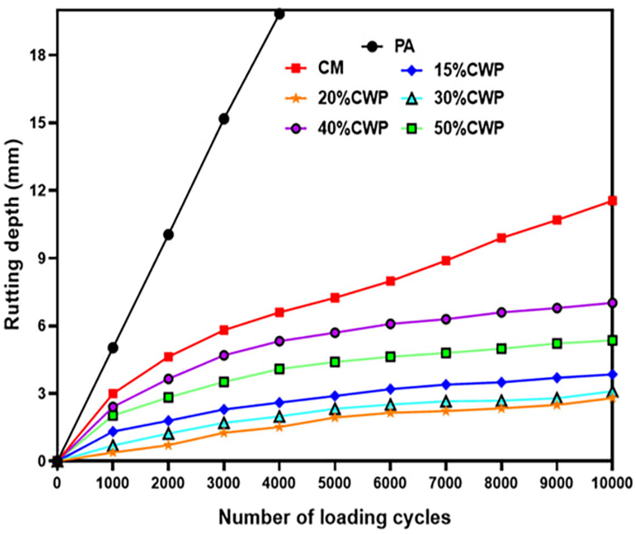


Fig. 15 PA and SFP rutting of the HWTT

mixture, and this is due to the high void ratio and the permeation of water inside the mixture, which led to its rapid failure and the fragmentation of the aggregate particles. Water leads to weak bonding between the asphalt and the aggregate. The CM records the second-highest rut depth. The reason for this is due to the little fluidity of this mixture because it does not contain SP. When injected with cement and water only, it does not penetrate all the voids, and a gap remains inside the slab that is not injected. When the wheel passes over it, the specimen undergoes high rutting. In addition, the lack of grout inside the CM slab leads to lower rigidity and an increase in its flexibility, which causes more rutting in it. It can be observed from Fig. 16 that the lower rutting depth was achieved in the mixture of 20% and 30% CWP replacement compared with the control mix. The mixture has 20% replacement recorded a decrease in rutting value by about 76% compared with CM at 28 days, while the mixture consisting of 30% replacement recorded a decrease of about 73% at the same curing time. The rutting values for these two mixtures went down

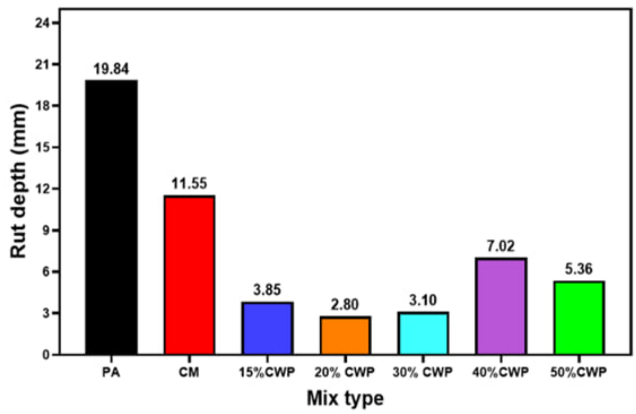


Fig. 16 The thickness of rut depth of the HWTT mixtures at 28 curing days

because they had a dense microstructure that covered all the aggregates and filled all the voids. This was because the CWP produced a lot of gel network that is responsible for the resistance of the rutting and therefore made a very strong structure that was filled with grout and kept water from getting into the mixture. Fig. 17 shows an SEM image of the overlapping of the hardened grout with the bituminous aggregate. In addition to that, this resistance to moisture deterioration is because these solid wastes contain a percentage of iron, according to EDX analysis Therefore, they formed a strong structure that can resist heavy loads and severe conditions, as shown in Fig. 18. For the mixture containing a 50% replacement percentage, it notes from Figs. 15 and 19 that this mixture resisted rupture, and the result of the depth of the rut was remarkable compared to the mixture containing a 40% replacement percentage, but there was serious concern about the visible crack on the surface of the sample near the track of the wheel. This is due to the fact that the gelatinous CSH is diluted due to an increase in the replacement rate of more than 30%, and thus the sample was exposed to cracking due to the brittle nature of the grout, as cracks appeared due to exposure to high pressures due to the movement of the wheel in a water

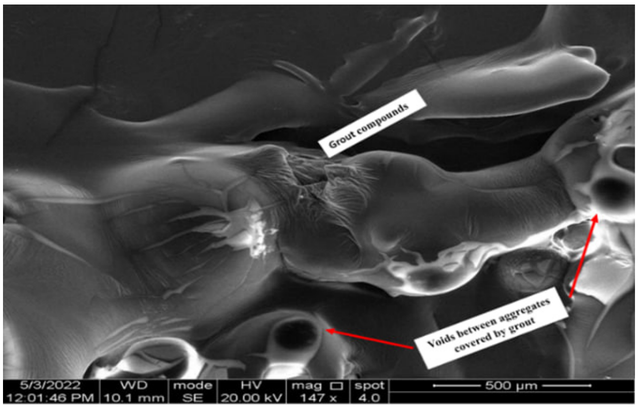


Fig. 17 SEM image for bitumen base and hardened cementitious grout material

Fig. 18 The overlapping of bituminous aggregates with CWP-modified grout

Fig. 19 The mixture's rutting depth at 28 days of curing: (a) CM, (b) 15% CWP, (c) 20% CWP, (d) 30% CWP, (e) 40% CWP, (f) 50% CWP

basin at a temperature of 60 °C. Also, there is another reason for these cracks, which is the very high fluidity of this mixture, as the fluidity of this mix recorded an amount of 11 s, which led to filling the slab completely with grouting material. The increase in the mortar leads to an increase in hardness, and thus it is prone to the appearance of cracks on the surface. It was also found in the previous study [45, 46].

Li et al. [7] revealed that the final rutting depth in the optimum SFP mixture was less than 2.5 mm. The researchers used cylindrical samples that were partially submerged in water in their investigation. In contrast, rectangular slabs were used in the present study, and they were fully immersed in water. Fig. 19 shows the SFP mixtures after the HWT test.

5 Conclusions

The objective of this study is to investigate the potential impact of the partial replacement of Portland cement with ceramic waste powder (CWP) on the reduction of moisture damage in conventional mixtures. The indirect tensile strength (ITS) and Hamburg wheel tracking test (HWTT) tests were used to assess the moisture resistance of the semi-flexible pavement (SFP) mixtures. The important results obtained from conducting these tests are presented in the following section:

The addition of CWP reduces water absorption and enhances the fluidity of the grout mix, allowing the grout to fully penetrate all the voids in the skeleton of the porous asphalt mixture.

CWP increases the ITS values; the mixture with 20% replacement has a higher ITS value of 1827.9 kPa, which is 63% higher than the control mix (CM). The increase in strength can be attributed to the enhanced tensile strength provided by polymer-modified bitumen and the increased fluidity of the modified grout containing superplasticizer (SP). The low fluidity of the CM made the ITS value low because many voids were formed that were not filled with grout material, which caused water to enter it and led to rapid failure of the mixture.

Due to the increased flowability of CWP and the higher efficiency of SP, all SFP mixes modified with CWP and SP perform better than the CM made up just of water and cement. The mixtures with modified grout by CWP had the highest tensile strength ratio (TSR) values, with an increase of 8.4 to 15.4% compared to the control mix at 28 days of curing. This is a result of the dense microstructure and the excellent pozzolanic interaction of these residues. The results of the scanning electron microscopy (SEM) images of CWP showed the density of CSH gel, which is responsible for the resistance and hardness.

All SFP mixtures with CWP showed good rutting resistance and excellent rutting performance under severe conditions. Rutting was reduced by 73%–76% in CWP mixes of 20% and 30% replacement, respectively, compared to CM.

Based on the results of the ITS, TSR, HWTT, SEM, and fluidity tests, the optimum cement replacement ratio is 20% ceramic waste. At this percentage of replacement, a denser microstructure, high resistance, and less rutting were obtained, and consequently, better performance was achieved.

The utilization of CWP as a sustainable grout used to replace cement reduces the cost. It also has a positive impact on the environment as it reduces solid waste resulting from construction, demolition, and industrial by-products by incorporating them into building and constructing roads.

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