

Mechanical Performance and Life Cycle Assessment of Semi-Flexible Pavement Using Sustainable Grout

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Abstract

The efficient utilization of construction waste in road engineering is essential for advancing sustainable infrastructure development. This study explores the application of ceramic waste powder (CWP) in cementitious grout for semi-flexible pavement (SFP) surfaces. Cement was partially replaced with CWP at proportions ranging from 15% to 50%, and its effects on SFP performance and environmental impact were evaluated using compressive strength testing, life cycle assessment (LCA), and statistical analysis. The obtained SFP mixtures were assessed for volumetric and mechanical properties through Marshall stability and wheel tracking tests. Experimental findings revealed that 20% cement replacement with CWP was the optimal level, leading to an 80% reduction in rutting depth and increases of 50% and 23% in compressive strength and Marshall stability, respectively, at 28 days of curing. These improvements are attributed to CWP's superior fluidity in filling the voids within the porous asphalt skeleton and its effective bonding capacity with aggregates, which densifies the microstructure, as confirmed by scanning electron microscopy (SEM) analysis. LCA results indicated that higher CWP replacement levels reduced both global warming potential and fossil fuel depletion, thereby enhancing the grout's sustainability. Statistical analyses, including quadratic regression, ANOVA ($p < 0.05$), and the Tukey HSD test, confirmed significant improvements in strength properties with CWP incorporation, while box plots effectively illustrated data trends and variations. In summary, this study underscores the dual environmental and performance benefits of incorporating CWP in SFP systems and supports its adoption in sustainable road construction aligned with circular economy goals.

Keywords

Semi-flexible pavement, recycling, rutting failure, ceramic waste powder, sustainability, life cycle assessment, analysis of variance.

42 1. Introduction

43 Semi-flexible pavement (SFP) has garnered attention for its unique ability to combine the beneficial properties of both
44 flexible and rigid pavements while mitigating their weaknesses. This pavement, comprising a porous asphalt skeleton
45 with 25–35% air voids and injected with cementitious grout, forms a composite structure that reduces asphalt
46 flexibility while achieving the compressive strength and rigidity of concrete pavement(Ling et al., 2024; Yao et al.,
47 2025). The porous asphalt layer offers flexibility and smoothness for dynamic loads, while the cementitious grout
48 enhances rigidity, skid resistance, and load distribution to the subgrade(Al-Nawasir et al., 2024). SFP is characterized
49 by its strength, resistance to deformation, and high durability, as it can withstand heavy traffic loads and adverse
50 weather conditions (Ghahremani et al., 2024). This type of construction is often used for industrial roads, airport roads,
51 and areas where traditional asphalt or concrete may not be practical or cost-effective(Khan et al., 2019).

52 SFP provides a solid and reliable road surface that is easier to maintain compared to other types of road construction
53 (Du et al., 2024). SFP surface materials effectively prevent rutting, with minimal deformation observed, though few
54 experiments have positively examined this aspect (Taghipoor et al., 2024). Researchers found that a semi-flexible
55 combination, including 4.5% asphalt and gradations from New Zealand and ASTM, had equal deformation
56 findings(Sunil et al., 2021). The mixture withstood 20,000 cycles without failure, showing minimal distortion, while
57 SFP mixtures exhibited excellent dynamic stability and low rut depth at 60 °C, and also demonstrated greater stability
58 at high temperatures as compared to hot-mix asphalt (HMA) (Xu et al., 2020). The rutting resistance and dynamic
59 stability of SFP were found to be 2.5 times greater than those of HMA. HMA had a dynamic stability of fewer than
60 5,000 passes/mm, whereas SFP had almost 11,000 passes/mm (Luo et al., 2020).

61 In SFP design, the cementitious grout composition is crucial since it affects the pavement's stiffness, durability,
62 performance, and behavior as a whole(Songqiang et al., 2024). The choice of grout components, including the w/c
63 ratio and superplasticizers, significantly influences the fluidity and strength of the grout(Al-Humeidawi et al., 2024).
64 Producing SFP surfacing demands considerable cementitious grout, raising construction costs. While ordinary
65 Portland cement (OPC) is commonly used in conventional grout, researchers are exploring alternative materials to
66 partially or fully replace OPC. This approach aims to lower costs and enhance sustainability by recycling waste
67 materials and reducing CO₂ emissions from the cement industry. Hasan and Sugiarto (2021) studied the mechanical
68 properties of SFP using natural zeolite as a cement replacement to produce cementitious grout material. Their study
69 concluded that the optimum cement replacement with natural zeolite for modifying SFP grout is 15%. They found
70 that the modified grout mixture at this percentage has the highest compressive and flexural strength. This optimum
71 cement replacement mixture also reduces shrinkage and increases permeability and durability for robust SFP
72 performance. These findings suggest that incorporating natural zeolite enhances the mechanical properties of SFP
73 grout and contributes to its long-term performance in SFP construction applications.

74 Hlail et al. (2021) evaluated SFP durability with sustainable cement-based grout, finding that mixtures incorporating
75 paper sludge ash (PSA) and silica fume (SF) improved moisture susceptibility and aging resistance compared to
76 conventional grout. In another study conducted by Gupta and Kumar (2021), it was found that the performance of SFP
77 improved when the cementitious grout was modified with fly ash and silica fume.

78

79 Davoodi et al. (2022) studied the effects of replacing cement with rubber powder and nano-silica, using ethylene vinyl
80 acetate (EVA) as a binder modifier. Their study found that modified grout improved low-temperature bending
81 strength, fatigue life, and rutting resistance, resulting in enhanced cracking resistance for SFP surfacing. Liu et al.
82 (2024) found that ultra-fine fly ash (UFA) enhanced grouting materials, achieving optimal fluidity at 9% UFA
83 concentration with a flow cone fluidity 12.33% to 17.63% lower than the control mixture while maximizing
84 compressive strength at 12% UFA compared to the control sample. Tan et al. (2024) investigated the use of red mud
85 as an alternative material in cementitious grouting to diminish energy consumption and CO₂ emissions of SFP. The
86 life cycle assessment (LCA) indicated that red mud substantially reduces energy consumption and the ecological
87 impact of SFP. Ecotoxicological evaluations have shown that red mud is safe for pavement applications, presenting
88 no substantial risks even under circumstances of traffic and precipitation. A microscopic analysis demonstrated that
89 substituting cement with red mud enhances the bonding contact in SFPs. Their study concluded that red mud may
90 emerge as a viable option for reducing the carbon footprint associated with traditional cement use. It can lead to
91 increased durability and longevity of the SFP structure.

92 In recent years, solid waste from construction and demolition, along with industrial waste like tile, has significantly
93 increased globally. Construction and demolition waste (CDW) is one of the largest waste streams, and in Iraq, its
94 rising generation poses major disposal concerns due to limited dumping land and associated costs. Furthermore,
95 disposing of these wastes in an open environment or across cities chokes river flows, may block surface drains, and is
96 an eyesore on the urban landscape (Faruqi & Siddiqui, 2020). Iraq generates 1,000 tons of CDW daily, with a recycling
97 capacity of only 6,500 tons, representing just 1% of total waste. Waste management challenges are increasing due to
98 a growing population, booming economy, rising disposable incomes, and past conflicts. Overall, Iraq produces 31,000
99 tons of solid waste daily, averaging 1.4 kg per person (Obaid et al., 2019). Most waste in Iraq ends up in unlicensed
100 landfills, posing a threat to human or environmental health because of a lack of an efficient and modern waste
101 management and transport system (Al-Hussein et al., 2024). Growing concerns about the environmental impacts of
102 cement production have led to increased demand for evaluating and comparing the sustainability of newly developed
103 alternative materials (Vieira et al., 2023). One of the most efficient tools to assess a cement plant's negative
104 environmental impacts is conducting a life cycle analysis (LCA), which may examine many ecological aspects,
105 specifically carbon dioxide emissions and energy consumption (Huarachi et al., 2020). Studies demonstrate that
106 ceramic tile waste contributes significantly to global construction and demolition waste. This results from elevated
107 breakage rates in the production, shipping, installation, and demolition of old buildings processes (Akhtar & Sarmah,
108 2018). Consequently, there is a growing need for sustainable practices to minimize this waste and promote recycling
109 initiatives within the demolition industry. Utilizing ceramic waste as a partial substitute for construction materials can
110 enhance environmentally friendly disposal, reduce landfill use, and lower construction costs. Previous studies have
111 widely utilized ceramic tile waste to replace some aggregate or cement in concrete (Tanash et al., 2023). Numerous
112 construction material applications, including cement paste, lightweight and heavy concrete, self-compacting concrete,
113 high-strength concrete, geopolymer, mortar, and masonry, have widely utilized ceramic waste powder (CWP). Medina
114 et al. (2016) proposed incorporating ceramic waste into the production of concrete from various sources, such as tiles,
115 blocks, and sanitary waste. Their study concluded that using ceramic waste as natural aggregate at 20% and 25%

116 increased electrical resistance and durability, and performed more satisfactorily over the service life compared to
117 conventional concrete. Muniandy et al. (2018) examined the potential benefits of partly replacing granite aggregate
118 with different ratios (between 20% and 100%) of CWP. The examination revealed that the mixture containing 20%
119 CWP is the optimum cement replacement. Their study concluded that the mixtures with 20% replacement demonstrate
120 improved stability and durability compared to the control mixtures.

121 Literature studies report that substituting cement with CWP enhances durability, including chemical resistance and
122 thermal characteristics of cementitious materials. El-Dieb et al. (2019) examined the feasibility of using CWP as a
123 substitute for cement in high-performance concrete. This substitution may increase durability and workability in
124 concrete. The study demonstrated that substituting 20–30% of cement with CWP improved compressive strength,
125 workability, and durability. AlArab et al. (2020) reported that CWP improved residual strength and thermal
126 conductivity for cementitious materials. Nepomuceno et al. (2021) investigated the partial replacement of OPC with
127 50% limestone dust, metakaolin, ceramic tile waste, and glass waste powder. Their study concluded that the CWP
128 grout had superior injectability characteristics, as seen by its higher flow rate and greater compressive strength,
129 compared to the other additives. Barreto et al. (2021) investigated the effectiveness of CWP by combining it with OPC
130 at a ratio of 10% and 20%. Their study concluded that 20% of CWP increases the compressive strength due to its
131 effective pozzolanic potential, as it interacts with CH (portlandite) and increases the gelatinous gel (C-S-H)
132 responsible for enhancing the strength. Serin et al. (2023) investigated the impact of using concrete waste powder
133 (COW) and ceramic waste powder (CWP) as materials for filler in HMA. The research results suggest that
134 incorporating CWP and COW into HMA enhances its stability and offers a potential eco-friendly alternative to the
135 typical use of limestone. Li et al. (2024) evaluated the effects of CWP on the characteristics of concrete. The findings
136 show that employing 20% CWP instead of cement keeps the changes in water absorption value and compressive
137 strength within the acceptable range. Concrete's thermal conductivity improved when CWP replaced 20% cement, and
138 its mechanical qualities remained unaffected even after 30 minutes of fire exposure. Hashim et al. (2025) examine the
139 efficacy of substituting cement with 5–20% CWP to enhance the durability of recycled aggregate concrete (RCA)
140 produced with 25% ceramic wall tile coarse aggregates. The results of their study concluded that the optimum
141 improvement in terms of performance and durability of RCA was recorded by the mixture containing 20% CWP, as
142 the compressive, tensile, and flexural strengths increased, and the total water absorption and voids decreased compared
143 to the reference mixture.

144 In this study, a scientometric analysis was conducted based on the literature published in the Web of Science (WOS),
145 utilizing VOS viewer software for applying CWP in construction materials and infrastructure for the last ten years,
146 from 2014 to 2024. Based on the results of bibliometric analysis (see **Figure 1**) and the literature presented in this
147 study, it was found that ceramic tile waste has been widely used as an alternative to cement, coarse and fine aggregates
148 in various construction material applications, such as ordinary concrete, lightweight concrete, high-strength concrete,
149 cement paste, mortar, geopolymer, and bricks, but its use in grout used for finishing the surface layer of semi-flexible
150 pavement remains relatively underexplored. Most existing research focuses either on the mechanical performance of
151 CWP in conventional concrete or mortar or on the use of industrial by-products in pavement systems. However, there
152 is a noticeable lack of comprehensive studies that evaluate both the mechanical properties and environmental impacts

153 of SFP when modified with CWP. Specifically, the influence of different replacement ratios of CWP on critical
154 performance parameters such as rutting resistance, stability, and compressive strength within the context of SFP
155 systems is not well understood. Additionally, while life cycle assessment (LCA) is increasingly recognized as a vital
156 tool for measuring environmental sustainability, few studies have integrated LCA with performance-based testing for
157 CWP-modified SFP to assess trade-offs between mechanical efficiency and ecological benefits. Furthermore, the
158 microstructural interactions between CWP and other components in the cement grout matrix have not been extensively
159 investigated, limiting the understanding of how these materials contribute to overall pavement durability. Thus, there
160 is a clear need for integrated research that systematically evaluates the mechanical performance, environmental
161 implications, and microstructural behavior of SFP incorporating ceramic waste powder. Addressing these gaps is
162 essential to validate the use of CWP as a sustainable alternative in pavement engineering and to support its adoption
163 in real-world infrastructure projects. This study addresses the existing gap by exploring the effects of partially
164 substituting Portland cement with ceramic waste powder (CWP) at 15%, 20%, 30%, 40%, and 50% in cementitious
165 grouts for SFP surfaces. SFP specimens were produced using a styrene-butadiene-styrene (SBS) as a binder modifier
166 and injected with developed cement grouts, followed by testing for volumetric characteristics and mechanical
167 properties, including the Marshall stability test and wheel truck test (WTT). A life cycle assessment (LCA) was
168 conducted to assess the environmental performance of the different CWP contents in the grouts. In addition to
169 experimental tests, statistical analyses such as quadratic regression, analysis of variance (ANOVA), and Tukey's
170 honestly significant difference (HSD) tests were conducted to evaluate the influence of CWP on the mechanical
171 performance of semi-flexible pavement. These analyses provided insights into significant variations in strength
172 properties, with box plots effectively illustrating data distribution and trends. This study advocates for utilizing CWP
173 in SFP surfaces as a durable, sustainable solution for waste disposal, reducing cement consumption and CO₂ emissions
174 while enhancing SFP performance and durability.

175 2. Materials and Methods

176 The following subsections comprehensively describe the technique and materials used in this laboratory experiment.
177 **Figure 2** depicts the methodology employed in the experimental program for this investigation.

178 2.1. Raw Materials

179 This investigation utilized ordinary Portland cement (OPC), neat asphalt (PEN 40/50), and crushed limestone
180 aggregate, which were sieved and graded to achieve the required gradation for the surface layer. The aggregate
181 gradation used complies with the standards set out by ASTM D7064 (ASTM, 2013e) for open-graded surface courses
182 (See **Figure 3**). **Table 1** presents the aggregate properties used in porous hot mix asphalt. Polymer-modified asphalt
183 (PMA) was produced by adding styrene-butadiene-styrene (SBS) polymer to the asphalt binder at an amount of 5%
184 by weight. This optimal ratio was chosen according to previous research (Al-Nawasir & Al-Humeidawi, 2023b). **Table**
185 **2** describes the engineering properties of neat and modified binders.

186 Ceramic tile waste was collected from commercial remnants and residential construction debris, cleaned of dust, size-
187 reduced using a Los Angeles abrasion drum, ground in a mechanical mill, and sieved through a No. 200 sieve (75 μm)
188 (**Figure 4**). The resulting CWP was utilized to partially replace ordinary OPC in the grout mixture at weights of 15%,

189 20%, 30%, 40%, and 50%, respectively. These percentages were determined according to their fluidity in the grout
190 cone test as per ASTM C 939(ASTM, 2010a). **Figure 5** presents a scanning electron microscopy (SEM) image of
191 ceramic waste powder, illustrating irregularly shaped CWP particles characterized by different sizes and random
192 arrangements. A high-performance grout superplasticizer that uses modified polycarboxylate ether is employed in this
193 investigation as the superplasticizer (SP). The recommended dose of SP is 0.5–2% by weight of OPC. Similarly, the
194 grouting mixture's liquid component is tap water. **Table 3** displays the engineering parameters of the grout materials
195 used in this investigation, while **Table 4** displays the compositions of the SFP mixtures.

196 2.2. Drain-down Test

197 This test measures asphalt drain-down in uncompacted asphalt mixtures at high temperatures, simulating conditions
198 during mixing, transportation, and placement, and is especially useful for porous asphalt mixes. To perform this test,
199 four samples were utilized. Two of them were examined at two different temperatures: the expected plant production
200 temperature and the anticipated plant production +15 °C, in accordance with ASTM D7064 (ASTM, 2013e). As shown
201 in **Figure 6**, the test is performed on a loose mixture in a conventional basket with a 6.3 mm mesh placed over a
202 weighted pan. Following ASTM D6390(ASTM, 2017) , the sample is conditioned in a force-draft oven for 1 hour and
203 5 minutes, then cooled to room temperature. The weight of the separated asphalt and filler in the pan is measured, and
204 the drain-down quantity is calculated using **Eq. 1**.

$$205 \text{ Drain down (\%)} = (D - C)/(B - A) * 100 \quad (1)$$

206 In this context, A is the mass of the empty wire basket, B is the mass of the basket and sample, C is the mass of the
207 empty catch plate, and D is the mass of the catch plate plus the drained material.

209 2.3. Preparation of Sustainable Cementitious Grout

210 Six mixtures were prepared, including a reference control mix with 69% cement and 31% water (45% W/C), and five
211 modified mixtures with 15% to 50% CWP replacing cement, along with 1.5% superplasticizer and 40% W/C, as
212 shown in **Table 5**. These ratios were chosen through experiments using an ASTM cone to measure the flow
213 time(ASTM, 2010a) , and it was found that an optimal time of 11 to 16 seconds, based on the literature (Al-Nawasir
214 & Al-Humeidawi, 2023a; Hassani et al., 2020). The properties of the final cementitious grouts were evaluated for their
215 resistance to applied loads using a tester of compressive strength at 7 and 28 curing ages according to the standard of
216 ASTM C942(ASTM, 2008) (see **Figure 7**).

218 2.4. Preparation of Semi-flexible pavement mixtures (SFP)

219 The stages of preparing sustainable SFP mixtures using CWP incorporated cement grout are summarized in the
220 following steps:

221 Step 1: Aggregate preparation involved sieving and grading to achieve the desired gradation for the surface layer,
222 ensuring proper air voids (25–35%) in accordance with ASTM D7064 (ASTM, 2013 e).

223 Step 2: The aggregate is first heated in an oven at 110°C for two hours, while the asphalt is heated to 150–160°C for
224 one hour to achieve the required viscosity. Finally, the aggregates are mixed with the asphalt at 170°C to ensure
225 homogeneity and complete coverage.

226 Step 3: After mixing aggregates and asphalt, the specimen is placed in a Marshall mold for compaction. A trial-and-
227 error process with different blows (18, 20, 25, 30) determined that 20 blows on each face produced the desired air
228 voids.

229 Step 4: Determining the optimum asphalt binder content is crucial for SFP mixtures, as it must balance the coverage
230 of aggregates without excessively filling voids, which decreases air void percentages and affects drain-down. Three
231 samples were prepared for five asphalt binder contents (4%, 4.5%, 5%, 5.5%, and 6% by total weight) using a mineral
232 filler material of lime dust (LS). Tests showed that 4% asphalt content is optimal for achieving the required air void
233 ratio while ensuring adequate drain-down of less than 0.3%. **Figure 8** shows the drain-down quantity results for
234 various asphalt contents.

235 Step 5: Finally, the specimens are wrapped in plastic and placed on a vibrating machine, gradually adding grout to
236 penetrate the voids thoroughly. Afterward, the plastic cover is removed, and the surface is sprayed with curing material
237 (Set Seal 22) to prevent evaporation and ensure complete hydration before storing the specimens in the lab until
238 testing. **Figure 9** depicts the procedures for producing the SFP mixes.

239 2.5. Volumetric Properties of Hot Mix Porous Asphalt (HMPA)

240 The procedure of estimating the volumetric characteristics for HMPA and SFP specimens is adopted according to the
241 Asphalt Institute manual series No. 2 (MS-2) (Asphalt Institute, 2014) and ASTM D2041 (ASTM, 2015f). These
242 characteristics have a significant effect on the long-term performance of SFP.
243

244 2.6. Marshall Stability

245 The Marshall stability test is commonly used to evaluate the strength, deformation resistance, and load-bearing
246 capacity of the semi-flexible pavement mixture according to ASTM D6927 (ASTM, 2015). The stability of
247 unmodified and CWP-modified SFP mixtures was evaluated at 28 days of curing age (see **Figure 10**).

248 2.7. Wheel Track Test (WTT)

249 The WTT assesses the rutting performance of asphalt mixtures by simulating traffic loads with a weighted steel wheel.
250 The standard permits testing using a cylindrical specimen or a rectangular slab. To replicate the impacts of vehicle
251 loads, an asphalt concrete sample was tested by rolling a steel wheel over its surface after it had been exposed to hot
252 air at 60°C with 10,000 wheel passes, according to the requirement stated by BS EN 12697-22 (BS, 2022). In this
253 study, a manually manufactured wheel truck specimen compactor was used to compact specimens in two layers,
254 adjusting compaction times to achieve the required void ratio, as shown in **Figure 11**. The slab specimens used for
255 the test have the dimensions depicted in **Figure 12**, which are (340×180×50) mm. **Figure 12** illustrates the WTT
256 device.
257

258 2.8. Life cycle assessment (LCA)

259 LCA is considered a powerful tool for evaluating the environmental impacts of products through their entire life cycle,
260 especially when considering a fair comparison between traditional and new products(Sheshadri et al., 2024). A
261 comprehensive LCA was conducted to assess the environmental impacts of mixtures incorporating CWP with different
262 cement replacement levels (15%, 20%, 30%, 40%, and 50%) and compare them to conventional grout mixtures made
263 with 100% cement.

264 One of the best methods to ensure reliable results of the LCA and fair comparison with existing literature is the use of
265 databases where all information regarding the emission factors of different products and processes can be accessed.
266 Estimating fossil fuel depletion and the global warming potential (GWP) of various cement grouts is the primary goal
267 of this work. These factors were considered as they are among the most significant environmental impacts, according
268 to (Marcelino-Sadaba et al., 2017). The system boundary used in this research was “cradle-to-gate”, as it is the
269 preferred and reliable option for the construction sector(Giama & Papadopoulos, 2015). The energy required to extract
270 and manufacture the raw materials, grind the CWP, and combine the raw components to formulate the finished product
271 falls under this category. Since the ingredients might come from anywhere, transportation wasn't considered a
272 significant factor. Similarly, its post-use considerations were not considered because recycling processes for the
273 finished product would remain consistent regardless of ingredient combinations. The data used for calculating GWP
274 and depletion of fossil fuels were obtained from the Ecoinvent 3.8 database, as Ecoinvent is widely the most utilized
275 database for LCA inventories(Lesage & Samson, 2016). The calculation of GWP and the depletion of fossil fuels of
276 each mix was conducted using the OpenLCA software. Quantities of the raw materials for producing 1 m³ of cement
277 grout for each mix were input into the OpenLCA software to calculate their contribution to GWP and depletion of
278 fossil fuels. As highlighted by Huarachi et al. (2020) , CML is among the most widely utilized life cycle impact
279 assessment methods; consequently, the CML-IA baseline method has been employed in this research. This research
280 encompasses the subsequent stages:

- 281 1. The CWP is considered waste material according to (Robayo-Salazar et al., 2017) , and the energy required
282 for the processing of this material is taken into consideration.
- 283 2. The specified product is one cubic meter of cementitious grout.
- 284 3. The calculated environmental impacts are the depletion of fossil fuels and the 100-year global warming
285 potential of cement grouts with different CWP content.
- 286 4. This study adopted a normalization technique due to the varying compressive strengths of the materials,
287 focusing on the environmental effect per MPa of the compressive strength of cementitious grouts modified
288 with CWP at 7 and 28 days of curing.

289 2.9. Statistical Analysis

290 Statistical analyses were carried out to assess the impact of CWP on the mechanical performance of semi-flexible
291 pavement. To predict performance trends, the relationship between cement replacement levels and strength properties
292 was modeled using quadratic regression. Tukey's honestly significant difference (HSD) test was used to pinpoint
293 particular differences between groups after analysis of variance (ANOVA) was used to assess the statistical
294 significance of strength variations across various replacement levels. Additionally, boxplots were used to illustrate

295 trends and possible outliers in the data distribution. These statistical techniques made sure that the impact of CWP
296 incorporation on grout performance was thoroughly evaluated.

297

298 3. Results and Discussions

299 3.1. Volumetric Characterization and Drain-down Testing for HMPA

300 **Figure 13** shows the bulk density test results for the control mixture (CM) and modified mixture (MM) with SBS
301 polymer. The addition of SBS slightly reduced the bulk density (Gmb) of the porous asphalt mix due to changes in the
302 physical and chemical properties of the asphalt binder, which increased its viscosity and toughness. **Figure 14** shows
303 the difference between the CM and the SBS polymer-modified mix.

304 **Figure 15** shows the volumetric parameters for the control mixture (CM) and the modified mixture (MM) with SBS.
305 These parameters are the air voids (VA), the voids in the mineral aggregate (VMA), and the voids filled with asphalt
306 (VFA). The results indicate an increase in VA and VMA, along with a decrease in VFA. The increase occurs because
307 pure asphalt's low strength leads to random aggregate distribution, while SBS-modified asphalt forms a cohesive
308 matrix that better binds the aggregates. Consequently, the increased toughness and flexibility of SBS-modified asphalt
309 result in higher VA and VMA, which enhance grout penetration in SFP mixtures. The decline in VFA values is
310 attributed to the complete dissolution of SBS particles in the asphalt mixture, which absorbs some asphalt and forms
311 hydrogen bonds. This increases the viscosity of the polymerized asphalt and reduces the void ratio filled by asphalt.
312 These findings align with results from a previous study (Gong et al., 2022).

313 Concerning the drain-down test, using polymers or fibers is essential for producing porous asphalt mixes to prevent
314 binder runoff. According to ASTM D6390 (ASTM, 2017). The drain-down percentage should not exceed 0.3%.
315 **Figures 16 and 17** show the drain-down test results for CM and MM at 160 °C and 175 °C. The addition of 5% SBS
316 reduced the drain in the modified mixture by 81%, achieving a permissible limit of 0.25%. This indicates that additives
317 enhance asphalt's adhesive properties and viscosity, stabilizing samples and minimizing moisture infiltration at the
318 asphalt-aggregate interface (Jiao et al., 2019; Mojabi & Mirbaha, 2020).

319 3.2. Characterizing The Performance of SFP Mixtures

320 This section presents the volumetric characteristics and mechanical performance of the SFP mixtures. These
321 characteristics were evaluated for both the control and modified grout mixtures containing various CWP contents.

322 3.2.1. Volumetric Characterization of SFP Specimens

323 The results of volumetric parameters, including VA, VMA, and VFA, of SFP mixtures are presented in **Figure 18**. The
324 results indicate that the values of VA for all mixtures increase with an increase in the replacement percentage of CWP.
325 This noticeable increase is due to the large surface area of CWP as well as its properties and its nature of absorption.
326 When mixed, it does not cause any water absorption and enhances the fluidity and workability of the grout mixture.
327 As a result, due to the hydration heat that the cement releases during the curing process, the water inside the mixture
328 will evaporate. Additionally, the temperature of the surrounding air will cause evaporation, resulting in the formation
329 of voids. The reference mixture (M0) recorded the highest percentage of voids due to the hot weather in summer. The

330 rapid increase in the temperature of the grouting material has a negative effect on the strength of the grout mixture.
331 During the hardening of cement, the temperature of the grout increases. Thus, the water in the grout evaporates,
332 causing rapid hardening because it does not contain SP, which causes shrinkage in the mixture. Shrinkage in the
333 reference mixture leads to the creation of voids, which later cause the formation of cracks. These cracks are weak
334 points in the reference mixture (M0), which weakens the strength of the mix. The rise in VA for all mixtures is directly
335 proportional to the increase in VMA. After grouting is applied through the porous asphalt mix, the characteristics of
336 the grout are affected by the surrounding conditions. Temperature directly influences the hydration process.
337 Temperature variations have a substantial impact on the setting time of grouting material, and an increase in
338 temperature may expedite the condensation of most types of grouting substances. Furthermore, curing temperature
339 has a significant impact on the strength properties of cement grout (Bohloli et al., 2019; Maowa et al., 2023).

340 Koting et al. (2014b) found the air voids of modified SFP mixtures at 28 curing days ranged from 3.0% to 5.8%. At
341 the same time of the curing age, Hou et al. (2015) revealed the VA between 4.8 and 5.1%, while Singh et al. (2021)
342 reported that the final air voids in SFP did not exceed 8%.

343 As for the observed decrease in VFA values, increasing the curing time and cement replacement rates decreases the
344 VFA of the SFP mixtures. This is due to the physical properties of CWP, the specific gravity, particle size distribution,
345 and the large surface area. As the replacement percentage increases, there is a corresponding decrease in the film
346 thickness of asphalt mortar. This effect can be attributed to the porous nature of the mixture, which contains a higher
347 proportion of gravel than sand. Consequently, the binder will effectively coat the larger aggregate granules, resulting
348 in a reduction of voids that would otherwise absorb the asphalt. Instead, these voids are filled by the grout due to its
349 high flowability. This aligns with previous study findings (Singh et al., 2021).

350 3.2.2. Compressive Strength of Conventional and Modified SFP Grouts

351 The compressive strength of the grouts was assessed at 7 and 28 days, as shown in **Figure 19**. The results indicated
352 an increase in compressive strength as cement replacement levels rose from 15% to 30%, followed by a decrease
353 beyond 30%, compared to the reference mix (M0). Specifically, compressive strength increased by 23% (M1), 78%
354 (M2), and 66% (M3) at 7 days, and by 15% (M1), 50% (M2), and 38% (M3) at 28 days, for mixes incorporating 15%,
355 20%, and 30% cement replacement with ceramic waste powder (CWP), respectively. This improvement is attributed
356 to the higher specific surface area of CWP (550 m²/kg) compared to cement (318 m²/kg), which enhances fineness,
357 promotes the formation of calcium silicate hydrate (C-S-H), improves microstructural densification, and accelerates
358 early-age strength development. Conversely, mixtures with 40–50% CWP substitution (M4 and M5) exhibited
359 compressive strength reductions of 13% (M4) and 28% (M5) at 7 days, and 11% (M4) and 27% (M5) at 28 days,
360 relative to the control mix (M0). This decline is due to the fact that replacing more than 30% of cement with CWP
361 slows the hydration process, limits C-S-H gel formation, and reduces the overall quantity of hydration products,
362 thereby lowering strength. Compressive strength testing identified 20% as the optimal cement replacement level with
363 CWP for SFP applications, providing the best balance between mechanical performance and sustainability. Similar
364 trends have been reported in previous studies (AlArab et al., 2020; Hoppe Filho et al., 2021; Jain et al., 2022).

365 3.2.3 Marshall Stability of SFP Specimens

366 The average Marshall stability results at 28 days of curing for both unmodified and CWP-modified SFP specimens
367 are presented in **Figure 20**. The results showed that Marshall stability increased by 13.1%, 22.6%, and 17.6% in the
368 mixtures with 15–20% of OPC replaced by CWP (M1, M2, M3) and decreased by 3.4% and 5.0% in the mixtures
369 with 40–50% OPC replacement (M4 and M5) when compared to the reference mixture (M0). The enhanced stability
370 observed in the SFP samples containing CWP (M1, M2, M3) is attributed to the diffusion of ceramic powder granules
371 within the cementitious matrix and their interaction with portlandite. This reaction promotes calcium silicate hydrate
372 (C-S-H) gel formation, which enhances mechanical strength at 28 days. Furthermore, CWP granules effectively
373 penetrate the voids of the porous asphalt skeleton, filling them completely, contributing to the strength required to
374 withstand applied loads, and thus improving stability. **Figure 21** presents the broken SFP specimens after testing. The
375 reduced stability observed in the mixtures with more than 30% cement replacement by CWP is attributed to a delay
376 in setting time caused by the higher ceramic content. Increasing the ceramic content in the cementitious grout extends
377 the setting time, slowing the formation of hydration products and reducing C-S-H gel development, ultimately
378 weakening the mixture. These findings align with previous research (Li et al., 2022). **Figure 22** presents the SEM
379 images of the reference grout mix (M0) and the optimum grout mix (M2). SEM analysis revealed significant
380 microstructural differences between the control and the CWP-modified grouts. The surface morphology of the optimal
381 mixture (M2) is relatively dense and compact, showing fewer visible pores than the control (M0). The C-S-H gel is
382 clearly visible, forming a continuous and well-connected matrix. The particle sizes in M2 (ranging from 236.0 nm to
383 359.2 nm) appear larger and more agglomerated than those in the control mixture, indicating improved microstructural
384 cohesion. This denser structure suggests increased formation of hydration products and fewer voids, leading to
385 superior mechanical performance. Moreover, the optimized particle distribution of CWP plays a crucial role in
386 achieving desirable performance characteristics, including durability and resistance to environmental degradation.
387 Based on the Marshall stability test results, it was concluded that the optimal replacement ratio was 20% CWP (M2),
388 as it demonstrated the highest stability among all modified SFP mixtures. This same mixture also produced a
389 substantial quantity of C-S-H gel, resulting in a denser microstructure than the control, as confirmed by SEM images.
390 Additionally, it exhibited an ideal flow time that allowed the grout to fully penetrate and fill the voids in the porous
391 asphalt, leaving no unfilled spaces (see **Figure 21**). These findings indicate that incorporating CWP at this specific
392 ratio enhances the mechanical and microstructural properties of SFP and contributes to sustainability by reducing
393 cement consumption and energy required for grinding.

394

395 3.2.4. Rutting Failure of SFP Specimens

396 The results of the rutting depth of SFP slabs conducted at 28 days of curing are presented in **Figure 23**. The rutting
397 results indicated that the reference mixture (M0) exhibited the highest rutting depth value. This effect is due to the
398 low fluidity of conventional grout, which contains only cement and water, and its inability to fill the porous asphalt
399 mixture gaps. Consequently, some voids remained unfilled with grout, which caused weak points in the sample after
400 a wheel passed. In certain areas where grout injection was not present, the device above it collapsed and failed. **Figures**
401 **23** and **24** reveal that all SFP mixtures modified with CWP exhibited less rutting than the reference mixture.
402 Specifically, mixtures with a cement replacement ratio of 15% (M1), 20% (M2), and 30% (M3) showed a decrease of
403 69.96%, 79.55%, and 74.61%, respectively. The mixture with a 20% (M2) cement replacement with CWP showed the

404 least rutting. The remarkable fluidity of the modified grout is responsible for this reduction; it fills up all the spaces in
405 the porous mixture, creating a sturdy structure that can withstand the weight of the device's wheels. Additionally, the
406 high percentage of silica (SiO₂) in ceramic waste accelerates the formation of calcium silicate hydrate gel (C-S-H),
407 which is responsible for resistance and strength at an early age. Concerning the mixes including 40% (M4) and 50%
408 (M5) cement replacement with CWP, a rut depth reduction was seen at 33.33% and 51.94%, respectively. According
409 to **Figures 23** and **24**, the mixture with a 50% (M5) replacement percentage showed resistance to rutting and had the
410 lowest rut depth compared to the mixture containing a 40% (M4) replacement with ceramic waste powder. However,
411 there was significant worry over a noticeable crack on the sample's surface along the wheel tracks. This is because the
412 gelatinous C-S-H becomes less concentrated when the replacement rate exceeds 30%. The wheel movement in a hot
413 air condition at 60 °C causes the grout to become brittle, leading to the formation of cracks under high pressure.
414 Furthermore, the mixture's high fluidity contributed to these cracks. The flow time of the mixture with 50%
415 replacement was measured at 11.2 seconds, resulting in the entire filling of the slab with grouting material. An increase
416 in grout material results in a corresponding increase in rigidity, making it more susceptible to surface crack formation.
417 The previous investigation also observed this phenomenon (Cheng et al., 2023; Dhandapani & Mullapudi, 2023; Tran
418 et al., 2018). The findings of the standardized wheel track test showed enhanced rutting resistance and durability under
419 traffic loading for the investigated specimens, which in turn indicates good long-term performance for SFPs containing
420 CWP as a grout material. The standard test should be carefully followed to simulate the real conditions in the field
421 under variable traffic and environmental loading. **Figure 24** shows the specimens of the wheel truck device after the
422 test.

423

424 3.3. LCA for conventional and sustainable grout

425 3.3.1. Global Warming Potential (GWP)

426 The Global Warming Potential (GWP) results for the different grout mixtures are plotted in **Figure 25-a**. As noted
427 from the GPW results, increasing the percentage of cement replaced with ceramic waste powder (CWP) consistently
428 reduces the GWP of the grout. Specifically, substituting cement with 15%, 20%, 30%, and 40% CWP resulted in
429 reductions of approximately 11.6%, 16.6%, 26.6%, and 36.5%, respectively. The maximum reduction observed was
430 approximately 46.4% for M5, which included 50% CWP. The results of all mixtures after normalization
431 (GWP/compressive strength) are presented in **Figure 25-b**. The data reveal that extending the curing period from 7 to
432 28 days significantly decreased the environmental burden per unit of strength (kg CO₂ eq./MPa) across all tested
433 formulations. These results highlight the potential of CWP as a sustainable binder material, offering a viable
434 alternative to conventional cement in grout production when evaluated from both mechanical and environmental
435 perspectives. Among the tested mixes, the formulation containing 30% CWP (M3) demonstrated the most favorable

436 performance and exhibited the lowest normalized GWP value. This suggests an optimal balance between strength
437 development and emissions reduction, making it a promising candidate for eco-efficient pavement applications.

438 3.3.2. Depletion of Fossil Fuels

439 The depletion of fossil fuels associated with cement grout production incorporating various percentages of CWP is
440 illustrated in **Figure 25-c**. Substituting cement with 15% and 20% CWP resulted in slight reductions in fossil fuel
441 consumption, by approximately 2.9% and 7.8%, respectively. Notably, substituting 50% of cement with CWP resulted
442 in a significant reduction of approximately 37.3% in M5 when compared to the control mixture (M0).

443 The results of different grout mixtures, considering both fossil fuel depletion (MJ) and mechanical performance, are
444 presented in **Figure 25-d**. The findings indicate that the environmental impact per unit of compressive strength
445 (MJ/MPa) declined with increased curing age, which can be attributed to strength gain over time.

446 All grout mixes containing 15% to 50% CWP showed better overall performance at both 7 and 28 days compared to
447 the control mixture. Specifically, mixtures with 15–30% cement replacement exhibited a proportional reduction in
448 MJ/MPa, reflecting an efficient balance between environmental and mechanical performance. However, mixtures M4
449 and M5 showed a marked increase in MJ/MPa despite having the lowest absolute fossil fuel depletion values. This
450 outcome is primarily linked to their relatively lower compressive strength values, which negatively affect normalized
451 environmental efficiency.

452

453 3.4. Statistical Analysis

454 Comprehensive statistical analyses were performed to validate the influence of CWP dosage on the volumetric and
455 mechanical performance of the SFP mixtures. Key properties such as compressive strength (CS), rutting depth,
456 Marshall stability, voids in asphalt (VA), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) were
457 examined if there were any significant differences between the different mixtures using one-way analysis of variance
458 (ANOVA). The variance in CWP content had a significant impact on the mixtures' performance, as demonstrated by
459 the ANOVA results, which showed statistically significant differences for all measured parameters with p-values less
460 than 0.05. Tukey's honestly significant difference (HSD) post hoc test was used to further evaluate the particular
461 pairwise differences between mixture groups. In comparison to the reference mixture (0% CWP) and higher
462 replacement levels, the post-hoc analysis showed that mixtures with 20% CWP showed statistically significant
463 increases in compressive strength and rutting resistance. For every performance metric, boxplot visualizations were
464 also produced, showing the distribution, variability, and central tendency across various CWP dosages. These plots
465 reinforced the observed trends, particularly highlighting the consistent performance enhancement at 20% CWP
466 replacement. Furthermore, the correlation between CWP content and all performance metrics was examined using
467 nonlinear quadratic regression analysis. The quadratic models yielded high coefficients of determination (R^2),
468 specifically $R^2 = 0.834$ for compressive strength, $R^2 = 0.899$ for rutting depth, and $R^2 = 0.855$ for Marshall stability,
469 alongside strong fits for VA, VMA, and VFA ($R^2 > 0.85$). These results suggest a clear nonlinear relationship, with
470 optimal performance observed at intermediate CWP dosages, particularly at 20%. The combined application of
471 ANOVA, Tukey HSD test, boxplots, and nonlinear regression analyses confirms the statistical significance of the

472 experimental results. It underscores the beneficial effect of incorporating CWP in enhancing the performance and
473 sustainability of semi-flexible pavements.

474 The results are graphically presented in **Figures 26-28**, including boxplots for visual comparison, regression analysis
475 plots with R^2 values, and ANOVA bar charts with error bars.

476 **4. Conclusions**

477 This study investigated the feasibility of using ceramic waste powder (CWP) as a partial cement replacement in semi-
478 flexible pavement (SFP) grouts. The study assesses its characteristics on SFP performance through mechanical testing,
479 volumetric analysis, life cycle assessment, and statistical analysis, leading to several key conclusions as follows:

- 480 • Asphalt binder modified by 5% SBS and 20 blows by Marshall hummers for both faces give maximum air
481 voids of 27.8%, which are adequate to ensure the penetration of cementitious grout in the porous asphalt
482 mixture.
- 483 • Using a 4% binder content with a 5% SBS polymer in a porous asphalt mixture formulation improves
484 volumetric properties, gives satisfactory Marshall stability, and reduces the amount of drain-down.
- 485 • Introducing CWP decreases water absorption and improves the grout mixture's flowability, enabling it to
486 completely fill the empty gaps in the porous asphalt mixture's structure.
- 487 • All SFP mixtures with CWP demonstrated improved volumetric properties over the reference mixture,
488 enhancing grout workability and reducing void percentages (Vair).
- 489 • Using 20% CWP in SFP specimens decreased rutting failure by 80% compared to the control mixture (CM)
490 due to improved adhesion properties and active pozzolanic reactions from the high silica (SiO_2) content,
491 which enhances strength through C-S-H gel formation.
- 492 • Replacing cement with 20% CWP enhanced the microstructure density and early strength of cementitious
493 grout, leading to increases in compressive strength and Marshall stability of 50 % and 23 % at 28 days of
494 curing, respectively. This indicates the pozzolanic reaction of CWP and its effective interaction with
495 portlandite to form CSH gel, as evidenced by SEM analysis.
- 496 • Increasing the substitution levels of cement with CWP enhanced the sustainability aspects of the cement
497 grouts.
- 498 • Considering both mechanical and environmental performance (normalization), substituting the cement with
499 up to 50% CWP resulted in better performance relative to the control mixture with 100% cement.
- 500 • Statistical analysis confirmed significant variations in strength properties, with ANOVA showing a p-value
501 < 0.05 and quadratic regression yielding $R^2 > 0.90$. Box plots further illustrated trends, validating 20% CWP
502 as the optimal dosage.
- 503 • Using CWP in grout production reduces CO_2 emissions and environmental impact by decreasing landfill
504 waste from industrial and construction activities. It also lowers cement consumption and minimizes SFP
505 construction costs. This innovative approach contributes to a more sustainable road construction industry and
506 promotes circular economy principles by repurposing waste materials.

507

508

509 **5. Limitations and Future Scope of the Study**

510 While this study provides valuable insights into using ceramic waste powder (CWP) as a partial cement replacement
511 in semi-flexible pavement (SFP) applications, certain limitations should be acknowledged. Primarily, all experimental
512 evaluations were conducted under controlled laboratory conditions, which may not fully capture the variability
513 encountered in real-world pavements exposed to fluctuating traffic loads, environmental stresses, and practical
514 construction challenges. Additionally, the study focused mainly on mechanical and rutting performance at 28 days of
515 curing, without extended evaluation of long-term durability aspects such as fatigue resistance, moisture susceptibility,
516 freeze–thaw performance, or thermal cracking potential. The bonding interaction between the cementitious grout and
517 the surrounding asphalt mix, which is critical for composite pavement integrity, was not explicitly examined.
518 Moreover, although environmental benefits were assessed through a life cycle assessment (LCA), economic aspects,
519 including material costs, maintenance savings, and life cycle cost analysis (LCCA), were not addressed.

520 Although the current research successfully demonstrates the effectiveness of CWP as a sustainable cement substitute
521 in SFP applications, several avenues remain open for further investigation. One key limitation is the experimental
522 setting, which may not reflect the full complexity of field conditions. Therefore, future research should involve
523 constructing full-scale trial pavement sections using the optimized CWP-modified grout. This would allow long-term
524 monitoring of pavement performance under real traffic, climate variations, and environmental factors, offering
525 practical validation of laboratory findings. While the mechanical and volumetric properties of the SFP mixtures have
526 been comprehensively evaluated, the interfacial bond between the cementitious grout and asphalt layer was not
527 directly analyzed. Future studies should investigate this bond in detail to ensure structural cohesion and prevent
528 premature failure under dynamic loading. Another promising research direction involves combining CWP with
529 reclaimed asphalt pavement (RAP) materials. This could further reduce virgin material use, support circular economy
530 practices, and potentially enhance mechanical behavior. Furthermore, extending the testing program to include long-
531 term durability evaluations such as fatigue performance, freeze–thaw resistance, moisture damage, and thermal
532 cracking would provide a more complete understanding of the lifespan and reliability of CWP-based SFP mixtures.
533 Complementing the LCA conducted in this study, a life cycle cost analysis (LCCA) would help assess the economic
534 feasibility of large-scale implementation, offering a comprehensive perspective on both environmental and financial
535 impacts. By addressing these areas, future research can provide a more holistic view of CWP’s potential in SFP
536 systems and support its practical adoption in road construction projects.

537

538 **6. Practical Applications**

539 Despite the limitations of this research, the findings of the experimental tests have significant practical implications.
540 The incorporation of CWP up to 20% as a partial cement replacement in SFP grout formulations has demonstrated
541 substantial improvements in compressive strength and rutting resistance, which translates to enhanced pavement
542 durability and load-bearing capacity. Reducing cement usage contributes to lower greenhouse gas emissions and
543 promotes sustainable construction by valorizing ceramic waste, a material often destined for landfills. This approach
544 aligns with sustainable infrastructure policies focused on waste recycling and resource conservation. The proposed
545 grout mixture can be feasibly adopted in urban roadways where high durability and reduced maintenance needs are

546 desired. Furthermore, the demonstrated environmental benefits indicate a strong potential for inclusion in green
547 building certifications or sustainability rating systems. Future large-scale field trials and cost-benefit evaluations are
548 recommended to facilitate the practical adoption of this sustainable SFP technology in roadway construction projects.
549 The results obtained from the LCA (GWP and depletion of fossil fuels) indicated that incorporating up to 50% CWP
550 in grout production as a replacement for cement improved environmental performance compared to a traditional
551 mixture made with 100% cement. Developing a sustainable SFP by utilizing eco-friendly grout for high traffic loads
552 and harsh conditions with improved environmental, mechanical, and durability performance aligns well with the
553 principles of the circular economy and efficient resource management by enhancing the recycling of waste materials.
554 Providing an optimized mix design for SFP with validated characteristics, including improved compressive strength
555 and volumetric properties, decreased rutting failure, lower CO₂ emissions, and reduced contribution to the depletion
556 of fossil fuels, will be an attractive choice for road construction, especially for heavy-duty applications such as
557 industrial pavements and airport runways. Developing SFP with superior environmental, mechanical, and durability
558 performance could significantly contribute to widening its application as a viable alternative to rigid pavement and
559 conventional asphalt in transport infrastructure, where governments and engineering bodies prioritize the dual
560 objectives of performance and sustainability. The findings of this research indicate the potential of CWP as a valuable
561 source in developing innovative SFP for future applications in industrial pavements and airport runways, paving the
562 way towards sustainable, resilient infrastructure globally.

563

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567

568 **Author Contributions**

569 **Rania Al-Nawasir:** Writing - original draft, Data curation, Formal analysis, Investigation, Resources, Methodology,
570 Visualization, Writing - review & editing. **Basim Al-Humeidawi:** Writing - review & editing, Supervision, Project
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572 **Ali Shubbar:** Writing - review & editing, Software, Validation. **Nasir Khan:** Writing - review & editing. **Muhammad**

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575

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577 The authors declare that they have no known competing financial interests or personal relationships that could have
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580 **Data Availability Statement:** Some or all data, models, or codes that support the findings of this study are available
581 from the corresponding author upon reasonable request.

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Table 1. The physical and chemical properties of aggregate.

Property	Standard	Result
Coarse Aggregate		
Bulk specific gravity, (g/cm ³)	C127(ASTM, 2012)	2.621
Apparent specific gravity, (g/cm ³)	C127(ASTM, 2012)	2.650
Saturated surface dry, (g/cm ³)	C127(ASTM, 2012)	2.603
Water absorption, (%)	C127(ASTM, 2012)	1.4
Percent of fractured surfaces, (%)	D5821(ASTM, 2014d)	95
Abrasion value, (%)	C131(ASTM, 2014b)	22
Flakiness indexes, (%)	D4791(ASTM, 2010)	1.2
Clay lumps, (%)	C142(ASTM, 2010c)	1.36
Fine Aggregate		
Bulk specific gravity, (g/cm ³)	C128(ASTM, 2015d)	2.61
Apparent specific gravity, (g/cm ³)	C128(ASTM, 2015d)	2.87
Saturated surface dry, (g/cm ³)	C128(ASTM, 2015d)	2.67
Water absorption (%)	C128(ASTM, 2015d)	3.95
Clay lumps, (%)	C142(ASTM, 2010c)	0.96

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Table 2. The neat and modified asphalt binder's engineering characteristics.

Test type	Neat asphalt	Modified asphalt	Standard
Penetration (0.1 mm), °C	44	26	D5(ASTM, 2013b)
Softening point, °C	52	70	D36(ASTM, 2014)
Flashpoint, °C	290	350	D92(ASTM, 2002)
Ductility (cm), °C	135	52	D113(ASTM, 2007)
Toughness (N.m)	12.2	33.2	D5801(ASTM, 2006)
Tenacity (N.m)	2.0	18.6	D5801(ASTM, 2006)
Mass change (%)	0.52	0.07	T240(AASHTO, 2013)
Elastic recovery elongation (100 mm), °C	23	77	T301(AASHTO, 2010)

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Table 3. The characteristics of grout materials.

Physical properties		
Property	Type of Materials	
	CWP	OPC
Surface area (m ² /kg)	550	318
Specific gravity(g/cm ³)	2.59	3.14
Loss of Ignition (%)	0.963	3.49
Chemical properties		
SiO ₂ (%)	58.55	22.24
Al ₂ O ₃ (%)	14.99	3.637
SO ₃ (%)	0.4	2.269
Fe ₂ O ₃ (%)	16.82	4.150
CaO (%)	0.39	61.10
MgO (%)	3.46	2.661
K ₂ O (%)	4.20	0.51
Na ₂ O (%)	2.01	0.2

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Table 4. Composition of porous asphalt and grout mixtures for producing SFP specimens.

Mix Composition for Porous Asphalt Skeleton		Composition of Grout	
Composition	Weight (%)	Grout control mix (OPC and water)	0% SP 45 % W/C
Asphalt binder	4%	Grout mixtures incorporating CWP involved the partial replacement of OPC at proportions of 15%, 20%, 30%, 40%, and 50%. The ratios are expressed in terms of the weight of OPC.	1.5 % SP
Filler (limestone dust)	4.78		40% W/C
Aggregate	91.22		
Voids content	27%		
Additive (SBS polymer)	5% by weight of binder		

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Table 5. Grout combination mixes.

Mixture No.	OPC, (%)	W/C, (%)	CWP, (%)	SP, (%)	Flow time, (sec)
Mix0	100	45	0	0	15.9
Mix1	85	40	15	1.5	14.7
Mix2	80	40	20	1.5	13.6
Mix3	70	40	30	1.5	13.1
Mix4	60	40	40	1.5	12.4
Mix5	50	40	50	1.5	11.2