Durability Evaluation: Sustainable Semi-flexible Pavement Mixtures

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Abstract. The modern paving industry requires the production of high-performance pavement using more sustainable approaches. Semi-flexible pavement (SFP), prepared by filling an open-graded asphalt skeleton with cement-based grouting material, has been shown to offer high performance for heavily loaded highway and airport pavement applications. The major aim of this study was therefore to evaluate SFP durability based on more sustainable preparation techniques and materials. In this research, a half warm bitumen emulsion semi-flexible mixture (HWBESFM) was designed using local materials and low energy heating technique; the contribution of various sustainable cementitious grout materials on the durability properties of the mix was then evaluated. The developed grouts were prepared using paper sludge ash (PSA) and silica fume (SF) as supplementary cementitious materials (SCM), and the durability of the HWBESFM was assessed with regard to ageing and water sensitivity. The results showed improvements in water sensitivity of HWBESFM containing OPC+PSA and OPC+SF to 66.62% and 65.73%, respectively, compared with the control mix, which demonstrated sensitivity of roughly 55%. Additionally, slight improvements were noticed in ageing resistance on incorporating SCM, those these results remained uncompetitive to traditional SFP mixtures. Overall, this initial investigation of a sustainable approach could, with some improvement, encourage further development and studies in this area.

Key words
Cementitious grout materials; flowability; paper sludge ash; semi-flexible pavement; silica fume; ageing; water sensitivity.

1. Introduction
There are two main kinds of road pavements generally used for the purpose, namely, flexible and rigid pavements, although roads may also be constructed as a composite of the two by changing the sequence of application. Another type of roadway pavement that exists is semi-flexible pavement (SFP), which offers an alternative to the flexible and rigid pavements [1]. Generally, most paving used in road construction is flexible pavement [2, 3], as rigid pavement is not widely used due to its increased construction time, discomfort for road users (poor riding quality), noise problems with panel surfaces and the joints required for expansion and contraction during service, and high cost of construction [4, 5]; however, it does offer better durability than flexible pavement. Flexible pavements are particularly sensitive to both traffic loads and temperature, and are unable to withstand heavy traffic loads, which cause structural failure [6]. The most important issues with flexible pavements are rutting and cracks due to heavy traffic loads and lack of durability.

The multiple shortcomings associated with the use of the two most common kinds of pavement clarify the importance of SFP as an alternative. SFP, which was developed in the 1950s [7], is made by filling an open-graded asphalt skeleton with air voids of around 25 to 35% [8, 9] with cement-based
grouting material. This supported layering combines the preeminent qualities of bituminous pavements (flexibility) and concrete pavements (rigidity) [10, 11]. Consequently, SFP offers several important advantages, including high load-bearing capacity, high wear resistance, high shear resistance, high water stability, and driving comfort [12]. SFP can thus be applied to areas experiencing both heavy and light traffic, such as industrial areas, harbours, warehouses, distribution centres, road crossing, bus terminals, parking areas, cargo centres, airports pavements, holding bays, and hangar pavements [13, 14].

According to Hou et al. [15], grouted macadam composite materials exposed to moisture offer better sensitivity performance than traditional HMA, which is supports by Bharath et al. [4], Al-Qadi et al. [10], Luo et al. [16], and Wang and Hong [17]. This superiority is in part due to the contribution of cementitious grout materials in terms of additional strength on increased curing time; however, there is another reason, which is the free Ca^{++} that results from the existence of OPC, which improves the adhesion or bond strength between the aggregate and asphalt binder even in the presence of water [18]. Ling et al. [19] reported that, in terms of wheel track testing, permanent distortions in such composite materials are reduced as compared to conventional hot mix asphalt, with dynamic stability improved. With regard to the low-temperature bending test, the flexural tensile strength for semi-flexible mixtures is lower compared to those of conventional hot mix asphalt because of the brittleness of hardened cement slurry. Hu et al. [20] concluded that the SFP has a higher ability to resist high traffic loads as well as the potential to resist permanent deformation under the influence of high temperatures and high loads, consistent with Hou et al. [15] and Ling et al. [19]. Bharath et al. [4] further showed that the indirect tensile strength of cement grouted bituminous mix is 2.5 times that of bituminous concrete, in agreement with Hu et al. [20], who found that the indirect tensile strength of semi-flexible mixtures is greater than that of traditional asphalt mixtures, but lower than that of cement concrete mixtures.

Supplementary cementitious materials play an important role in improving the mechanical properties and water sensitivity of cold asphalt mixtures (CMA), as SCM help reduce the curing time of CMA and allow them to acquire strength more rapidly, thus allowing more timely opening of roads to traffic [21-24]. Half-warm asphalt mixtures have also gained more interest recently due to sustainability aspects, as half-warm bitumen emulsion mixtures (HWBEM) show some advantages over HMAs in this respect [25, 26]. HWBEMs can be prepared using a low energy heating technique which proven to be a successful alternative to traditional heating methods [25-28]. Sustainable approaches have also achieved some success based on the addition of supplementary cementitious material (SCM), with extensive research having proven the validity of this technique in enhancing performance with regard to various sustainability aspects [26-30]. This paper is just one part of comprehensive study that aims to consolidate the benefits from the low energy heating technique and SCM to produce an effective half warm bitumen emulsion semi-flexible mixture (HWBESFM). This study thus investigates the durability of HWBESFM in terms of aging and water sensitivity (TSR).

2. Experimental work

2.1 Materials

Ordinary Portland Cement (OPC) was obtained from the Muthanna Cement Plant; this met the specifications of Iraqi standard No: 5/1984 type I. The physical and chemical characteristics of the OPC are shown in Table 1.

Silica fume (SF) is a by-product material of the smelting processes used in the silicon and ferrosilicon industry. The chemical and physical characteristics of used SF are listed in Table 2. Paper Sludge Ash (PSA) is a waste material generally arising from the paper industry, though in this form it is unavailable locally. A substitute was prepared by preliminary burning of waste paper at 350 to 450 °C, to reduce the material size. The product was then burned at 800 °C for 2 hours to convert it to a pozzolanic material as recommended by [31]. Finally, this was ground in a mill for 30 minutes to simulate real PSA [32]. The chemical and physical characteristics of PSA are illustrated in Table 2.

Superplasticizer (SP), under the trade name MegaFlow 1000, was obtained from CONMIX. MegaFlow 1000 is a modified polycarboxylate ether-based superplasticizer utilising a unique carboxylic ether polymer with long lateral chains. It is an effective cement dispersant and high range water reducer,
as well as increasing fluidification. RO water was used in the development of the cementitious grout mixtures, while tap water was used for curing the samples.

The aggregates (coarse and fine) used in this research were sourced from Badra quarries, located in Wasit city, Iraq. These aggregates were sieved, separated and graded to match the gradation required for surface layer coarseness according to the Anderton [8], to achieve an air voids content within the permissible range of 25 to 35%, and to ensure penetration of the grout into the porous mixture. Figure 1 shows the adopted gradation, classified as an open grade.

### Table 1. Physical and chemical properties of OPC.

| Property                  | Results | Requirement |
|---------------------------|---------|-------------|
| Fineness (m²/Kg)          | 339     | 250         |
| Density (gm/cm³)          | 2.00    | Not specified |
| Initial Setting Time (min)| 148     | ≥ 45        |
| Final Setting Time (hr.)  | 3.15    | ≤ 10        |
| Expansion (mm)            | 1       | ≤ 10        |

| Property | Value | Requirement |
|----------|-------|-------------|
| SiO₂     | 19.91 | Not specified |
| Al₂O₃    | 4.58  | Not specified |
| Fe₂O₃    | 4.83  | Not specified |
| CaO      | 61.10 | Not specified |
| MgO      | 3.14  | ≤ 5%        |
| SO₃      | 2.23  | C₃A ≤ 5% SO₃ ≤ 2.5% |
| Na₂O₃    | 0.20  | Not specified |
| K₂O      | 0.51  | Not specified |
| Chloride | 0.019 | Not specified |
| L.O. I   | 2.91  | ≤ 4.0%      |
| Eq. Alkalis | 0.54 | < 0.6% for low alkalis |

**Figure 1.** Particle size distribution of aggregate.
The filler used in this study was OPC. The type and dose of the filler added to an asphalt mixture provides specific properties to, and plays an important role in determining the overall performance of, the resulting asphalt mixture. The asphalt emulsion used was supplied by the Fosroc company under the trade name Nitoproof 10. Nitoproof 10’s properties, as provided by the manufacture, are summarised in Table 3.

Table 3. Properties of asphalt emulsion.

| Property                                      | Standard ASTM | Limits                                      | Results              |
|-----------------------------------------------|---------------|---------------------------------------------|----------------------|
| Emulsion type                                 | D2397 [33]    | Rapid, medium and slow setting              | Medium setting (CMS) |
| Colour appearance                             | D6934 [34]    | Min. 57                                     | Dark brown liquid    |
| Residue by evaporation                         | D70 [35]      | ------                                      | 1.03                 |
| Specific gravity, gm/cm$^3$                   | D5 [36]       | 100-250                                     | 235                  |
| Penetration, mm                                | D113 [37]     | Min. 40                                     | 44                   |
| Ductility, cm                                  | D7226 [38]    | 110-990                                     | 225                  |
| Viscosity, rotational paddle viscometer 50 °C, mPa.s | D6929 [39]    | Homogenous, broken                          | Homogenous           |
Solubility in trichloroethylene, %

| D2042 [40] | Min. 97.5 | 97.8 |

Emulsified asphalt/job aggregate coating practice

| D244 [41] | Good, fair, poor | Good |

Miscibility

| D6999 [42] | ------ | Non miscible |

Aggregate coating

| D6998 [43] | ------ | Uniformly- thoroughly coated |

2.2 Methods

The production of semi-flexible mixtures required three phases: the design of cementitious grout materials; the design of HBESFM, including the extraction of the optimum percentage of asphalt emulsion; and finally, the injection of cementitious grout materials into the HBESFM specimens to produce semi-flexible mixtures.

2.2.1 Design of Cementitious Grout Mixes.

Extensive and comprehensive laboratory tests were performed to obtain the optimum mixing proportions for cementitious grout materials, as shown in Table 4. A detailed study of the process used to obtain this optimum comprising mixture is published separately [44].

Table 4. Cementitious grout details.

| Mix | % OPC | % PSA | % SF | % W/B | % SP |
|-----|-------|-------|------|-------|------|
| M1  | 100   | 0     | 0    | 0.5   | 0    |
| M2  | 85    | 15    | 0    | 0.5   | 1    |
| M3  | 97.5  | 0     | 2.5  | 0.5   | 1    |
| M4  | 85    | 10    | 5    | 0.5   | 1    |

2.2.2 Design of Half-Warm Bitumen Emulsion Porous Mixtures.

The HBESFM design included the same steps followed in the design of the CMA, as by the American Asphalt Institute MS-14 [45], with one modification: the loose mixture was subjected to microwave heating after mixing at a specific time.

2.3 Preparation of Grouts and HBESFM

Grout was prepared by mixing the dry materials to a homogenised state, then mixing water with SP to homogenization also and combining these mixes. HBESFM was then prepared by mixing the dry materials forming the aggregate and adding the asphalt emulsion to the aggregate using mechanical mixing; the loose mixture after mixing was then subject to the microwave heating for three minutes to produce HBESFM. Finally, 35 blows were applied on each face for Marshall specimens to achieve air voids in the range 25 to 35%; while the American standard ASTM D7064 [46] recommends 50 blows for each face or 50 gyrations for porous asphalt, the required air voids were not achieved by doing this, so 35 blows were used per face instead.

HBESFM specimens were wrapped in a plastic food wrap membrane, and then the cementitious grout materials were injected into the HBESFM specimens to produce SFP, utilizing gravity without the use of vibrators to prevent material separation. After the injection of the cementitious grout materials to the specimens, these were covered with plastic to prevent the evaporation of water. Finally, after the first hardening of the cementitious grout materials, the surface of the specimens was sprayed with a curing material supplied by CONMIX under the name JetCure GP - Clear in order to preserve the internal water and to constrain the hydration processes to the desired form.

2.4 Tests Methods and Conditions
The grout was checked for flowability, which is an important characteristic for grout design, as this is required to ensure complete penetration of HWBESFM specimens; this was achieved by using a flow cone test which conformed to ASTM C 939-10 [47].

An indirect tensile strength test (ITS) was adopted to extract the optimum asphalt emulsion percentage for this research work. The testing program was performed according to ASTM D6931[48] at 25 °C.

The durability properties of HWBESFM mixtures were determined at 28 days using Cantabro abrasion (aged and unaged) according to ASTM D7064 [46]. The specimens were divided into two groups. The first group were not subject to an ageing process, while the second group underwent an ageing process at a temperature of 85 °C for 5 days in a forced draft oven per Bell et al. [49]. Durability was evaluated in terms of water sensitivity (TSR) according to ASTM D4867/D4867M [50] by means of comparing an ITS test at age 28 days in conditioned specimens (immersion in a water bath for 24 hours at 60 ± 1 °C, then 1 hour in a water bath at 25 ± 1 ºC) as compared to ITS at age 28 days for unconditioned specimens (dry).

3. Results and Discussion
3.1 Cementitious Grout Materials

The results obtained from the laboratory flow cone test are illustrated in Figure 2. The optimum mixtures of M2, M3, and M4 give lower flowability than seen in the control mixture, M1, due to the introduction of SP, which plays a major role in the dispersion of cement particles and thus releases some of the water trapped between the molecules. In addition, the surface area of materials affects the flowability, as the higher the surface area, the greater the flow time, in agreement with Fava et al. [51]. The surface area of the PSA is less than that of SF, but the flow time shows the opposite response due to the nature of PSA hydration activity and morphology, which suctions additional water between the particles.

![Figure 2. Fluidity of optimum mixtures cementitious grouts materials.](image)

3.2 Half-Warm Bitumen Emulsion Porous Mixtures

Figure 3 shows that the value of ITS begins to rise initially, reaching its highest value, which is 85.45 kPa, when the bitumen emulsion content is 6.9%; a gradual decrease then occurs as the bitumen emulsion content is increased further. This gradual decrease is due to two reasons: the first is the increase in asphalt film thickness, as a result of the increase of the bitumen emulsion content, which causes contact between the aggregates and the resulting interlock to decrease [52]; the second reason is an increase in the water content, which negatively affects the hydration process of the cement used as a filler material, as during the curing process, the water evaporates and exits the air voids, leading to a decrease in density and
consequently a decrease in the ITS values [53]. From this stage, the 6.9% emulsion content is nominated as an optimum emulsion content for the development of the next stage, the development of a semi-flexible HWBESFM.

![Figure 3. ITS value for HWBEP].(59.81, 64.84, 85.45, 79.12, 75.24)

### 3.3 Durability of Half Warm Bitumen Emulsion Semi-Flexible Mixtures

The durability of a bituminous mixture is defined by its resistance to weathering and the abrasive actions of traffic [54]. Roads are exposed to wear due to repeated traffic, ageing as a result of oxidation and volatilization, as well as water damage as a result of a rainstorm or any other sources of water; all of these have effects on the road’s durability. A Cantabro test was used to determine the resistance to abrasion, and TSR water sensitivity testing was also used to determine resistance to water damage.

#### 3.3.1 Ageing Test

According to ASTM D7064 [46], a Cantabro durability test is recommended for open-graded asphalt mixtures; however, the test has attracted little interest among those testing dense-graded mixtures, as it is recommended that the abrasion loss from this test should not exceed 20% for unaged specimens and 30% for aged specimens. Samples of all mixtures prepared with different cementitious grout materials were tested in this study, however, and the results are displayed in Figure 4. The results demonstrate that the values of Cantabro loss in aged specimens are higher than those in unaged specimens, which is a reflection of the curing that occurs during oven drying, when cracks appear in the cementitious grout material injected into the HWBESFM specimens, reducing adhesion between the grout and the asphalt film. The grout also becomes a brittle material as a result of exposure to heat. The results obtained in this research thus contradict Koting et al. [55], which found Cantabro loss of 12.9, 10.1, and 8.9% and also disagrees with Bharath et al. [4], where the Cantabro loss was 16.1%. The main reason for this is that those studies used HMA in designing porous mixtures, while in the current study, asphalt emulsion was used.
3.3.2

Figure 5 shows the results of ITS and TSR for both conditioned and unconditioned specimens at the age of 28 days. As indicated, unconditioned mixtures containing OPC+PSA+SF showed the highest ITS. However, in conditioned mixtures, the highest ITS value was observed for the mixture containing OPC+SF. The results also indicate that ITS for unconditional specimens is greater than ITS for conditional specimens, suggesting that the deterioration that occurs in the mixtures is the result of adapting the specimens to moisture, which has a significant effect on reducing the ITS of the mixtures. The highest value of TSR for all mixtures was 66.62%, which does not agree with the results obtained by Hou et al. [15], where TSR values higher than 80% were obtained, nor with those of Sun et al. [56], where the TSR values were higher than 90% due to the porous asphalt design based on HMA technology. Importantly, Iraqi specification GSRB/R9 [57] requires that the value of TSR be no lower than 70%.

Figure 4. Cantabro Loss for aged and unaged specimens

Tensile Strength Ratio (TSR).
4. Conclusion

Sustainable paving materials are a key item of interest for current highway and pavement researchers, and conserving high performance while introducing a sustainable approach is a major target. This paper attempted to achieve one step in this development process by introducing a new HWBESFM. Based on an extensive experimental programme intended to evaluate the durability of the HWBESFM, the following conclusions can be drawn:

1. The surface area of cementitious grout materials is highly related to flowability: the greater the surface area, the higher the flowability.
2. Using PSA and SF collectively as SCM with an optimum SP in the production of grout facilitates the development of significant characteristics more than the use of OPC only in terms of mechanical properties as measured using ITS.
3. Sensitivity to water damage for HWBESFM containing OPC+PSA, OPC+SF is better than that of materials containing OPC alone; however, despite increases to resistance, the materials still do not reach specification limits.
4. The Cantabro abrasion results disclose the superiority of the developed HWBESFM over the control mix with OPC; however, the result still much higher than highway specifications.
5. In general, HWBESFM clearly needs further development; however, some promising improvements were made in this study, suggesting that a more extensive development program for HWBESFM would be worth the time and resources required.

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