Semi-Flexible Material: A Solution for High-Performance Pavement Infrastructures

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Abstract. Asphalt pavement technology has been widely adopted due to its good mechanical performance, its excellent surface properties, the ease of construction and driving comfort. Nevertheless, asphalt pavements, commonly also known as “flexible pavements” have demonstrated to present high moisture susceptibility, low resistance to several chemical agents and poor long-term performance. Moreover, both high and low temperatures can produce different damages in flexible pavement such as rutting and cracking. On the other hand, rigid pavements have been losing popularity mainly due to the presence of transversal joints, required to consider the expansion of concrete slabs that produce a reduction of user-comfort and safety. In addition, Concrete pavement need longer construction procedure and a curing time before opening to traffic. Hence, a new technology has been developed in the last years in order to gather the essential properties that characterize rigid and flexible pavements. This technology, usually called semi-flexible pavements, or grouted macadam, consist in producing a highly open porous asphalt mix (voids around 25-30%) and filling the voids with selected cementitious grout. Thus, the ease and speed of construction of flexible pavement, joint with the optimal surface properties is combined with the concrete good mechanical behaviour, resistance to chemical agents and limited temperature susceptibility. The final product is a high performance pavement material, particularly indicated to high traffic volume roads, airports, ports, and industrial areas. However, the fact that this type of pavement is still innovative compared to rigid and flexible pavement has made that there is no standard procedure to produce this type of mixture. For this reason, the characteristics of the mixtures vary with authors and in the different real scale applications. In this manner, this paper aims at studying the most significant advances in the area of semi-flexible pavements, describing, comparing and statistically analysing the different investigation and practical experiences. Mix-design details, i.e., asphalt binder characteristics, aggregate properties and cementitious grout composition are deeply investigated, as well as mixing and compaction procedures, lab testing and real application performance of this innovative and promising pavement material.

1. Introduction

Asphalt pavement technology has been widely adopted due to its good performance and driving comfort, in addition no shrinkage in joint, good anti-skid performance, low driving noise, short construction duration and easy maintenance. However, flexible highway pavements have demonstrated to have poor resistance to aging, inadequate moisture susceptibility and temperature stability \([1]\). On the other hand, in terms of comfort for users, rigid pavements have been losing popularity mainly due to the presence of transversal joints, required to combat thermal movement of concrete slabs. Thus, in the last 50 years...
a new pavement technology has been developed in order to improve the pavement performance, users comfort and prolong the lifetime of roads [2]. This technology, usually called Semi-flexible pavements (SFP), grouted macadam or Asphalt-Portland cement concrete composite (APCCC) [3] consists in producing a highly open porous asphalt skeleton (voids ratio around 25-30%) and filling the voids with selected cementitious grouts.

Multiple advantages have been attributed to this technology such as excellent skid resistance, good oil-resistance and colourability, high static bearing capacity and rutting resistance. Besides, its viscoelastic behaviour can ensure a higher tolerance of loads without causing any ruts and reduce the quantity of temperature joints or even make it unnecessary to set, which leads to an improvement of the driving comfort [4,5]. Nevertheless, the performance of semi-flexible pavements constitutes a poorly understood branch of pavement technology whose performance is based on empirical evidence and not on theoretical formulations that describe the mechanical behaviour of this material [6]. As an another disadvantage, SFP have to be constructed on two stages: (i) hot mix porous asphalt layer and (ii) the porous asphalt layer has to be filled with the grouting materials, which causes an increase in construction time compared to a traditional flexible pavement construction process.

Regarding to the use of SFP, [3] state that semi-flexible pavements have been extensively used in Europe since 1964 and tested in the United States in the early 1970s with no positive results. However, further studies showed that this hybrid material provides good rut resistance and performance against fuel spillage and abrasive forces. Hence, it has been demonstrated [7] that those properties allow it to have multiple applications in pavements frequently associated with heavy and slow traffic, e.g., industrial areas, harbours, warehouses, road crossing, bus terminals, cargo centres, airports [4,8]. Some investigations affirmed that the application of SFP in airports has been the result of the maintenance cost of cement concrete airport pavements that tend to get very high and the need for more flexible airport pavement that can obtain deformations without cracking [8]. As real examples of applications, there were constructed 165,000 m² of semi-flexible pavement in Copenhagen Airport and the pavement outside the Delft railway station in Netherlands [9].

Taking into account the above and given the importance of developing new asphalt pavement technologies, this paper describes the most significant advances in the area of SFP pavements. First in the article, a tour of each of the elements that make up the mix is present, including (i) mineralogical and mechanical properties of aggregates and size distributions used in grouted macadam, (ii) asphalt binder properties and (iii) cementitious grout components and properties. Then, laboratory mixing and compaction procedures are reviewed. Besides, the performance of grouted macadam is reviewed by means of mechanical testing and full-scale testing. Finally, general discussions and conclusions are presented.

2. Mixture components

2.1. Aggregates

Aggregates properties have a significant influence on the mechanical and volumetric behaviour of concrete mixes. In this manner, pavement technologists have established specific properties that aggregates used for roads must meet, e.g., gradation limits, resistance to degradation, etc., either for flexible pavement or for rigid pavements. However, due to the lack of procedures for designing semi-flexible mixes, there is not a standard methodology that establishes what properties aggregates used for semi-flexible pavement must meet. Hence, the properties of the aggregates used for the production of SFP vary according the authors or patents [10]. Nevertheless, the standardized properties of aggregates used for open-graded asphalt mixtures are usually adopted for producing grouted macadam asphalt skeleton. Studies conducted by [8] shows that the compressive strengths of SFP are highly influenced by the strength of the aggregates. Hence, [11] states that the aggregates used in this type of mixtures must consist of sound, durable, stiff particles crushed and sized to provide an adequate gradation.

It is well known that aggregate gradation is a noteworthy characteristic of asphalt mixtures due to its influence on total voids of the mix, which influences mechanical properties such as resilient modulus
and indirect tensile strength. Thus, resilient modulus on grouted macadams are significantly affected by the changes of aggregate gradation. According to [12] the resilient modulus in SFP increase with the increase of voids because there is more volume of porous to be filled with cementitious material. Then, [13] state that it is necessary to study the effect of aggregate gradation on grouted macadams. Figure 1 shows various gradations used for producing grouted macadam. It can be noticed that the gradations are single sized aiming at achieving the desired voids in mix, in order to facilitate rapid impregnation of cementitious grout. Nevertheless, the grouting results of asphalt mixture skeleton is not related to the initial volume of voids but by the morphological characteristics of voids, pore structure and size [13,14]. Thus, the selection of the size distribution of aggregates is mainly determined by the need to provide void interconnectivity and adequate porosity [13,15].

![Graph showing various gradations used in SFP.](image)

**Figure 1.** Aggregate gradations used in SFP.

### 2.2. Asphalt Binder

The asphalt binder used for producing grouted macadam also varies depending on the author or patent. In general, it can be found that most used bitumen types for SFP are usually bitumen 60/70 [1,17], bitumen 80/100 [7], bitumen 100/150 [18], bitumen 160/220 [10,19] and SBS modified binder [20]. Notwithstanding, [16] suggest that the selection of the type of binder should always dependent of the location of the site and weather conditions.

Regarding to optimum binder content (OBC) [13] states that porous asphalt mixes usually have less bitumen than that of conventional dense mixtures. Thus, several methods based either on empirical formulas or laboratory tests specified in design guidelines set in investigation on open graded asphalt design have been used in last years. [3,7,15] used the empirical formula proposed by [21] based on the specific area of aggregates. However, for many authors the bitumen content obtained through empirical formulation is simply an initial value, which it is split to evaluate other contents. In general, laboratory tests including porosity test, Cantabro scattering loss [13], binder drainage [13,22,23] and Marshall procedures [24] have been used to determine OBC. According to [15] SFP has a prospect to be designed SFP as high-performance pavement, thus, he conducted other tests aiming at selecting the optimum bitumen content. In his investigation, the optimum bitumen content was selected based on high mix performance parameters including: indirect tensile strength, stiffness modulus, unconfined compressive
strength, resistance to abrasion test and hydraulic conductivity. Table 1 presents the limits for the determination of OBC used in [25].

Table 1. Limits used by Kumar (2017) [25]

| Limit       | Porosity | Cantabro scattering loss | Binder drainage |
|-------------|----------|--------------------------|------------------|
| Minimum     | 20%      | Maximum                  | 20%              |
| Maximum     | 5%       |                          |                  |

2.3. Cementitious Grout

Cementitious grout is one of the most important materials that compose the mixture. It was found in the research and application of SFP that the key issue of this material is the performance of the cementitious material due to the fact that the strength of the hot mix grouted macadam is predominantly influenced by the strength of the cementitious grout [8]. In general, Portland cement, water and chemical admixtures, compose the cementitious grout. However, the use of sand in the composition of cementitious grout has also been documented [26].

In general, superplasticizers e.g., naphthalene and polycarboxyoxylene-based superplasticizer (PS) and flexible admixture belong to the most common chemical admixtures used in the cementitious grout. Superplasticizers or high range water reducer (HRWR) is known as it allows a significant reduction in water/cement ratio while maintain the desired pourable consistency [12]. In fact, the main requirement for fluid grout is to have a pourable consistency that allows rapid penetration into the asphalt skeleton. Thus, a flow cone test is usually performed in order to assess the workability the cementitious grout [27]. Bearing this in mind, [27] studied the influence of three types of superplasticizers while varying the water cement ratio in the workability and mechanical performance of cementitious grout used in SFP. He found, as expected, that SP plays a significant role in producing high workability for the grout, however, the mechanical influence of SPs was not clear. Moreover [26] conducted a study where the effect of a polycarboxylic acid-based SP and a naphthalene-based SP on cementitious grouts containing sand were evaluated by means of consistency test and mechanical performance. As a result, it was evidenced that the flowability of the cementitious material increased with the increase of W/B ratio and superplasticizer dosage and decrease with the decrease of S/B ratio. Regarding to the type of plasticizer, it was found that the dosage of the polycarboxylic acid type was nearly half of the naphthalene type when the same flowability was achieved. However, considering the economic efficiency and the effects of naphthalene based SP, a dosage of 1% is acceptable for this type of SP [28]. Table 2 presents various ingredients and doses used for producing cementitious grout.

Table 2. Various conventional ingredients and doses

| Water-cement ratio | Polycarboxylate SP content (%) | Naphthene SP content (%) | Expansion admixture content (%) | Sand (%) | Reference |
|--------------------|-------------------------------|--------------------------|---------------------------------|----------|-----------|
| 0.55-0.57          | 0.5-1.0                       | -                        | 10%                             | -        | [5]       |
| 0.50               | -                             | -                        | -                               | -        | [25]      |
| 0.45               | 0.25-0.30                     | -                        | -                               | 10-33    | [26]      |
| 0.40-0.50          | -                             | 0.40-0.60                | -                               | 25       | [26]      |
| 0.30               | 3.5wt%                        | -                        | 5 wt%                           | -        | [31]      |
| 0.60               | 1%                            | -                        | 2% (flexible admixture)         | -        | [28]      |
| 0.75               | -                             | -                        | -                               | 20       | [32]      |

According to [26] high W/B ratio and dosage of superplasticizer may induce the bleeding phenomenon and segregation of the mortar, in addition to a decrease in mechanical properties [28]. In
addition, [28] state that if the cement slurry fluidity is too high, it would not be able to easily permeate in full depth the asphalt mixture skeleton. However, if fluidity is too low, the cementitious material may drain out from bottom or lateral side. Thus, they state that cement slurry with fluidity between 9 and 13 s is acceptable, which nearly agrees with the range recommended by [3]. Taking this into account, the lower water/cement ratio should be selected uttermost when the cementitious grout has already met the grouting requirements.

Despite the widely use of conventional materials for the grout composition, other authors have suggested the use of other ingredients as supplementary cementitious materials. Zhang and his colleagues [2] conducted a study aiming at investigating the effects of composition and formulation of cementitious grout containing fly ash and powder. They found that for the cement paste as grouting material for SPF, water-cement ratio possesses the largest effect on fluidity, strength and drying shrinkage, followed by fly ash and mineral powder. Similarly, [30] evaluated different types of cementitious grout containing Portland cement, silica fume, fly ash and silica sand. In addition, detailed cementitious grout composition of resin can be found on literature. Table 3 shows the proportions of resin-modified cement slurry commonly found.

| Reference       | Portland cement (%) | Sand (%) | Fly ash (%) | Modifier (%) | Water (%) |
|-----------------|---------------------|----------|-------------|--------------|-----------|
| UFGS [29]       | 34-40               | 16-20    | 16-20       | 2.5-3.5      | 22-26     |
| Al-Qadi et al. [3] | 38.50               | 12.70    | 19.20       | 2.8          | 26.8      |

3. Laboratory mixing and compaction procedures

In general, it has been found that the mixing and compaction procedures are the same to that of conventional hot mix asphalt. Depending upon the type of specimen produced, i.e., cylindrical or slabs, the compaction method varies. Typical Marshall procedure has been used to compact asphalt mixture cylindrical skeleton specimens for SPF, however, gyratory compaction is also documented for producing grouted macadam [10, 33]. As stated in [34], Ahlrich and Anderton [35] conducted a study aiming at determining the energy compaction by means of Marshall blows that have to be applied to specimens in order to produce air voids content in the range of 25 and 30%. It was found that this compaction energy was equivalent to 25 blows applied to only one side of the specimens. Likewise, [3] also evaluated the air voids as a function of Marshall blows and found that a compaction 10 blows at each surface was adequate for achieving the required air void content. Nevertheless, 50 blows on upper and lower face of the sample are applied in recent studies [12,13,22,23].

| Test                          | Standard      | Evaluation indexes          | Reference          |
|-------------------------------|---------------|-----------------------------|--------------------|
| Marshall Stability and Flow*  | ASTM D 1559   | Marshall Stability and Flow  | [1,3,5,18,25]      |
| Indirect Tensile Strength*    | ASTM D 4123   |                             | [3,18,26]          |
| Resilient Modulus             | ASTM D 4123   |                             | [3,12]             |
| Compressive Strength*         | ASTM D 1074   | Retained indirect tensile strength | [1,3,512,23,18,26] |
| Modified Lottman Test         | -             | Retained Marshal Stability   | [1]                |
| Immersion Marshall test       | ASTM D 1559   |                             |                    |
Wheel tracking test AASHTO TP 63-07 Rutting depth and dynamic stability [1,18,25,26,28] /* Also conducted on asphalt mixture skeleton.

4. Performance of lab produced grouted macadam

In the study of the mechanical performance of SFP, several variables including w/c ratio, binder type, gradation, etc., have been studied over the years. In general, the following test presented in Table 3 have been used in order to assess the mechanical performance of SFP.

4.1. Mechanical testing

Early studies conducted by [3] determined the effect of moist curing on the properties of SFP. It was found that stability tends to increase with the increase of moist curing time, which agree with recent studies conducted by [25]. Nevertheless, studies conducted by [24] showed that no significant difference is found when having more than 90 days of curing. On the other hand, [1] found that Marshall Stability increase along with the air voids of asphalt mixture skeleton. The reason stated by Cai and his colleagues [1] is that when the air voids in the asphalt skeleton increase, there is more space to be filled with the cementitious grout and the strength of grouting material is much higher than that of the asphalt mixture skeleton. Thus, the greater grouting volume, the better high temperature performance [24]. Similar results were found with Wheel tracking test.

[3] evaluated the Indirect tensile strength of lab-produced SFP specimens. It could be evidenced that though the ITS of SFP and HMA are similar when tested after one-day curing, it increases significantly with the increase of curing time. However, the difference in resilient modulus between different moist curing periods was found to be minimal. It was also found that the resilient modulus was higher for SPF when comparing to conventional HMA, which agrees with [12]. In fact, after 28 days the resilient modulus of SFP was the double to that of HMA. On the other hand, [1] state that the moisture susceptibility is also an important indicator to reflect the filling degree of grouting materials in composite grouting material. In their investigation they found that to meet moisture susceptibility requirements, air voids should be at least 21%. Similarly, [3] found that SFP have higher moisture resistance compared to control mix SM-5. In general, it was found that all tensile strength ratio and resilient modulus ratios of grouted macadam’s exceed 75 and 80% respectively.

Furthermore, [13] compared the grouted asphalt mixes with ordinary porous asphalt mixes. By means of rutting resistance, Grouted asphalt mixture exhibited higher resistance to rutting compared to that of ordinary porous asphalt mixture. According to [13,36] this is due to the process related to the grouted material mechanisms including solution process and hydration process. In this manner, the fiber-like hydrated products are generated between the cement slurry and asphalt film on the aggregates. Thus, the matrix of hydrated products and asphalt film wraps aggregates closely, which improves the whole strength and high temperature performance. In the same way, [26] performed Wheel tracking on SFP and obtained a dynamic stability of 36000 cycles/mm, around 10 times higher of that obtained with regular polymer modified asphalt concrete. Similar results were found by Ding et al., 2011 [31] with 30000 cycles/mm and [24]. Therefore, from comparison it can be concluded that SFP have greater potential to reduce permanent deformation under high temperature conditions [24].

Regarding to the low temperature performance, studies reported by [1] showed that low-temperature bending properties such as flexural-tensile strength, maximal flexure-tensile strain, flexural-tensile stiffness modulus and energy density are higher in asphalt mixtures containing high-performance cement pastes when compared to AC-16 mix performance. Hence, the slightly better low-temperature performance compared to that of AC-16 is evidenced. Furthermore, when comparing the splitting tensile strength and failure tensile strain it can be evidenced that those containing cementitious grout are lower than that of AC-16, which is also evidenced in [24]. This is attributed to the hardened cement past filled in porous asphalt skeleton. It has been stated that the reason of the above is that grouting material has a greater strength and brittleness compared with the ordinary asphalt mixture, which results in an increasing modulus and decreasing strain. The same results were reported by [13,24] In conclusion,
better low-temperature and crack resistance are obtained with SFP when comparing to conventional HMA.

In addition to low-temperature performance, it has been found that when air voids are increased, the low temperature properties become poorer [24]. Hence, [1] states that low-temperature performance of SFP reaches its optimal state when the target air voids of the asphalt mixture skeleton are between 23 and 25%.

4.2. Fatigue and durability
Authors [1] evaluated the durability of SFP by means of the rutting depths. It was found that the rutting depths of grouting material mixture are significantly lower than that of AC-13 specimens, which indicates SFP has better rutting resistance and water damage performance than that of AC-13. Besides, [23] also found that SFP exhibited higher compressive resistance and durability compared to conventional flexible pavement resistance of 3Mpa. Nevertheless, asphalt mixture with different material composition offers different service performance. Bearing this in mind, [8], studied SFPs composed with different grouting materials containing silica fume, fly ash, Pozament and OPC obtaining compressive strengths of 11.85, 13.82, 13.71 and 13.82 at 28 days of curing respectively. In general, it is stated that for a fully hydrated composite, the strength of SFPs is approximately 11% of the strength of the cementitious grout. Beside this, it was found that compressive strength is more affected by the particle strength of the aggregates used and the structure of pores than the shear strength of the skeleton. In this investigation, the compressive strength of grouted macadams was approximately 25% of cement concrete specimens.

Other studies have been conducted regarding the thermo-response of SFPs. [33] performed a study where the compression strength of cubic specimens after both fire and high temperature test were performed. It was found that the compression resistance of SFPs decreases after being subjected to fire test. However, compared to conventional HMA, SFPs exhibits a better response to high temperature conditions. This is probably due to presence of a non-thermo-dependent material such as the grouting material. [10] concluded that the influence of temperature on the mechanical properties of SFPs is more significant in terms of stiffness modulus instead of other properties such as fatigue performance, where minimal effect of temperature is observed when its kept under 20°C. In fact, the results showed that only when the temperature is increased above the softening point, the fatigue line of the mixture is changed.

Fatigue life of is traditionally defined by the number of load applications that can subjected to a material before failure a particular stress or strain level [37], which make this a noteworthy parameter in pavement design. Taking this into account, [10] evaluated the influence of multiples parameters on the fatigue performance of SFP. Among the main results it was found that (i) mixtures containing low dosages of binder presented a reduced fatigue performance (ii) the resistance to thermal cracking is related to the thin binder film, i.e., mixture with thick bitumen film exhibit the better resistance to thermally induced cracking, and (iii) polymer modified bitumen have a positive influence in the fatigue behaviour of SFPs without compromising the modulus of the mixture. In addition, [38] presented a series of laboratory test performed at the University of Nottingham aiming at contributing to a better understanding of the fatigue behaviour of semi-flexible pavements. It was found that the traditional failure criterion, i.e., half of the initial stiffness value, demonstrated a difference in the stiffness reduction curves for grouted macadam and DBM 50 (conventional asphalt mixture in United Kingdom). Consequently, the traditional failure criterion may not represent adequately the fatigue behaviour of SFPs.

5. Conclusions
According to the reviewed researches about semi-flexible pavement, and based on its pavement performance, i.e., high-temperature performance, low-temperature performance, durability, etc., it can be concluded that this material represents a solution for high-performance pavement infrastructure. Nevertheless, efforts have to be done in order establish a standard mix design methodology.

The following are the main points concluded in this paper.
Aggregates properties have a significant effect on the mechanical and volumetric response of semi-flexible pavements.

The mechanical performance of the cementitious material significantly is significantly related to the mechanical response of semi-flexible pavements.

Having higher grouting volume implies better high-temperature performance.

In comparison to conventional asphalt mixtures, semi-flexible pavements exhibit a better moisture, low-temperature and crack resistance.

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