Semi-Flexible Pavement: A Review of Design and Performance Evaluation

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Abstract. It is known to researchers in the field of road construction and development. Three types of pavement are rigid, flexible, and composite paving. The composite pavement consists of a layer of flexible pavement on top of which a layer of rigid pavement is placed or vice versa. All of these types have advantages in addition to disadvantages that affect road performance on the one hand and user convenience on the other. About 50 years ago, work began establishing a type of pavement characterized by its semi-flexible performance, which combines rigid pavement's rigidity and flexible pavement's flexibility. It is called semi-flexible pavement and grouted macadam in some sources. It consists mainly of an open-graded asphalt mixture in which the percentage of air voids ranges from (25 to 35%), and in some sources, it is mentioned that it ranges between (20 to 28%) grouted with a high-performance cementitious material. Work began on this type of pavement in the sixties of the last century. However, there is no approved specification for its design, as its design methods differ according to the researcher's vision. This scientific paper aims to facilitate the way for new researchers in this field by knowing the basic stages of semi-flexible pavement design and presenting the existing design methods and what is required for laboratory tests to evaluate the performance of the completed pavement design. It was found that the performance of semi-flexible paving depends mainly on the bonding between its components, as it is considered a composite material. For this reason, the direction in the future may be to study the bonding between asphalt and cement, in particular, as they are two basic materials in their composition.

Keywords: Semi-flexible pavement; review; performance; evaluation.

1. INTRODUCTION

Developing and establishing transportation roads is one of the signs of the progress and development of countries; on the one hand, it is directly related to users' convenience. It is known that there are three types of paving, namely flexible, rigid, and composite paving. These types are subject to damages due to high traffic loads or obsolescence in the pavement created due to weather conditions. In the last 50 years, the technology of creating a new type of pavement has been developed to improve performance, increase user comfort, and extend the builder's life [1]. This type of pavement is called semi-flexible pavement (SFP), also known as grouted macadam surfacing or resin-modified pavement [2, 3]. Semi-flexible pavement is a composite pavement made by grouting cement slurry into a porous asphalt mixture with voids percent between 20% and 28% [1] or between 25% and 35% [4,5]. This type of pavement Combines the flexibility of a flexible paving component with the rigidity of a rigid paving component, as shown in Figure 1 [6].

Figure 1: Open-graded asphalt mixture photograph [6].

Using this type of pavement as a surface layer may be an alternative solution to reduce the disadvantages of both previous types [7]. Early 1970s tests in the United States produced no conclusive results. Still, subsequent research revealed that this hybrid material provides high rutting resistance and a good performance against fuel spillage and abrasive forces. This type of pavement has been used extensively in Europe since 1964. [8]. These characteristics allowed this type of pavement to be used in road sections subjected to high and slow traffic loads [8, 9]. Generally, SFP has high resistance to rutting and less shrinkage compared to the traditional asphalt mixture [10,11]. As real examples of applications, 165,000 m2 of semi-flexible pavement was constructed at Copenhagen Airport and the pavement outside the Delft railway station in the Netherlands [12]. This scientific paper aims to present different design and performance evaluation methods for this type of pavement. As mentioned previously, this type of paving design is not subject to specific controls but differs according to the researcher's vision. Therefore, different design methods have been observed in terms of determining the gradation and optimal asphalt content for the porous mixture or in terms of design for grouting material and its components.

2. METHODOLOGY FOR THE COMPONENTS OF SEMI-FLEXIBLE PAVEMENT AND DESIGN

The traditional SFP consists of a porous asphalt mixture with a void ratio of 25% to 35%, which is filled with high-fluidity cementitious grout [4]. This type has traditionally been used as a specialized surface to benefit from its excellent resistance to both fuel spills and deformation. However, paving layers containing these materials are rarely used and are determined based on successful past performance. This has led to the emergence of different design methods in different countries [13]. In general, the process of designing SFP goes through two stages. The first is designing the porous asphalt mixture with an acceptable ratio of air voids. This stage includes determining the optimal amount of bitumen and the gradation of the required aggregate. The second stage is to design the appropriate grouting material in terms of compression resistance, flexural resistance, and fluidity. These stages will be explained separately in the next paragraphs.

2.1 Porous Asphalt Mixture Design

The process of designing the porous asphalt mixture includes determining the optimum binder content, appropriate aggregate gradation, and compaction effort.

2.1.1 The Optimum Binder Content:

The type of asphalt used in the production of the porous asphalt mixture for grouting purposes is the type of asphalt with penetration of 60-70 and more concerning the cold weather in which it is produced for service [14] suggested that the type of asphalt used always depends on the work site and the weather conditions of the area. Asphalt with low viscosity and low penetration, rubber asphalt, SBS asphalt, and high-viscosity asphalt can increase the strength of the mixture and reduce Cantabro loss. However, the effect of the type of asphalt is small on the ratio of voids, strength, and moisture resistance of the semi-flexible paving [15,16]. Normally, the optimal asphalt content for porous asphalt mixes is less than that of conventional densely graded asphalt mixes [17]. In reviewing previous studies, two methods of extracting the optimum asphalt content were observed. The first one was an empirical formulation to extract the optimal asphalt content theoretically based on the specific area of the aggregates [18, 19] by using Eq. (1) [18].

$$\mathrm{OBC} = 3.25\,(\alpha)\,\Sigma 0.2 \tag{1}$$

$$\alpha = 2.65/\mathrm{SGagg} \tag{2}$$

$$\Sigma = 0.21C + 5.4S + 7.2s + 135f \tag{3}$$

where: OBC = optimum bitumen content, SGagg = apparent specific gravity of aggregate blend, Σ = specific surface area, C = percentage of material retained on 4.75mm sieve, S = percentage of material passing 4.75mm sieve and retained on 600μm sieve, s = percentage of material passing 600μm sieve and retained on 75μm sieve, f = percentage of material passing 75 μm sieve.

The volume of the asphalt and the aggregate's total surface area can be used to calculate the asphalt-to-aggregate ratio. According to Chinese specifications for the construction of highway asphalt pavement, when the asphalt layer covering the aggregate is between 10 and 14 micrometers thick, the asphalt mixture is stable enough to withstand material flow. [20]. The second method is based on the laboratory test, which includes the porosity test, Cantabro loss test [17], binder drainage [17,21,22], and Marshall procedures [23]. Another method Bharath et al. [24] used is the optimum bitumen content for the high voids bituminous mix, which was determined based on a drain-down test. The maximum drain-down loss was taken as 0.3 percent [15]. The type of asphalt binder used is usually SPS-modified asphalt, 60/70 penetration asphalt, and 50/70 modified with polymers. Table 1 shows different types of asphalt in addition to their amount, the effort of compaction, and the percentage of air voids that were reached for a group of previous studies.

Table.1: Different asphalt binder types used in previous studies.

Reference	Type of binder	% Binder	Compaction effort	% Air voids
Luo et al. [20]	SBS modified asphalt	3.4-3.2	50 blows on both sides	22.47-24.34
Hasan and Sugiarto [25]	60/70 penetration asphalt	3.5	-	24.7
Hou [26]	SK-90	3.8	50 blows on each side	29.5
Solouki et al. [27]	PmB 25/55 modified bitumen	4.2	gyratory compacter 50 cycles	25-30%
Al-Taher et al. [28]	60-70 penetration	4.4	50 blows	24.6
Gong et al. [29]	Pen 70 asphalt SBS- modified asphalt High-viscosity-modified asphalt	The binder-aggregate ratio of 3%	-	32.18 31.6 31.38
La Agostinacchio et al. [30]	50–70 (modified with polymers).	5% 4.5%	g 20 blows to the specimens	20% 25%

2.1.2 Aggregate Gradation and Blending

The gradation of the aggregate used to produce the porous asphalt mixture varies according to the percentage of required air voids, which ranges between [31] (%32-25) or between (18-22%) [32]. But more than 20% is generally considered acceptable for grouting purposes. Two main points that control the selection of aggregate gradation for the porous asphalt mix are the ratio of the air voids and the internal connection between the voids to facilitate the penetration of the high-fluidity grouting material [15]. The porous asphalt skeleton's mechanical properties were crucial in selecting the optimum bitumen content and type. It is well known that the gradation of aggregates is one of the noteworthy properties specified for asphalt mixtures due to its direct effect on the size of the total voids of the mixture, and this, in turn, affects the mechanical properties such as the resilience modulus and indirect tensile strength, as the resilience modulus of semi-flexible paving is strongly affected by changes in the overall gradient, as it increases with the increase in the proportion of voids Due to the presence of a larger volume of voids, it can be filled with cement materials [31]. Good gradation also increases compressive strength and provides internal connectivity between voids [33]. The coarse gradation can provide the porous mixture's required properties to facilitate the injection material's penetration [15,17]. During the review of previous studies, it was noted that two types of gradients were used in the production of the porous asphalt mixture, the first containing a more significant number of fine sieves, which are less than 4.75 mm [34] and the second type was used a high percentage of coarse aggregate [28]. Figures 2 and 3 show these two types, respectively, from previous studies.

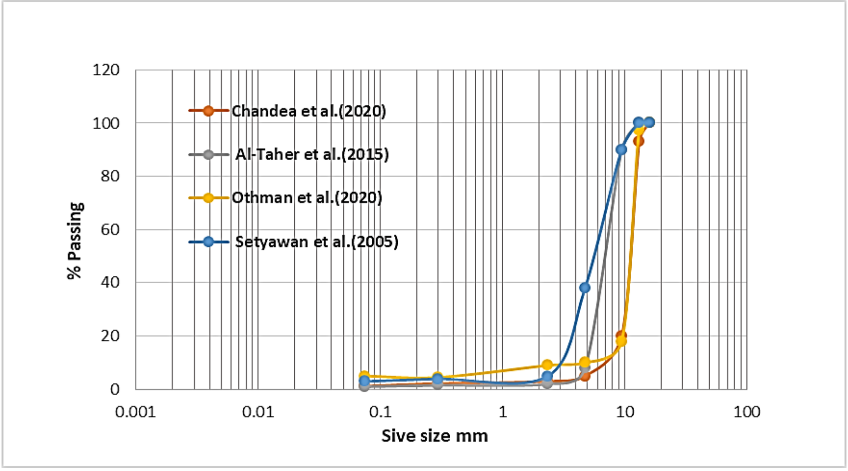

Figure 2: Various coarse aggregate gradations from the literature.

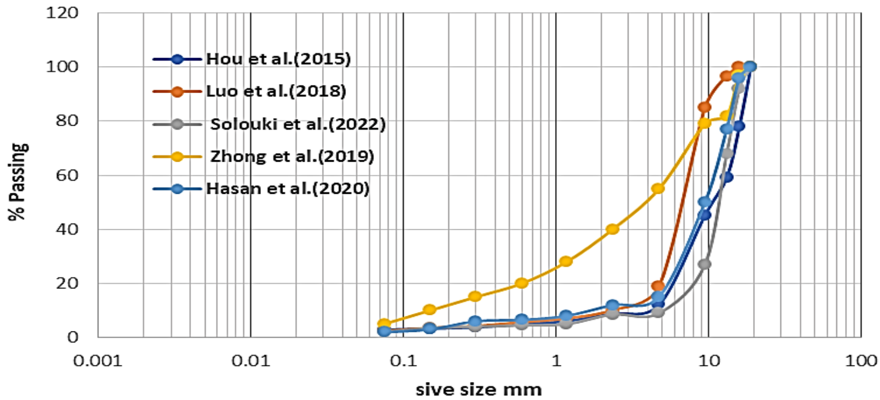

Figure 3: Various fine aggregate gradations from the literature.

2.1.3 Effort of Compaction

As mentioned earlier, there is no specific design method for the porous asphalt mixture, and the process of humping varies from one agency to another [35]. Therefore, different compaction efforts were used during the previous studies to obtain the optimum void ratio that ensures the cementation grout's penetration for the aggregate's skeleton. The American standard (ASTM D7064) [36] recommended 50 blows for each face or 50 gyrations for porous asphalt. The 50 compaction blows were acceptable compaction values for medium traffic flow [37] and a good value to produce the desired voids in the mix. Al-Qadi et al. [7] applied 10 blows for each face of the specimens, while Tran et al. [38] suggested 25 blows for one face to achieve the required air voids, as illustrated in Table 1.

2.2 Cementitious Grout Design

The grouting material is considered a very important part of the performance of semi-flexible pavement, as it works to bind the paving components together in addition to providing the required strength, as the pavement strength is directly affected by the strength of the grouting material [15]. It is necessary to possess high fluidity to ensure penetration of the skeleton of the porous asphalt mixture to form semi-flexible pavement. According to previous studies, the suitability of the grouting material is determined based on three main properties: fluidity, compressive strength, and flexural strength. Table 2 shows different combinations of materials for grouting material design. Since a larger surface area increases the time needed for the material to flow through the porous mixture, the fluidity of the grouting material is closely related to the surface area of the material in question. The superplasticizer based on polycarboxylic ether polymers is more effective at dispersing cementitious particles than the superplasticizer based on sulfonated naphthalene formaldehyde. However, both the type and quantity of the superplasticizer have a significant impact on the fluidity of the inje ction material [21].

Table 2: Different combinations of materials for grouting material design.

Reference	Design of grouting material	Fluidity value (sec.)
Liu et al. [39]	0.35w/c, sand/binder0.3, water reduser0.08, rubber pouder0.1	10-14
Solouki et al. [40]	Metakaolin 24%, Calcined silt 16%, KOH (solution) 48%, NaOH (8M) 12%	-
Luo et al. [41]	Cement, sand, fines, latex powder, water (different ratios)	10-14
Hou et al. [42]	Water, cement, additives (different ratios)	9-11
Ling et al. [23]	-w/c 0.65, sand/cement0.14, 6%fly ash, 10% mineral powder -w/c 0.65, sand/cement0.2, 10%polymer, 10% mineral powder.	11.4 11.1
Koting et al. [43]	5%silicafum, 2%suoerplasticizers, w/c 0.32	14.2

The water-cement ratio is considered the main factor affecting the fluidity and strength of cement slurry, as the fluidity is directly proportional to the water-cement ratio and inversely proportional to the sand-cement ratio. Vijaya et al. [44] found that the ratio of water to cement is equal to or less than 0.55 [45], while Saboo et al. [46] found that the ratio ranges between 0.4~0.6. The ratio of water to cement and the ratio of superplasticizers should be moderate, as their increase leads to the bleeding phenomenon and its effect on the material's mechanical properties in the future [47]. One of the tests used in calculating the fluidity of the material is known as the cone flow test according to the American specification [48] or the marsh cone test, as shown in Figure

4. Fang et al. [47] mentioned that if the liquidity value of the extracted material from the test is very high, it is difficult to penetrate the entire thickness of the layer. Still, its very low value may lead to leakage of the grouting material from the sides and bottom of the layer. In light of this, they claim that cement slurry with fluidity between 9 and 14 s is appropriate, which almost accords with the range suggested by Fang et al. [7].

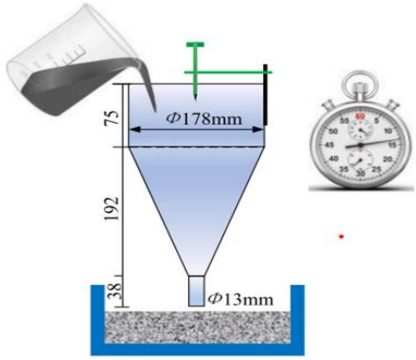

Figure 4: Fluidity test [39].

3. PERFORMANCE EVALUATION OF SEMI-FLEXIBLE PAVEMENT

The raw materials and the semi-flexible paving structure are among the basic elements that affect the laboratory performance, which may lead to future problems, as the bond between asphalt, cement, and aggregate is what builds the total strength of the paving. In other words, the properties of raw materials and mixtures and their formation directly affect the Semi-flexible pavement quality [48,49]. Numerous tests are performed on SFP regarding mechanical and durability properties. The researchers have used the following tests to assess the mechanical and durability performance of SFP.

3.1 Marshall Stability Test

There is a relationship between the curing period and the properties of the semi-flexible pavement, where it was found that the stability is increased by increasing the wet curing age, which is consistent with the findings of recent studies [7,50]. Cai et al. [51] stated that Marshall stability increases with the amount of air voids in the porous mixture. This is because more air voids are filled with cementitious grout as they grow, and cementitious grout has a much higher strength than porous asphalt mixtures. According to Jatoi et al. [52], the Marshall stability is more stable at various ages than the hot asphalt mixture, as shown in Table 3. It was also determined that the Marshall stability value increases by 85% over the course of 28 days, starting at the age of 7 days. This indicates that seven days after casting,

Table.3: Different Marshall stability test values from previous studies.

Reference	SFP	HMA
Al-Taher et al. [28]	6861 lb	2147 lb
Bharath et al. [24]	114.7 kN	17.3 kN
Huo et al. [53]	29.52 kN	-
Hao et al. [54]	17.12 kN	-
Jatoi et al. [55]	44.91 KN	14 KN

3.2 Compressive strength test

Bharath et al. [24] found that SFP showed higher compressive strength than conventional flexible paving, as illustrated in Table 4. As Setyawan[9] reached, the compressive strength is affected by the strength of the aggregate particles used and the structure of the pores more than by the shear strength of the skeletal structure of the porous mixture. The compressive strength of SFP reaches approximately 25% of the compressive strength of cement concrete, as it continues to increase with the increase in the volume of air voids of the grouted porous asphalt mixture [56]. Huu et al. [57] found that the rate of development of compressive strength of the cold asphalt mixtures is greater than that of the heated mixtures because the properties of the cold mixtures evolved.

Table.4: Different compressive strength test values from previous studies

Reference	SFP	HMA
Bharath et al. [24]	6	2.2
Al-Taher et al. [28]	556 psi	165 psi
Wang and Hong [56]	4.61-5.41	1.7-3.8
Hu et al. [57]	5.68	2.65

3.3 Indirect tensile strength (ITS)

Despite being comparable after a single day of testing, the value of ITS for semi-flexible pavement significantly rises with increasing curing age. Although it was discovered that there was little difference in resilient modulus between various moist curing times [7], it also claims that the ITS develops significantly as curing time increases, with ITS being superior to conventional HMA at ages 3, 7, and 28 days after curing as shown in Table 5.

Table.5: Different ITS test values from previous studies

Reference	SFP	HMA
Bharath et al. [24]	2400 kPa	900
Al-Taher et al. [28]	149 psi	85
Hu et al. [57]	2180 kPa	1000-1500
AlQadi et al. [7]	975-1200 kPa	750

3.4 Rutting Test (High-Temperature Performance)

The rutting performance of semi-flexible pavers is evaluated using the Track wheel test, as this type showed high rutting resistance compared to the conventional type, according to Hou et al. [17]. This results from the grouted material mechanisms, specifically the hydronation and solution processes. In this way, fiber-like hydrated products are produced between the cement slurry and asphalt coating on the aggregates. Aggregates are, therefore, tightly wrapped by the matrix of hydrated products and asphalt layer, improving overall strength and high-temperature performance. Huo et al. [57] applied heel tracking on SFP and obtained dynamic stability of 36000 cycles/mm, about ten times what was obtained from the usual polymer-modified asphalt concrete, while Ding et al. [58] reached 30000 cycles/mm. It is similar to the previous result. Therefore, comparing the results, it can be said that the semi-flexible pavement has a higher resistance to permanent deformations under high temperatures [23]. Table 6 summarizes the dynamic stability values.

Table.6: Different dynamic stability test values from previous studies.

Reference	Dynamic stability (times/mm)
Hao et al. [54]	10242
Huo et al. [42]	15750
Zhang [59]	21000
Luo et al. [41]	11200-13800
Ling et al. [23]	15750

3.5 Low-Temperature Performance

The following tests evaluate the performance of semi-elastic tiles at low temperatures: Semi-circular bending (SCB), small beam bending (SBB), and splitting tests are also used. To examine the anti-cracking resistance of SFP, the creep test and indirect tensile strength (ITS) test are also used at 10ºC. [54,60]. As Hou et al. [17] and Ling et al. [23] reported, SFP achieves superior low-temperature and crack resistance compared to traditional HMA. The above is because grouting material is more brittle and stronger than regular asphalt mixture, which causes a rise in modulus and a fall in strain. In addition to low-temperature performance, it has been discovered that the low-temperature qualities deteriorate as air spaces rise [23]. Hence, Cai et al. [51] stated that when the target air voids of the asphalt mixture skeleton are between 23 and 25%, the low-temperature performance of SFP is at its best. Table 7 summarizes the results of different studies' small beam bending and splitting tests.

Table 7: Different small beam bending and splitting test values from previous studies.

Reference	Small beam bending test 10ºc)	Splitting test (-10ºC,1mm/min)
Huo et al. [42]	5.2	29.5%
Huo et al. [53]	-	25%
Hao et al. [54]	6.408	25%
Zhang [59]	6.71	25%

4. CONCLUSIONS

After studying many types of research related to the type of semi-flexible pavement and for different years since its inception and until the last period, the following was found:

- There is no unified specification adopted in the design of this type of pavement at present but rather depends on the design of the researcher's vision and the results that are reached through laboratory tests.
- The effective performance of SFP in resisting common deformations for both rigid and flexible paving types can be an alternative solution to many road problems.

- High performance at high temperatures to resist permanent deformations and acceptable at low temperatures makes it an ideal choice for use in different atmospheres for different places.
- The performance of semi-flexible paving depends mainly on the bonding between its components, as it is considered a composite material. For this reason, the direction in the future may be to study the bonding between asphalt and cement, in particular, as they are two basic materials in their composition.

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