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Toward Semi-Flexible Pavement Application for Iraqi Highway and Airport Pavements: Review its feasibility

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Abstract:

The paving industry within the last century has developed extensively, mainly two paving technologies have targeted in this development, namely: flexible and rigid pavements. Although such technologies' development is deeply enhanced, they still have unsolved shortcomings. Therefore, pavement researchers and engineers suggested benefiting from these two technology advantages by gathering them in a new technology called semi-flexible paving (SFP) to overcome the pointed shortcoming. The structural composition of SFP consists of porous asphalt, which contains air voids (25-35) % that inject with cementitious grout materials. As a result, the SFP surface course combines the pre-eminent qualities of bituminous pavements (flexible) and concrete (rigid). Serving the literature disclosed that the SFP has a very high resistance to the effect of traffic loads and weather conditions compared to conventional hot mix asphalt (HMA). Previous studies have shown that it can be applied in places with heavy traffic, i.e. heavy and slow traffic, for example, industrial areas, harbors, warehouses, distribution centers, road crossing, bus terminals, parking areas with heavy traffic, cargo centers, airports pavements, etc. Therefore, under uncontrolled high axle loads and extreme high summer and low winter ambient temperatures, SFP represents a suitable and achievable technique.

Keywords: Cementitious grout, flowability, high trafficked highway, porous asphalt, semi-flexible pavement.

1. Introduction

Most of the highways in Iraq are constructed using the flexible pavement, while highways lack rigid pavement due to its high cost, poor riding quality, and slow construction time. The paving system in Iraq is exposed to many failures at an early phase of the pavement life. This is due to the harsh environmental factors, in addition to the increased traffic loads imposed on the pavement [3]. The climate of Iraq is very hot in summer, when temperatures exceed the 50 °C barrier, while winter temperatures are low, and this affects the performance and durability of asphalt pavement [4]. Increased temperatures and lack of control over traffic loads lead to the phenomenon of rutting that the pavements suffer from in Iraq [5]. While low-temperature leads to crack problems due to the inability of the asphalt layer to resist the tensile stresses imposed by the vehicle's tire [6]. Therefore, the trend is to use SFP in Iraq in order to withstand high traffic loads and change in excessive temperature and give better performance and durability.

SFP was developed for the first time in France in the 1950s, to protect the surface course from the effects of oil and fuel spills [7]. This procedure, recognized as Salviacim, was developed by a French construction company called Jean Lefebvre Enterprises as a cost-effective alternative to Portland cement concrete [8]. After the successful Salviacim operation, its use has spread to other countries such as Britain, South Africa, Japan, Australia, and Saudi Arabia [9]. Since then, this type of pavement has been used with various designations depending on the location of the countries. Consequently, in the United States, it is known as Resin Modified Pavement (RMP) [8]. In Europe, this type of pavement is called some brand name, for example, Hardicrete Heavy Duty Surfacing [10], Worthycim Heavy Duty Paving [11], in Japan this type of pavement is known as RP-Pavement (Rut Proof Pavement), Densiphalt® [12]. Generally, it is classified as grouted macadam, although some authors have as well referred to it as combi-layer [7].

However, due to the high summer temperature with high traffic load and applications, SFP mixture has to clarified more and more in Iraq highways and airports. Identifying the characteristics could help the paving industry to upgrade the current practices. The introduction of this technology will facilitate more sustainable application of local paving industry.

2. Application Areas of SFP

Semi-flexible pavement can be applied to areas experiencing heavy and slow traffic, for example, industrial areas, harbors, warehouses, distribution centers, road crossing, bus terminals, parking areas with heavy traffic, cargo centers, airports pavements, holding bays, hangar pavements and other fields undergo heavy and light loads [13, 14]. Some investigations have stated that the use of SFPs at airports is a result of the high cost that rigid pavement needs during maintenance and the need for a more flexible airport pavement to prevent deformations without cracking [13]. Between 1988 and 2000, 165000 m2 SFP was constructed at Copenhagen Airport and the pavement outside the Delft railway station in the Netherlands [15].

3. Composition of SFP

The SFP is a layer consisting of porous asphalt and injected with cementitious grout material and used as a surface layer to resist heavy and light traffic loads. In core, SFP comprises an open-graded asphalt mixture, in which cementitious grout material is injected into the porous asphalt skeleton, which contains air voids of (25-35) % [8, 16], as shown in Figure 1. Thus, the final product gathers the preferable properties of rigid and flexible pavements (i.e., joints disposal, high bearing capacity and wear resistance) [17-19]. The period for the construction of SFP and openness to traffic is witnessing significant progress on traditional concrete pavements [13]. This type of paving may be applied as a surface layer with a thickness of (30-60) mm [12]. Some SFP work has been accomplished with a thickness of 80 mm [7] and some grout providers claim that it is conceivable to use thicknesses of up to 200 mm [20].

The process of creating an SFP is achieved in two stages because the porous asphalt layer must be allowed to cool down and then the cementitious grout materials are injected into its voids. The construction process is normally carried out on two consecutive days. The porous asphalt layer is constructed using natural paving and then lightly compacted using a steel roller without vibration to avert the formation of cracks or tracks in the porous asphalt structure. Then, once the porous asphalt layer has cooled down, it is injected with a highly fluidity cementitious grout material [21]. Grout is publicized on the surface layer with the help of rubber scrapers (squeegees). To ensure that the air voids are filled with the grout completely, a light steel roller may be used in the vibration mode for ensuring the grout penetration. After stuffing the voids, the surface layer may be cured to get its better properties, namely skid resistance, durability, and aesthetics.

Figure 1 Pouring of cementitious grout in the porous asphalt skeleton [2].

Figure 2 Porous asphalt pavement [1].

4. Influence of Material Properties on SFP Characteristics

The SFP characteristics are varied according to the selection of an aggregate gradation, the type of asphalt used, and the materials used in the design of grout.

4.1 Porous Asphalt Mixtures

Porous paving technology is used for decades, which consists of a mixture containing air voids within range (18-22) % [22]. when used as a surface layer, this technique is called as "open-graded friction course (OGFC)", or it is also known as the permeable friction coarse (PFC) [23], as can be shown in Figure 2.

Practically, porous asphalt was designed and applied for the first time in the Netherlands in 1972 [24]. It was widely applied as a wearing course in 1987. So far more than 90% of porous asphalt has been laid as top layers of highways in the Netherlands and the goal is 100% [25]. The advantages of this type of pavement are reduced spray and splashing, as well as the risk of skidding when the pavement is wet, improving visibility by eliminating the light reflected on the road surface, also improving the visibility of pavement marks when the weather is rainy [26]. Besides, it provides an important feature which is improving the riding quality and reducing noise compared to the HMA [27].

In SFP, the porous asphalt design differs in terms of air voids, higher range is recommended to ensure grout injection. The porous asphalt for SFP application is designed according to the required air voids content, this depends on the type and gradation of the aggregate, the asphalt used, and the number of blows, as shown in Table 1 and Figures (3, and 4).

Table 1 Different components of porous asphalt from the literature.

Researchers	Aggregate type	Filler type	Bitumen type	Bitumen content	No. of blows	Air voids, %
Al-Qadi [28]	Dolomitic limestone	limestone	Virgin Asphalt	4.05	10 x 2	25 – 30
Koting [29]	Granite	Limestone	Asphalt 80/100	3.7	50 x 2	27.2
Hu [30]	Basalt	Limestone	SBS modified	3.2	50 x 2	26.0
Ling [31]	Limestone	Limestone	Asphalt rubber	3.6	50 x 2	20 – 28
M. G. Al-Taher [32]	Limestone	Limestone	Asphalt 60/70	4.4	50 x 2	27.7
Hou [33]	Limestone	Hydrated Lime	Virgin Asphalt	3.8	50 x 2	29.0
Tran [34]*	Limestone	Limestone	Asphalt 60/70 Fiber	3.0 0.3	25 x 1	28.5 – 30
Jatoi [35]	Limestone	Limestone	Asphalt 60/70	4.35	25 x 1	25 – 35
Wang and Hong [36]	Limestone	Mineral powder	Polymer Modified	2.9	50 x 2	24.8
Luo [37]	Basalt	Limestone	SBS modified	3.4	50 x 2	26.43

∗ In his study, the aggregate gradient based on the aggregate gradient of [8] study.

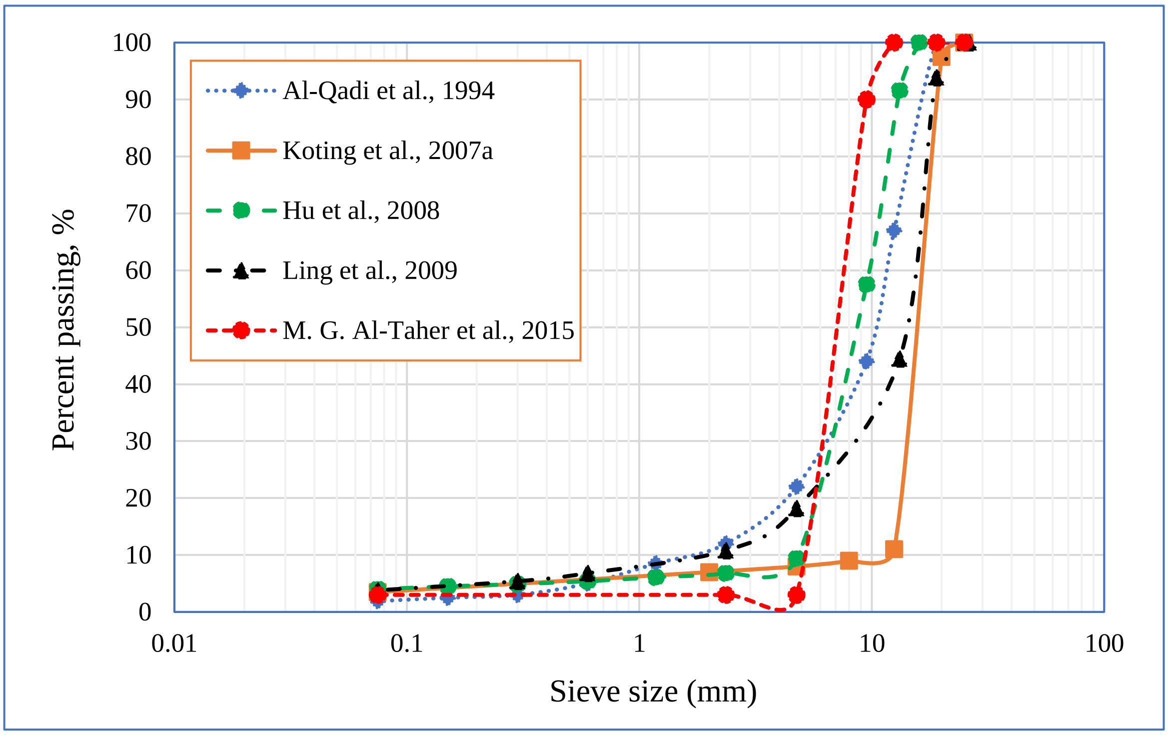

Figure 3 Various aggregate gradations acquired from literature.

The type, size, characteristics of aggregate, and type of bitumen used to produce porous asphalt were varied according to the available local materials and also guidelines produced by authors. The aggregate is either in the form of granite, limestone, or basalt, while the common filler used by researchers is almost limestone powder as can be shown in Table 1. In addition, the type and grade of bitumen and additives for bitumen are different, and sometimes cellulose fiber may be added to prevent the drain down that occurs in the mixture. Through Figures (3, and 4), it is observed that the gradations of the aggregate are different among researchers, but some of them showed a slight difference in the percentages passing. Also, the nominal maximum aggregate size (NMAS) of the aggregate is different, depending on the researchers, the NMASs were (12.5, 13.2, 20, 16, and 19 mm).

Air voids, number of blows, and asphalt content are variable as shown in Table 1. Noticeably the air voids have a very close relationship to the number of blows and the asphalt content. The American standard ASTM D7064 [38] recommended 50 blows for each face or 50 gyrations for porous asphalt, but [28] reported 10 blows for each face, while others [34, 35] suggest 25 blows for one face to achieve the required air voids for porous asphalt that is ended to be SFP.

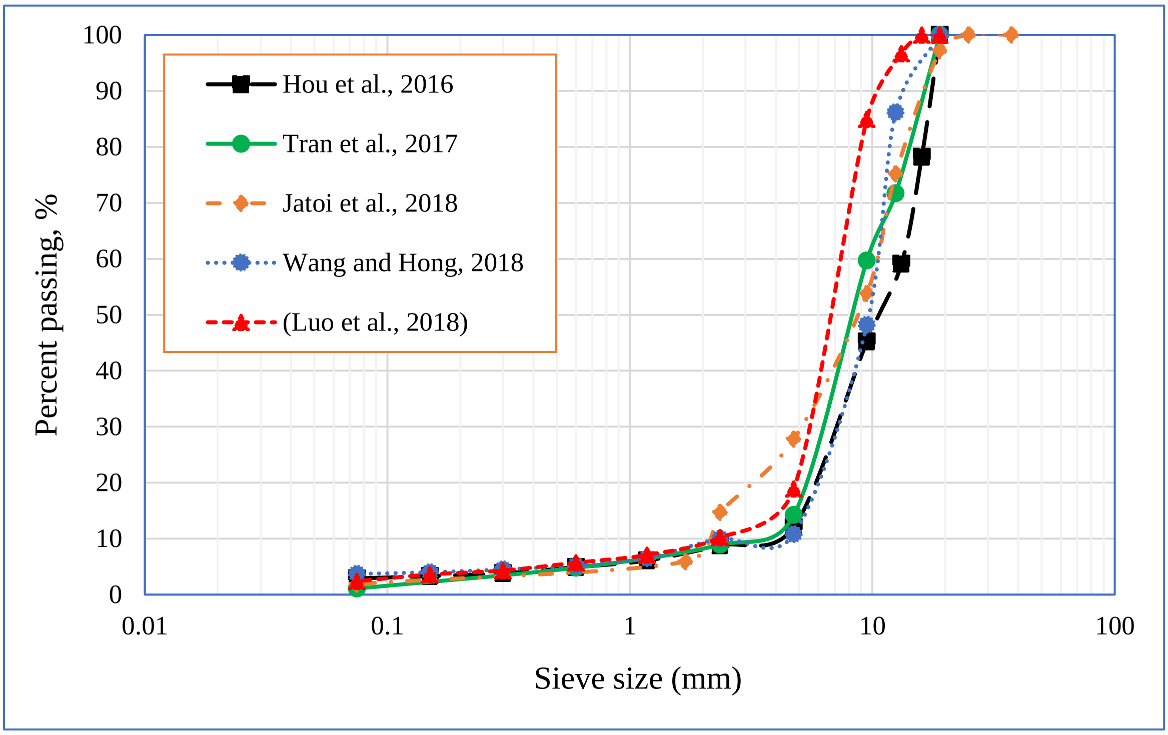

Figure 4 Another aggregate gradations used in SFP from literature.

In as a summary, the porous asphalt structure is affected by the type and gradation of the aggregate, the type and content of the asphalt in addition to the number of blows. Unfortunately, to date, there are no approved standard specifications for porous asphalt design with air voids within the required range for SFP application. The main point is achieving a high air void (25-35) % to ensure grout penetration, therefore different compaction efforts have been suggested.

4.2 Cementitious Grout Materials

Usually, cementitious grout materials production depends on the need to easily produce a flowable material in the porous asphalt structure. Thus, the grout should be a material with high strength to resist the effects of stress and strain without failure. Nevertheless, various grouts are created for commercial purposes, yet most producers conserve their formulations confidential. In this part, available cementitious grout materials components are offered, jointly with the properties commonly controlled, depending on the specifications. Table 2 shows different designs grout, according to various research studies.

Table 2 Various design proportions of grout from literature.

Authors	Proportions of the materials used in designing the grout	Fluidity (sec)
Al-Qadi [28]	38.5 % OPC + 19.2 % Fly ash + 12.7 % Sand + 26.8 % Water + 2.8 % additive (strength + water-reducing)	8.1
Anderton [8]	36.6 % Portland cement + 17.1 % Fly ash + 17.1 % Sand + 25.7 % Water + 3.5 % Resin modifier	9.0
Zoorob [21]	95 % OPC + 5 % SF + 1 % SP + 0.28 % W/B	9 – 11
Hu [30]	(0.92% OPC + 0.08 UEA*) as binder + 0.45 W/B + 0.25 S/B + 0.3 SP/B	11.51
Ling [31]	0.65 W/C + 14 % Sand + 10 % Mineral powder + 6 % Fly ash	11.4
	0.65 W/C + 10 % polymer/C + 20 % Sand + 10 % Mineral powder	11.1
Koting [39]	95 % OPC + 5 % SF + 0.3 W/C + 2.0 % SP	15.0
Hou [33]	(Cement + Water + additives), by trial and error	9 – 11
Tran [34]	37 % Portland cement + 16 % Sand + 11 % SF + 4 % Fly ash + 28 % Water + 4 % SP	High fluidity
Jatoi [35]	(1 Portland cement: 0.5 Sand: 0.5 Water) by weight + 2 % SP	12.0
Wang and Hong [36]	0.80 % Portland cement + 0.05 % SF + 0.15 % Fly ash + 0.29 % W/B + 8 (ml/kg) SP + 3 (ml/kg) SRA**	23.0
Luo [37]	(720 Water + 1000 Portland cement + 497 Sand + 249 Filler + 30 Latex powder) by gm	12.8

* Expansion agent type UEA.

** Shrinkage-reducing admixture (SRA).

According to the literature, the main difference between the studies is the materials involved in designing of the grout, i.e., the type of cementitious material. Moreover, the fluidity is very closely related to the surface area of the materials involved. The higher surface area of cementitious grout materials leads to greater flow time and vice versa. On the other hand, the type and dosage of the superplasticizer play an important role in affecting the fluidity of the grout, that is, the superplasticizer based on Polycarboxylic ether polymers more effective for dispersing cementitious particles than the superplasticizer based on Sulphonated Naphthalene Formaldehyde and, therefore it gives fluidity capable for penetrating the porous asphalt structure [40]. Also, the variation in W/C or W/B ratio plays a big impact on both: fluidity and strength properties of cementitious grout materials. Through Table 2, the lowest fluidity value is 8.1 sec, which was obtained through [28] study, where a high proportion of water and superplasticizer was introduced, while the highest value of the fluidity is 23 sec, which found through [36] study, as they used a lower percentage of water.

There are no global specifications that determine the extent of the fluidity of used grout in SFP injection, but it is determined based on previous studies or works carried out on the ground, as can be shown in Table 3. Al-Qadi [28] recommended that the time after mixing the grout and determine the flow time should not exceed 15 sec to avoid separation of the components. Compressive and flexural strength is also important factors that must be taken into account during the design of grout. In SFP production, grout is prepared based on the flow time in order to guarantee penetration of the grout for the porous asphalt, thus giving the required performance properties.

Table 3 Limitation of flow time from literature.

Study	Range of flow time (Sec)	Type of flow cone	Volume of grout (ml)
Al-Qadi [28]	7 – 9	Marsh flow cone	1000
Anderton [8]	8 – 10	Marsh flow cone	1000
Zoorob [21]	9 – 11	Flow cone test	1725
Hu [30]	11 – 14	Flow cone test	1725
Ling [31]	10 – 14	------	------
Koting [39]	11 – 16	Malaysian mortar flow cone	1000
Husain [41]	11 – 16	Malaysian mortar flow cone	1000
Hou [33]	9 – 11	Leeds flow cone	1000
Jatoi [35]	8 – 12	Marsh flow one	1000

5 Properties of SFP

There are numerous tests performed on SFP in terms of the mechanical and durability properties, therefore extensive experimental programs have been conducted by different studies to portray the characteristics of SFP using different testing methods, as follows:

5.1 Marshall Stability

Al-Qadi et al. [28], concluded that stability increases with increasing age, in the case of samples curing or without it. Afonso et al. [42] proved that the stability of porous asphalt mixtures injected with grout exceeds the stability of the semi-flexible mixtures based on the cold asphalt mixture. Additionally, it has been demonstrated that stability increases with increasing air voids content in the porous asphalt mixture. The reason for this is that the amount of grout increases with the increased air voids content, also the strength of grout is greater than the matrix asphalt mixture, which leads to great Marshall stability. Cai et al. [43] and Bang et al. [44] inferred that Marshall stability of the semi-flexible mixtures depended heavily on the fluidity of the cementitious grout materials rather than the strength of the cementitious grout materials. Moreover, Jatoi et al. [35], demonstrated that the Marshall stability for different ages exceeded the stability of the hot mix and also concluded that the value of Marshall stability at the age of 7 days is 85% of 28 days, which means that the road can be opened to the traffic after 7 days of casting. Table 4 shows the results of stability from literature @ 28 days.

Table 4 Stability for different mixtures.

Authors	SFP		HMA (control)
	HMA	CMA	
Al-Qadi [28]	13-19	------	8.7
Afonso [42]	28.2-53.9	9.9-22.9	------
Bang [44]	21.2-24.4	------	------
Jatoi [35]	44.91	------	14.0
Bharath [45]	114.6	------	17.3

5.2 Compressive Strength

Hu et al. [30] explained that the compressive strength of the semi-flexible mixtures exceeds the compressive strength for the traditional asphalt mixtures, this agrees with (Zoorob et al. [21], Wang and Hong [36], Bharath et al. [45]), but is much lower than the compressive strength of the cement concrete mixtures. Setyawan et al. [46], concluded that the compressive strength of cold mix grouted macadams is lower than that hot mix grouted macadams due to the low compressive strength of the cold porous structure, this corresponds to Afonso et al. [42]. It was also concluded that the rate of development of the compressive strength of cold mixtures is higher than hot mixtures due to the fact that cold asphalt mixtures develop over time. Table 5 shows the results of compressive strength from literature at 28 days.

Table 5 The results of compressive strength from literature at 28 days.

Authors	SFP		HMA (control)
	HMA	CMA	
Al-Qadi [28]	5.5-7.0	------	------
Zoorob [21]	12-13.7	------	
Hu [30]	5.68	------	2.65
Setyawan [46]	11.85- 13.82	9.80-11.99	------
Afonso [42]	7.0-14.3	2.6-4.3	------
Wang and Hong [36]	4.61-5.41	------	1.7-3.8
Bharath [45]	6.0	------	2.2

5.3 Indirect Tensile Strength (ITS)

Tran et al. [34] deduced that the ITS of the semi-flexible mixtures after 7 days of curing is equivalent to that of the conventional HMA. But this somehow contradicted with Al-Qadi et al. [28] findings, who stated that the ITS is developed with increasing curing time significantly, where ITS at the ages of 3, 7, and 28 days after curing is superior to the conventional HMA. Bharath et al. [45] proved that the ITS of cement grouted bituminous mix is 2.5 times that of conventional HMA. This corresponds to Hu et al. [30], where they were found that the ITS for semi-flexible mixtures overcomes the traditional asphalt mixture, but less than the cement concrete mixtures. Table 6 shows the results of ITS from literature @ 28 days.

Table 5 ITS of SFP and HMA for different authors.

Authors	ITS (kPa)	
	SFP	HMA (control)
Al-Qadi [28]	975-1200	750
Hu [30]	2180	1000-1500
Tran [34] @7 days	1150	1150
Bharath [45]	2400	900

5.4 Low-Temperature Bending

Ling et al. [31] concluded that the value of flexural tensile strength for semi-flexible mixtures is low compared to the conventional HMA, because of the brittleness of hardened cement slurry, and the greater air voids of the porous asphalt skeleton. This agrees with Hou et al. [33], who interpreted that the low-temperature cracking for grouted macadam composite materials showed an acceptable reduction due to the relative brittleness of hardened cement paste at low-temperatures. Luo et al. [37] demonstrated that the strength of grouted open-graded asphalt concrete to low-temperatures is less than the traditional HMA, but its performance is at an acceptable level. However, this does not correspond to Pei et al. [47], who concluded that the performance of the semi-flexible mixture under low-temperatures gives slightly better performance than the traditional asphalt mixture. Sun et al. [48] proved that the injection of cement mortar materials improves mechanical properties up to 90 % and better paving performance, including low-temperatures. Table 7 shows the results of low-temperature bending from literature @ 28 days.

Table 6 Low-temperature bending of SFP and HMA for various authors.

Authors	Low-temperature bending MPa)	
	SFP	HMA (control)
Ling [31]	6.73-7.57	8.29
Hou [33]	5.2	6.63
Luo [37]	9.3-10.5	8.3-9.0
Sun [48]	6.53-8.65	------

5.5 Moisture Susceptibility

Hou et al. [33] proved that the grouted macadam composite materials exposed to the moisture sensitivity give a better performance than the traditional HMA, this agrees with (Al-Qadi et al. [28], Luo et al. [37], Wang and Hong [36], Bharath et al. [45]). This superiority is due to the contribution of cementitious grout materials that gives additional strength when increasing the curing time, and there is another reason is the free Ca++ that results from the existence of OPC. Table 8 shows the results of moisture sensitivity from the literature @ 28 days.

Table 7 Moisture sensitivity of SFP for various authors.

Authors	SFP		HMA (control)	
	RMS, %	TSR, %	RMS, %	TSR, %
Ling [31]	103	86	83	78
Hou [33]	110.1	85.5	87.8	81.8
Luo [37]	93-95	85-86	91-92	87.5-92
Bharath [45]	96.28		80.87	

5.6 Wheel Track and Dynamic Stability

All researchers agreed that semi-flexible mixtures give a very high resistance to rutting in addition to providing high dynamic stability at high traffic loads and temperatures, compared with conventional HMA. Test results confirmed that cementitious grout materials can significantly increase the rutting resistance of the asphalt mixture, due to the strength of the asphalt mixture skeleton and the hardened cementitious grout materials in addition to the adhesion between the asphalt mixture and hardened cementitious grout materials (Hu et al. [30], Ling et al. [31], Hou et al. [33], Tran et al. [34], Karami [49], Bang et al. [44], Sun et al. [48], Wang and Hong [36], Luo et al. [37], Bharath et al. [45]). Table 9 shows the results of WTT and DS from literature @ 28 days.

Table 8 WTT and DS for various authors.

Authors	SFP		HMA	
	WTT (mm)	DS (cycles/mm)	WTT (mm)	DS (cycles/mm)
Hu [30]	------	36000	------	3000
Ling [31]	------	15750	------	2325
Hou [33]	0.040	15750	0.553	1140
Tran [34] @ 28 days	0.7	------	1.9	------
Sun [48]	1.14-2.16	8034-28984	------	------
Wang and Hong [36]	< 2.5	------	6-9	------
Luo [37]	------	11200-13800	------	5000-5100
Bharath [45]	2.0		19	

6. Conclusion

As a summary, based on the wide studies, the SFP is superior in terms of its performance compared with the traditional asphalt mixture in many test indices, however, the following points can be highlighted from SFP technology:

1. At present, there is no global standard specification in place for the design of SFP,
2. SFP has not been studied in detail at low-temperatures, where it showed some weakness compared to the traditional asphalt mixture, but within an acceptable level.
3. An extensive attempt is tending to prepare grouts using supplementary cementitious materials to reduce the use of cement, which has a harmful impact on the environment.
4. Ultimately, with high mechanical and durability properties the SFP can be the most promising paving technique in the future.

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توجيهات تطبيق التبليط شبه المرن لارصفة الطرق السريعة والمطارات العراقية: مراجعة كدراسة جدوى

الخلاصة: *تطورت صناعة الرصف خلال القرن الماضي على نطاق واسع، وقد استهدفت تقنيتان أساسيتان من تقنيات الرصف في هذا التطور، وهما: الأرصفة المرنة و الخرسانية. على الرغم من تعزيز تطويرهذه التقنيات بشكل كبير، إلا أنها لا تزال تعاني من أوجه قصور التي لم تُحل. لذلك، اقترح الباحثون والمهندسون في مجال الرصف الاستفادة من هاتين الميزتين التقنيتين من خلال جمعهما في تقنية جديدة تسمى الرصف شبه المرن (SFP) للتغلب على النقص الواضح فيهما. يتكون التركيب الهيكلي لـ SFP من إسفلت مسامي يحتوي على فراغات هوائية (25-35) % ثم يتم حقنها بمواد الحقين الاسمنتي. نتيجة لذلك، فإن الطبقة السطحية للتبليط شبة المرن تجمع بين الصفات البارزة للأرصفة البيتومينية (المرنة) والخرسانة (الصلبة). اتضح من الأدبيات أن SFP لديه مقاومة عالية جدًا لتأثير أحمال المرور والظروف الجوية مقارنةً بالخلطة الاسفلتية التقليدية (HMA). أظهرت الدراسات السابقة أنه يمكن تطبيقه في الأماكن ذات الاحمال المرورية العالية، التي تشهد حركة المرورالكثيفة والبطيئة، على سبيل المثال ، المناطق الصناعية، والموانئ، والورش، ومراكز التوزيع، تقاطعات الطرق، ومحطات الحافلات، ومواقف السيارات المزدحمة، ومراكز الشحن، وارصفة المطارات، إلخ. لذلك، في ظل أحمال محاور المركبات المرتفعة غير المنضبطة ودرجات الحرارة المحيطة الشديدة في الصيف والمنخفضه في الشتاء، يمثل SFP تقنية مناسبة وقابلة للتحقيق.*