Performance Evaluation of Semi-Flexible Concrete by Laboratory and In-Situ Testing

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ABSTRACT

Open-graded asphalt concrete with a high air void content, filled by injecting special grouting materials, forms the basis of a new pavement technology known as Semi-Flexible Concrete (SFC) pavement. In pavement engineering, SFC has been applied in environments with high temperatures and heavy loads. This study conducted an experimental investigation to evaluate the performance of SFC both in the laboratory and in situ. The laboratory results indicated that the SFC met the specification requirements for high-traffic roadways, achieving an air void content of 25.7%, a flexural strength of 3.27 MPa, an Indirect Tensile Strength (ITS) of 0.97 MPa, an Indirect Tensile Strength Ratio (ITSR) of 84.1%, and a flexural strain of 4.1×10^{-3} mm/mm. Field data confirmed that the pavement satisfied current specifications for high-traffic conditions, exhibiting excellent surface smoothness, an average surface texture depth of 0.85 mm, an average skid resistance value of 69, an average elastic modulus of 230.8 MPa, and an average ITS of 0.92 MPa. These results demonstrate that SFC pavement can be proposed as an alternative solution to overcome the limitations of conventional asphalt pavements under heavy loading and adverse climatic conditions.

Keywords-semi-flexible concrete; flexural strength; indirect tensile strength; indirect tensile strength ratio; skid resistance; elastic modulus

I. INTRODUCTION

Rutting and cracking distress are closely related to the viscoelastic behavior of the asphalt binder, which significantly influences the pavement's performance life. Due to increased heavy loading and high temperatures, traditional asphalt pavements cannot maintain satisfactory performance in terms of deformation, cracking, and skid resistance. To address these issues, researchers used current additives, including polymers, rubber, nanomaterials, and fibers, to modify the asphalt binder and enhance the performance of asphalt concrete mixtures [1–10]. However, the pavement is frequently subjected to heavy loads on some road sections with high traffic volumes, such as those near toll stations, parking lots, material storage facilities, intersections, industrial zones, and port regions. Especially at extremely high temperatures, rutting or shoving still appeared in asphalt pavements [11]. Hence, the SFC pavement can be applied due to excellent resistance to high-temperature deformation and cracking.

The SFC is a composite material consisting of an open-graded asphalt mixture with large Air Voids (AV) and a cement-based grouting material [12]. To ensure proper flow and complete filling of the voids, open-graded mixtures with 20%–35% AV are typically proposed [12, 13]. It has been shown that SFC provides superior performance compared to conventional asphalt pavements [14–17]. Specifically, authors in [14] reported that SFC exhibits improved moisture stability and rutting resistance, while authors in [15] demonstrated that it also achieves higher Marshall Stability (MS) as well as greater compressive and tensile strengths. Compared to modified asphalt mixtures, SFC is significantly more resistant to low-temperature cracking and permanent deformation [16]. Authors in [17] noted that SFC outperforms stone mastic asphalt in terms of dynamic modulus, crack resistance, shear resistance, deformation resistance, and water resistance. Although many studies have evaluated SFC under laboratory conditions, comprehensive in-situ assessments remain limited. Therefore, this study aims to evaluate the performance of SFC both in the laboratory and in the field. Laboratory tests included measurements of air void content, flexural strength, ITS, and ITSR. Field tests included evaluations of surface texture depth, skid resistance, elastic modulus, and ITS. The results were compared against current specifications for high-traffic roadways.

II. EXPERIMENTAL PROGRAM

A. Materials

In this study, a 60/70 bitumen was used as the base asphalt binder, and its properties were detailed in Table I. The technical properties of Ordinary Portland Cement (PCB40) and mineral powder are presented in Tables II and III, respectively. The STP-VN additive was obtained from Taiyu Vietnam Company, and its properties are displayed in Table IV. The test results of semi-flexible grouting material are depicted in Table V.

TABLE I. GENERAL CHARACTERISTICS OF 60/70 BITUMEN

No.	Test name	Test result	Specifications
1	Penetration at 25°C, 0.1 mm (1/10mm)	62.3	60÷70
2	Softening point (Ring and Ball Method) (°C)	48.6	≥46

TABLE II. TECHNICAL PROPERTIES OF PCB40 CEMENT

No.	Test name	Test result	Specifications
1	Compressive strength at 3 days (MPa)	21.01	≥18
2	Compressive strength at 28 days(MPa)	40.91	≥40
3	Initial setting time (min)	120	≥43
4	Final setting time (min)	180	≤420
5	Sieve residue on 0.09 mm (%)	1.2	≤10
6	Volume stability (%)	0.5	≤10
7	Specific gravity (g/cm^3)	3.1	-

TABLE III. PROPERTIES OF MINERAL POWDER

No.	Test name	Test result	Specifications
1	Moisture content (%)	0.38	≤ 1
2	Hydrophilicity coefficient (%)	0.68	⩽ 0.8
3	Specific gravity (g/cm^3)	2.7	⩾ 2.5

TABLE IV. TECHNICAL PROPERTIES OF STP-VN ADDITIVE

No.	Test name	Test result	Specifications
1	Sieve residue on 0.09 mm (%)	46.23	< 60
2	Specific gravity (g/cm^3)	2.67	2.5 ÷ 2.7

TABLE V. TEST RESULTS OF SEMI FLEXIBLE GROUTING MATERIAL

No.	Test name	Test result	Specifications
1	Fluidity (s)	12.06	10 ÷ 14
2	Flexural strength at 1 day (MPa)	1.39	-
3	Flexural strength at 7 days (MPa)	2.08	⩾ 2,0
4	Compressive strength at 1 day (MPa)	6.71	-
5	Compressive strength at 7 days (MPa)	17.07	15 ÷ 36

B. Mix Design of SFC

The mix design process for SFC was conducted for both preliminary and detailed design, in compliance with the requirements outlined in [18]. For the preliminary design process, three Asphalt Content (AC) levels were made in compliance with the mix design, namely 3.2%, 3.4%, and 3.6%. Moreover, three aggregate gradations were used, as shown in Figure 1.

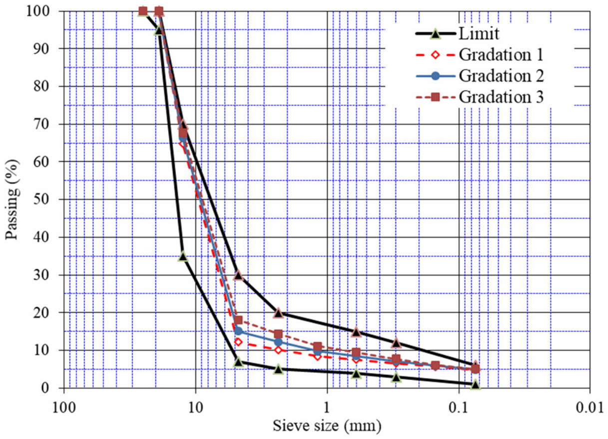

Fig. 1. The gradation of aggregate was utilized for preliminary design.

According to the mix design process, Table VI summarizes the results for bulk specific gravity, AV, Connected Air Voids (CAV), asphalt run-off content, MS, and flow.

TABLE VI. THE RESULTS OF THE MIX DESIGN CONCEPT FOR PRELIMINARY DESIGN

Gradation	AC (%)	Bulk specific gravity (g/cm^3)	AV (%)	CAV (%)	Asphalt run-off (%)	MS (kN)	Flow (mm)
Gradation 1	3.2	1.862	28.9	26.5	0.42	3.1	3.4
	3.4	1.874	28.2	25.6	0.68	3.2	3.7
	3.6	1.912	26.5	23.2	1.13	3.6	4.1
Gradation 2	3.2	1.906	27.2	24.5	0.34	3.5	3.6
	3.4	1.938	25.7	23.1	0.49	4	3.7
	3.6	2.008	22.8	19.1	0.66	4.6	4.1
Gradation 3	3.2	2.061	21.2	17.4	0.22	4.7	3.2
	3.4	2.107	19.2	14.6	0.40	5.8	3.5
	3.6	2.136	17.8	12.9	0.57	5.2	4
Specifications		≥1.9	22÷28	≥13	≤1	≥ 3	2÷4

Table VI shows that the Optimum Asphalt Content (OAC) and gradation were selected to satisfy the required AV content, while also meeting the criteria for bulk specific gravity, CAV, asphalt run-off, MS, and flow specified in [18]. Based on these requirements, Gradation 2 was selected for the detailed mix design. The OAC for this mixture was determined to be 3.4% by total mixture mass. For the detailed design process, after obtaining the preliminary design results, the plant is run, and samples are taken from the hot bin to determine the aggregate gradation. Then blending is performed. The blending results in three gradation curves, which are illustrated in Figure 1. The testing results of the mixture are outlined in Table VII. According to [18], the gradation 3 with a 3.4% AC was determined to be the most optimal and was selected for laboratory and in-situ testing.

TABLE VII. THE RESULTS OF THE MIX DESIGN CONCEPT FOR DETAILED DESIGN

Gradation	**AC** (%)	**Bulk specific gravity (g/cm3)**	**AV** (%)	**CAV** (%)	**Asphalt run-off** (%)	**MS (kN)**	**Flow (mm)**
Gradation 1	3.2	2.124	18.6	14.5	0.13	4.9	3.7
	3.4	2.130	18.2	13.2	0.34	5.8	3.9
	3.6	2.161	16.7	13.0	0.61	5.9	4
Gradation 2	3.2	2.086	20.1	16.6	0.46	5.9	4
	3.4	2.093	19.6	15.4	0.67	6.6	3.8
	3.6	2.117	18.4	14.8	0.90	6.9	4.1
Gradation 3	3.2	1.932	26	23.7	0.29	3,6	3.6
	3.4	1.945	25.3	22.7	0.6	3.6	3.7
	3.6	1.992	23.2	20.7	1.06	4.2	3.9
Specifications		≥1.9	22÷28	≥13	≤1	≥ 3	2÷4

C. *Mixture Tests*

The number of grouting materials for one specimen of the mixture can be determined using:

$$V = 3.14 \times \left(\frac{D}{2}\right)^2 \times H \times AV \times (1 + K_{TT}) \qquad (1)$$

where V is the number of grouting materials for one specimen (mL), H and D represent the specimen's length and diameter (cm), AV represents the air voids (%), and K_{TT} is the loss ratio of grouting materials.

The flexural strength of the specimen was determined from the maximum load at failure, while the tensile strain at breaking was calculated based on the mid-span deflection at the time of failure. The flexural strength and tensile strain were computed as:

$$R_F = \frac{3 \times L \times P_L}{2 \times b \times h^2} \qquad (2)$$

$$e_F = \frac{6 \times h \times d}{L^2} \qquad (3)$$

where R_F is the flexural tensile strength (MPa), ε_F is the flexural tensile strain (mm/mm), b is the width of the mid-span section of the test specimen (mm), h is the height of the midspan section of the test specimen (mm), L is the span of test specimen (mm), and P_L is the load when the specimen fails (N).

To evaluate the ITS of SFC, the requirements of [19] were utilized. The specimen measured 116 mm in height and 101.6 mm in circumference. Each SFC mixture was evaluated using three replicate specimens, and the average value of the results was utilized for evaluation. The ITS is determined as:

$$\text{ITS} = \frac{2P}{\pi HD} \qquad (4)$$

where H and D represent the specimen's length and diameter (mm), respectively. The ITS and P stand for the splitting tensile strength (MPa) and force (N), respectively.

The ITSR (%) was calculated using:

$$\text{ITSR} = \frac{\text{ITS}_{\text{wet}}}{\text{ITS}_{\text{dry}}} \times 100 \qquad (5)$$

where ITS_{wet} is the ITS at wet condition (MPa) and ITS_{dry} is the splitting tensile strength at dry condition (MPa).

III. RESULTS AND DISCUSSION

A. *Evaluation of SFC in the Laboratory*

Table VIII presents the test results for the flexural strength, ITS, ITSR, and the amount of grouting material used in the SFC samples.

TABLE VIII. RESULTS OF SFC MIXTURE IN THE LABORATORY

No.	**Test name**	**Test result**	**Specifications [18]**
1	The amount of grouting material (%)	85.1	≥80
2	The flexural strength for 7 days (MPa)	3.27	≥2.5
3	The flexural tensile strain (mm/mm)	4.1	≥3x10^{-3}
4	The ITS at 25^{0}C for 7 days (MPa)	0.97	≥0.9
5	ITSR (%)	84.1	≥80

The grouting infiltration rate in the asphalt sample was 85.1%, as shown in Table VI, exceeding the minimum requirement of 80%. This indicates that the grouting material effectively filled the voids within the asphalt mixture, ensuring strong bonding and improved structural integrity. The flexural tensile strength reached 3.27 MPa, about 30% higher than the required 2.5 MPa, demonstrating that SFC provides excellent flexural performance suitable for high-load applications. The mixture also exhibited good ductility, with a failure strain of 4.1×10^{-3} mm/mm, surpassing the required threshold of 3×10^{-3} mm/mm, thereby reducing the risk of brittle failure. Additionally, the ITS value of 0.97 MPa exceeded the minimum standard of 0.9 MPa, indicating strong resistance to tensile cracking. The ITSR value of 84.1% also surpassed the required 80%, confirming good moisture resistance and minimal strength loss after water exposure. Overall, all test parameters met or exceeded the specified requirements, demonstrating that the produced SFC mixture possesses high stability, durability, and load-bearing capacity. Therefore, SFC is well-suited for pavement construction in areas subjected to heavy traffic loads.

B. *Evaluation of Applying SFC In Situ*

A trial section in Dong Nai Province, southern Vietnam, was selected to evaluate the in-situ performance of SFC pavement. The test location was a deteriorated 60 m segment of National Highway 13 (NH13), from Km 77+680 to Km 77+740, where rutting and potholes were present. The construction process involved several steps: milling the existing asphalt layer to a depth of 5 cm, applying a tack coat at 0.5 kg/m², paving a new 5 cm asphalt layer, preparing and applying the cement grouting material to the surface, and allowing the SFC layer to cure. The construction procedure is illustrated in Figure 2.

Fig. 2. The construction process of the SFC layer.

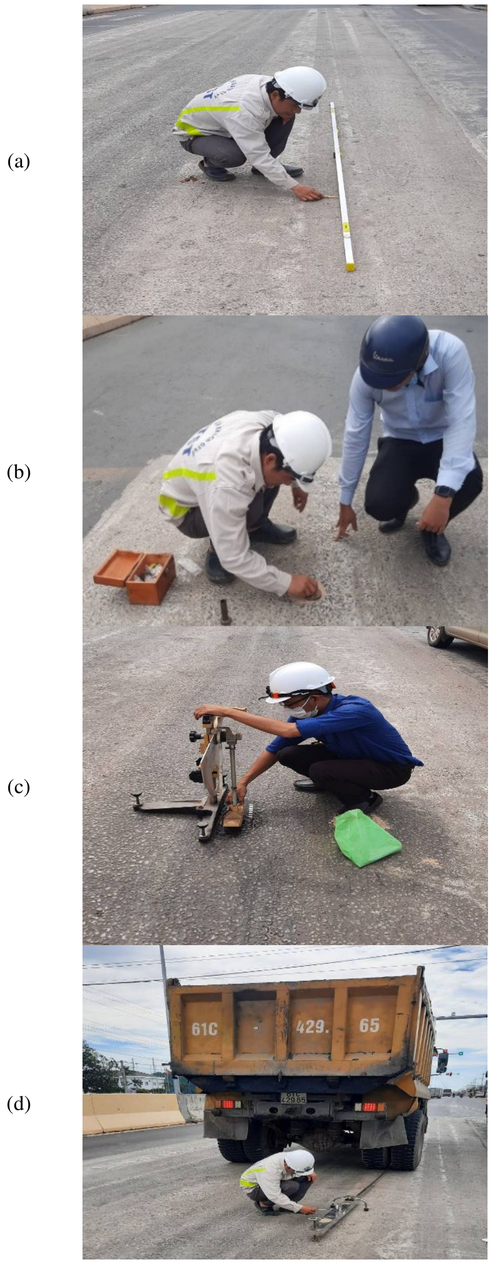

Fig. 3. SFC layer test: (a)- pavement surface roughness, (b)- pavement macrotexture depth, (c)- surface frictional properties, (d)- elastic modulus.

To evaluate the quality of the SFC layer after construction, several tests were conducted. These involved measuring pavement surface evenness using a 3 m straightedge in accordance with [20], measuring pavement macrotexture depth using the volumetric method from [21], assessing surface frictional properties using the British Pendulum Tester presented in [22], determining the elastic modulus with the Benkelman Beam based on [23], and coring samples to assess the ITS in accordance with [19]. The SFC layer testing procedures are portrayed in Figure 3.

The flatness of the SFC pavement was measured using a 3-m straightedge, as shown in Figure 4. Out of the total 56 gaps measured, 55 are less than 3 mm, accounting for 98.2%, and 1 is exactly 3 mm. Therefore, the flatness is excellent and meets the requirements for expressway, Class I, and Class II roads, in accordance with [20].

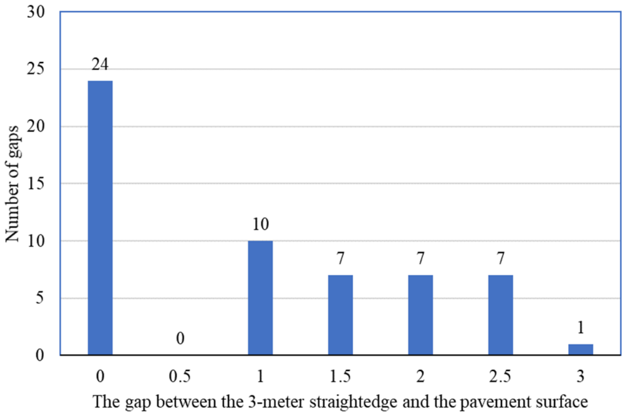

Fig. 4. Pavement surface roughness results.

The mean texture depth of the SFC pavement was measured using the volumetric technique, ranging from 0.67 mm to 1.04 mm, as depicted in Figure 5. According to [21], the pavement surface is classified as rough to very rough, with an allowable operating speed of over 120 km/h (0.8 mm < Htb < 1.2 mm).

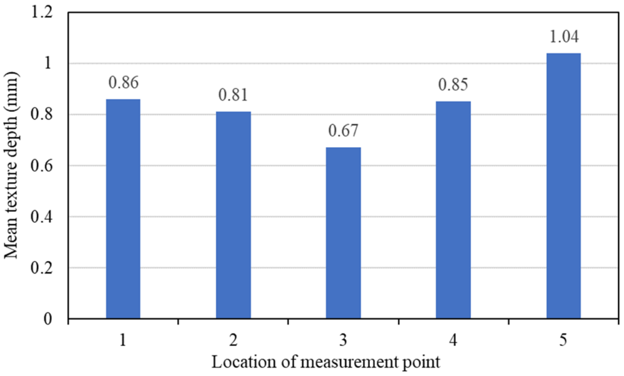

Fig. 5. The pavement macrotexture depth using a volumetric technique.

Furthermore, using the British Pendulum Tester, at five measurement locations the skid resistance values ranged from 61.6 to 83, as shown in Figure 6. According to [22], the pavement surface is classified as rough to very rough, allowing safe operation at speeds exceeding 120 km/h (Rtb > 65).

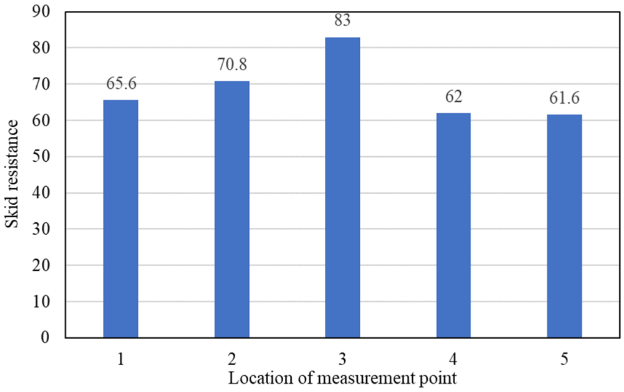

Fig. 6. British pendulum tester results.

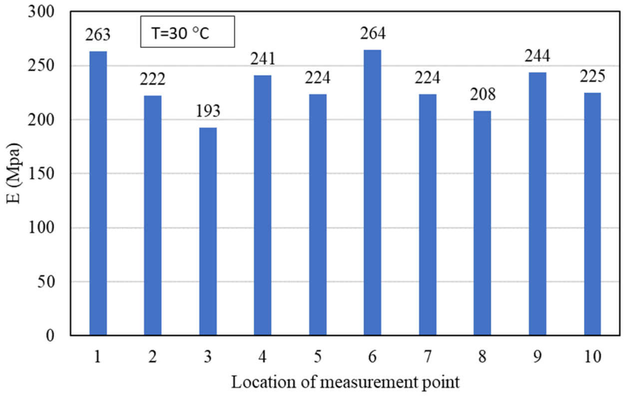

Fig. 7. The elastic modulus using the Benkelman beam.

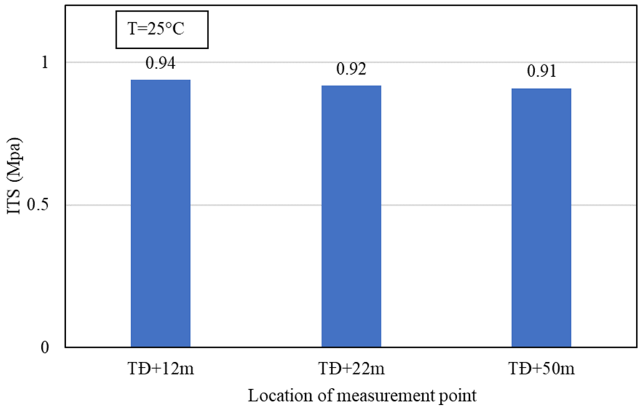

Fig. 8. The ITS uses coring samples.

As depicted in Figure 7, the elastic modulus of the SFC pavement ranged from 193 MPa to 264 MPa, meeting the specification requirements for high-traffic roadways. Similarly, the field ITS values obtained from core samples ranged from 0.91 to 0.94, as illustrated in Figure 8. These values exceed the minimum required ITS of 0.9, confirming compliance with [18].

IV. CONCLUSIONS

All performance indicators of the Semi-Flexible Concrete (SFC) mixture met or exceeded Vietnamese standards, including grouting infiltration (85.1%), flexural strength (3.27 MPa), tensile strain at failure (4.1×10^{-3} mm/mm), Indirect Tensile Strength (ITS) (0.97 MPa), and moisture resistance (ITSR = 84.1%). These results confirm that the mixture offers excellent strength, ductility, and resistance to moisture damage, making it suitable for heavy-load pavement applications. The in-situ evaluation further demonstrated that the constructed SFC pavement meets all relevant standards, exhibiting outstanding flatness, adequate surface texture, and high skid resistance, ensuring safe operation on expressways and high-speed roads. In addition, the pavement's elastic modulus falls within the required range for high-traffic roadways, indicating strong load-bearing capacity and long-term structural performance. Core sample ITS values also exceeded the specified minimum, validating the material's durability and integrity under field conditions. Overall, the findings confirm that SFC pavement is a technically feasible and effective solution for expressways, providing excellent smoothness, skid resistance, stiffness, and durability for high-speed, heavy-traffic environments. Future work will focus on assessing the long-term performance of SFC under actual heavy-traffic conditions.

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