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Research Article

The Effect of Spent Fluid Catalytic Cracking Filler on Performance Testing of Asphalt Concrete Mixture

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The spent fluid catalytic cracking (SFCC), waste from the petroleum industry, is nonstop increasing and causing environmental pollution in Vietnam. This study is an attempt to recycle SFCC in pavement construction. The study investigated the effect of SFCC, as a filler material in the hot-mix asphalt (HMA), on the essential characteristics of the asphalt concrete mix. First, the optimum percentages of bitumen and SFCC rate were investigated based on the Marshall design method. The HMA with SFCC showed more enhanced stability, flow, and other Marshall properties than the asphalt concrete mixture with the optimum limestone filler of 5%. Besides, the effects of SFCC rates on Marshall characteristics were explored. Second, performance tests were conducted to compare the mix with the different optimum content fillers of SFCC, limestone, and Portland cement. The tests include wheel tracking, indirect tensile, fatigue, and dynamic modulus tests to evaluate the performance of HMA with SFCC. It was found that the asphalt mixture with the optimum SFCC filler content can enhance pavement performance and improve the rutting and cracking resistance of the asphalt pavement.

1. Introduction

Currently, materials exploited from natural sources used in construction are increasing dramatically. It requires a replacement with new materials to conserve natural resources. Meanwhile, the spent fluid catalytic cracking (SFCC), waste from the petroleum industry, is nonstop increasing and causing environmental pollution. It is one of the types of waste that causes environmental pollution in Vietnam and the world. Vietnam has two working oil refineries. The Dung-Quoc oil refinery is located in the Quang-Ngai province, and the Nghi-Son oil refinery is located in the Thanh-Hoa province. An oil refinery discharges approximately 5-6 tons of SFCC per day. Factories often classify catalysts as hazardous waste and hire environmental companies to collect and landfills without recycling or recovering the remaining SFCC. In Vietnam, recycling waste materials such as the SFCC to save energy and natural resources is an urgent requirement. Several studies on reusing the spent catalysts were conducted to solve this problem [1–6].

Spent fluid catalytic cracking (SFCC) is not a hazardous waste based on metal contamination. The main components of SFCC are SiO_2 and Al_2O_3, similar to aluminosilicate compounds in construction materials. The main elements found in SFCC are Si and Al. The rest are Mg, K, Fe, Ti, S, V, and Ni. Ni, V, Fe, and S in SFCC may originate from crude oil. Based on the studies by Su et al. [7], the spent catalysts should be classified as general nonhazardous industrial waste. Thus, the spent catalysts could be used as a construction material with high confidence [7].

Several researchers studied reusing spent catalysts in cement concrete. They evaluated the effect of mortar compressive strength with spent catalysts, partly replacing cement and sand. The replacement percentage varies depending on the chemical composition and particle size distribution of the spent catalysts [2]. Based on the experiment, SFCC could replace 15–20% cement content [8], replacing 10% of sand [5, 7]. Notably, it was not causing an adverse effect.

SFCC could enhance the cement mortar compressive strength after 28 days of curing [2]. SFCC could enhance the compressive strength due to its microscopic size, filling the voids between coarse particles. SFCC conducts the calcium hydroxide reaction to contribute more hydrated calcium silicate gel [5, 7].

The mineral powder as a filler is an essential ingredient in asphalt mixtures [9–11]. When the mineral powder is mixed with asphalt, it hardens the asphalt and creates an asphaltic mixture with many excellent characteristics. Some enhanced features could be listed, such as increasing adhesion between the stone and plastic, increasing stability, and increasing durability in humid environments [11].

Mineral powders need to be dry, nonlumped, and porous when mixed with bitumen. The filler powder must be absorbed into bitumen. In addition, it must satisfy the mechanical and physical criteria specified in the respective standards. In Vietnam, mineral powders from carbonate stone such as limestone, dolomite stone, and powder lime are proposed for freeways, highways, and ports. People use limestone in cases where the adhesion between the natural stone and asphalt binder is required. For roads with low tonnage axle load, such as urban roads or roads in rural areas, HMA can use mineral powder derived from crushed stone or industrial waste dust. Besides cement, fly ash, and marble powder, the blast furnace slag was also used in Vietnam to produce asphalt concrete mixtures [12]. In this study, limestone (LS) as a reference filler was selected in asphalt concrete mixtures.

However, the effect of each type of mineral powder is presented when the filler is used in appropriate amounts. The overdose of mineral powders does not bring positive effects. It may destroy the structure and reduce the physical and mechanical properties of the asphalt concrete [13]. For example, too much mineral powder causing a more hardened binder leads to asphalt concrete cracking under the high-pressure value of axle loading. Besides, it reduces the film thickness of the asphalt binder surrounding large aggregates, reducing the mixture stability and making the aggregates quickly dislodge from the pavement surface. To create a high-quality asphalt concrete product, besides selecting the appropriate asphalt binder grade and stone, it is necessary to ensure a source and mineral powder rate [14].

The demand for mineral powder is very high because of the enormous asphalt concrete required in Vietnam construction. For example, Mai-Tien-Thanh Ltd. in the Quang-Nam province estimates about 500 tons of asphalt concrete production per day, which needs an average demand of about 40 tons of mineral powder/day. This study is an effort to use SFCC as filler replacing completely mineral powder in asphalt concrete in Vietnam.

Waste materials used as fillers in hot-mix asphalt concrete were investigated. These waste materials could be listed as andesite waste [15], hydrated lime [4], recycled fine aggregate powder [5], waste ceramic materials [16], coarse recycled aggregates [17], recycled waste lime [10], recycled brick powder [18], and marble dust [19].

The main objective of this paper is to study the use of spent catalysts collected from refineries in Vietnam as a filler of asphalt concretes. Marshall parameter tests and several pavement performance tests were conducted in the study. This study used the natural gradation of SFCC, which was directly obtained from the factory without pretreatment because of its easy application. Besides the asphalt concrete mixture with limestone (LS), the asphalt concrete mix with Portland cement (PC) was compared to the asphalt concrete mix with the SFCC filler in performance testing. The asphalt concrete mix with Portland cement replaced with the LS powder was the compared mixture because Portland cement was reported to improve HMA performance.

2. Experiment Preparation

2.1. The Experimental Plan. In this study, asphalt concrete specimens were prepared following the road technical standard, TCVN 8820-2011 (or ASTM D6927) [20], published by the Ministry of Science and Technology. This standard is based on the Marshall method.

A flowchart summarizing the experimental study plan is presented in Figure 1. As seen from the figure, hot-mix asphalt (HMA) samples were divided into two groups. One group of samples was prepared with conventional fillers such as limestone, while another group with samples was prepared with SFCC as a filler material (the particle size is less than 75 μm). Four different LS filler proportions (4, 5, 6, and 7%), five different SFCC filler proportions (2, 3, 4, 5, and 7%), and five different bitumen contents (4, 4.5, 5, 5.5, and 6%) were used, and the samples were tested with Marshall characteristics for determining the amount of optimum bitumen. There are three samples prepared for each of the bitumen content fractions. Marshall stabilization (MS), Marshall flow (MF), void volume values (Vh), void percentages (Vf), and voids in mineral aggregate (VMA) values were determined through the Marshall method [13, 20].

The best filler rate (FR) and the corresponding binder content for LS, SFCC, and Portland Cement PC40 were found based on the Marshall properties. Asphalt concrete mixtures with different component ratios but with the same binder type and the aggregate resource were used in the experiments. The values are summarized in Figure 1. These values of filler rate and the binder content were further investigated for the pavement performance tests considering the effect of environmental factors including moisture and temperature.

Comparison of the two cases was performed to explore the SFCC filler affecting mixture design following the Marshall design procedure. On the one hand, the investigation was performed for the mixture with the same aggregate and different SFCC filler rates. On the other hand, the investigation was performed for the mixture with the same bitumen content and different filler rates.

Various laboratory tests were conducted to evaluate the performance of the HMA containing SFCC. The laboratory performance tests were performed to compare mixtures with the optimum filler content of SFCC to mixtures with LS and PC. The test includes the dynamic modulus, static modulus, Cantabro mass loss, indirect tensile strength, moisture susceptibility, wheel tracking, and indirect tensile fatigue

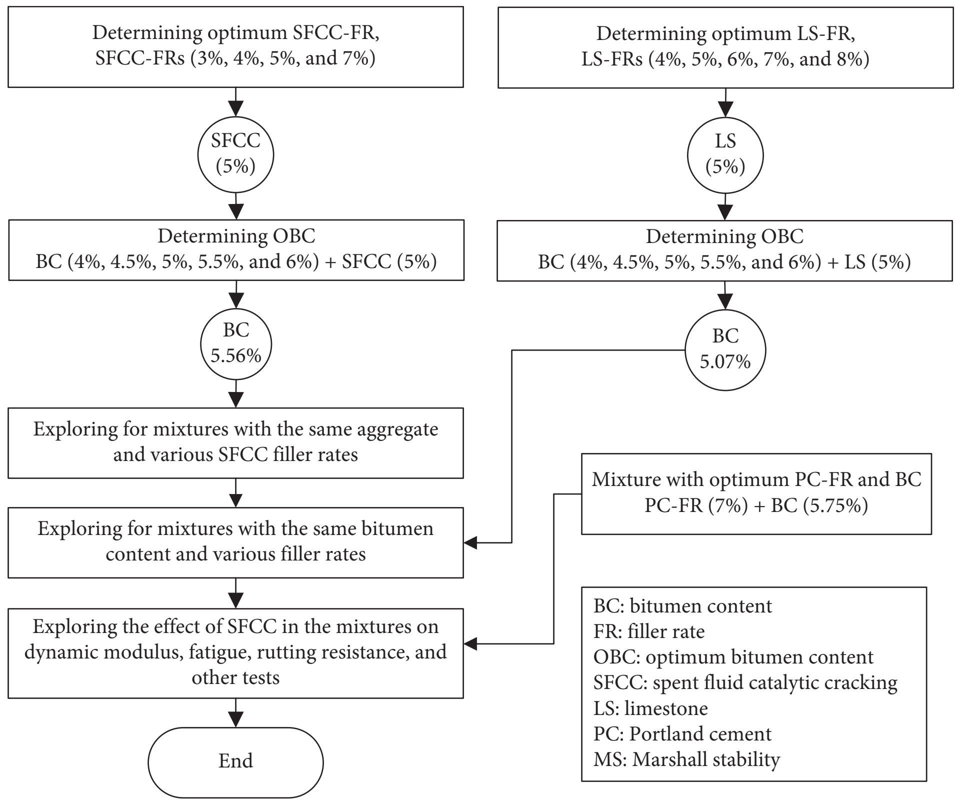


Figure 1: Experimental program.

tests. All the materials used in the laboratory tests are the same as the materials used in the Marshall tests. Some necessary equipment used for the HMA performance test is presented in Figure 2.

2.2. Mineral Aggregate. Limestone was the crushed aggregate obtained from the Binh-Duong province, mainly used in asphalt concrete supplied for Ho Chi Minh city. The properties of the aggregate are summarized in Table 1. In the study, aggregate grading curves for asphalt mixtures were obtained from TCVN 8820-2011 [20]. The chosen aggregate gradation for the asphalt concrete mix is the aggregate gradation of the nominal maximum aggregate size of 12.5 mm. This aggregate gradation was employed in the entire study. The selected aggregate grading curve was between the upper and lower limit curve given in the specification, as shown in Figure 3.

2.3. Asphalt Binder. The asphalt binder grade of 60–70 penetration was utilized to prepare the Marshall samples. One type of asphalt binder was employed for all test specimens in this study. This asphalt binder, which had a penetration of 64 (0.1 mm at 25°C, 100 g, and 5 s), ductility larger than 110 mm (at 25°C), softening point of 46°C, and specific gravity of 1.03 Mg/m^3, was supplied by Vietnam National Petroleum Group, Vietnam.

2.4. Filler. In Vietnam, the mineral filler powder used in the asphalt concrete mix is usually a fine powder obtained from crushed rocks (calcite limestone and dolomite) or the slag of furnaces or cement. It is pronounced that the mineral filler in the mixture has contained high percentage of particles that could pass through the No. 200 (0.075 mm) sieve. The mineral filler powder must have at least 70% of particles that can pass through the 0.075 mm sieve.

The SFCC filler was obtained from the Quang-Ngai province, where the Dung-Quoc oil filtering company is located. Table 2 shows the chemical analysis results of the SFCC samples. Table 3 shows the properties of the SFCC samples used in the test. Scanning electron microscopy (SEM) images of the SFCC filler are shown in Figure 4 [21]. The SFCC powder is very fine, and most particles are approximately 20 μm. The particle size of the SFCC powder is determined according to ASTM C117-95 [22] and TCVN 4030-85 [23] and summarized in Table 3.

The LS filler and PC filler used in this study were INSEE Bitu Fill and Portland Cement PC40. The INSEE Bitu Fill mineral powder is a high-quality filler product in Vietnam. The INSEE Bitu Fill has high surface area (the specific surface area is 3,000 cm^2/g). Other characteristics of the mineral filler are summarized in Table 3. The specific surface area of SFCC is equivalent to that of the mineral powder (2,980 cm^2/g). SFCC has lower specific gravity than the compared mineral powder. Thus, the optimum percent by weight of SFCC might be less than the ideal percent by LS weight.

2.5. Asphalt Mixture Preparation. All materials were prepared a day before mixing to produce asphalt concrete (following ASTM D6926 [24]). The aggregates and fillers

(a) (b) (c) (d) (e) (f)

FIGURE 2: Equipment used for (a) fatigue and dynamic modulus tests, (b) static modulus test, (c) Cantabro loss test, (d) Marshall tests, (e) wheel tracking test, and (f) vacuum equipment for retained tensile strength ratio test.

TABLE 1: Properties of aggregates used in the tests.

Material	Specific gravity (g/cm^3)		Water absorption (%)
	Bulk specific gravity	Apparent specific gravity	
Aggregate size 10–16	2.698	2.746	0.65
Aggregate size 5–10	2.678	2.749	0.97
Aggregate size 0–5	2.656	2.746	1.23
Los Angeles abrasion loss (%)		14.64	

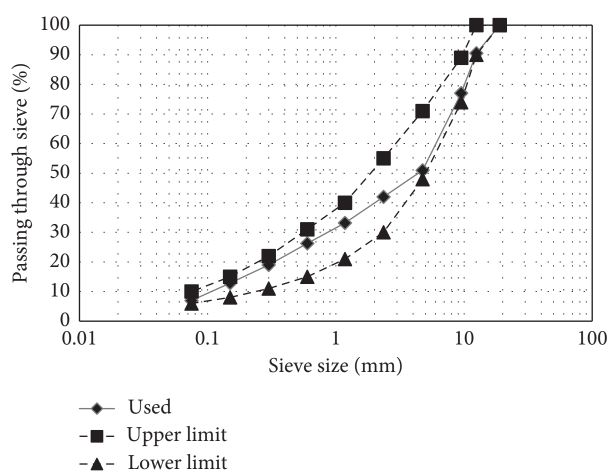


FIGURE 3: Grading curves of aggregates.

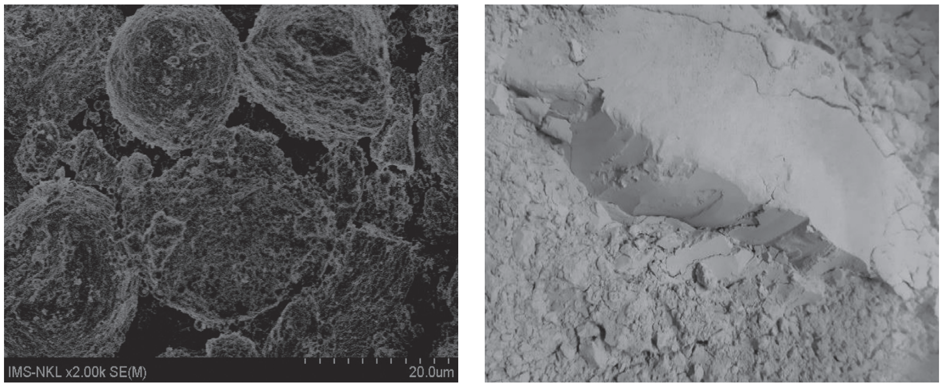
TABLE 2: Chemical composition of the SFCC from X-ray fluorescence analysis.

Compound	SiO_2	Al_2O_3	La_2O_3	Fe_2O_3	TiO_2	NiO	P_2O_5	Na_2O	CaO	CeO_2	V_2O_5	MgO	LOI
Weight (%)	46.81	45.4	2.52	1.52	1.38	0.53	0.33	0.32	0.23	0.18	0.14	0.07	0.57

LOI: loss on ignition.

TABLE 3: Properties of the filler used in the tests.

Properties	Standard	SFCC	LS
Specific gravity (g/cm^3)	TCVN 4030-85	2.248	2.739
Specific surface area (cm^2/g)	TCVN 4030-85	2980	3000
Percentage by weight passing through sieve No. 200 (%)	TCVN 4030-85	93.5	85
Percentage retained on the sieve of 45 μm (%)	ASTM C117:95	28	—



(a) (b)

Figure 4: Spent FCC catalysts: (a) Scanning electron microscope image and (b) SFCC filler.

were heated overnight at 100 ± 5°C in the oven to ensure a moisture-free condition. After that, the aggregates and fillers were heated for four hours at a temperature of 150 ± 5°C. Before mixing with aggregates, the asphalt binder was heated until the mixing temperature of 150 ± 5°C is reached.

The asphalt concrete mixture was designed based on the Marshall method. The specimens were compacted using the Marshall hammer at 135 ± 5°C, with 75 blows for each end of an asphalt concrete prismatic specimen. The final sample dimensions were approximately 101.6 mm in diameter and 65–75 mm in height. All specimens were removed from their steel mold after a 24-hour curing period. The volumetric measurement was conducted for all specimens. The Marshall stability test was carried out according to TCVN 8820-2011 [20] (or ASTM D6927 [24]).

For the fatigue, static modulus, and dynamic modulus test, cylindrical samples of the asphalt mixtures with a diameter of 150 mm and a height of 200 mm were prepared by the hydraulic pressure equipment. The compacted samples were cut into test samples. In the fatigue test case, the sample dimensions were 150 mm in diameter and 60 mm in thickness. In the static modulus test, the test sample dimensions were 100 mm in diameter and height. The sample dimensions were 100 mm in diameter and 150 mm in height in the dynamic modulus test.

3. Test Setup and Procedure

3.1. Marshall Tests. The Marshall test is the current mix design method in Vietnam. The Marshall test was utilized to find the optimum asphalt content based on the Marshall test results and the volumetric parameters. Thus, several volumetric parameters were determined, including unit weights, maximum theoretical bulk specific gravities, air voids, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), Marshall flow, and Marshall stabilities [13]. In this study, the criteria of mixture characteristics were considered based on both TCVN 8820-2011 [20] and MS-2 asphalt mix design methods [13].

3.2. Cantabro Test. The Cantabro mass loss test was conducted for the abrasion resistance test using a Los Angeles abrasion testing machine without steel balls under ASTM C 1747 [25]. A set of three identical cylindrical specimens of 100 mm diameter and 64 mm height were prepared and placed in the Los Angeles abrasion testing machine. The test was performed under a condition of 25°C. The initial weight of each specimen (A) was recorded before placing it into the machine. Then, the machine was allowed to rotate at a revolution level of 300 revolutions. After that, the abraded specimens were cleaned from any debris and weighed (B). Finally, the percentage loss was calculated using equation (1). According to the Vietnamese standard, the Cantabro abrasion of the studied asphalt sample was specified as CL ≤ 20%:

$$\mathrm{CL} = \frac{A - B}{A} \times 100\,(\%), \tag{1}$$

where CL is the Cantabro mass loss (%), A is the initial weight of the test specimen (grams), and B is the weight of the test specimen (grams).

3.3. Static Modulus Tests. Elastic modulus is a fundamental property of an asphalt mixture that can be used, in an analytical method, to determine the thickness of pavement layers. It is also one of the parameters to determine the stress-strain analysis in the finite element method (FEM). It was experimented according to 22TCN 211-06 [26]. The following formula was used for the calculation of elastic modulus:

$$E = \frac{pH}{L}, \tag{2}$$

where E is the elastic modulus (MPa), L is the elastic deformation measured during the pressing test (mm), H is the sample height (mm), and p is the force acting on the sample. The experiment usually takes $p = 0.5$ MPa [26].

3.4. Dynamic Modulus Tests. The dynamic modulus tests were performed on the cylindrical asphalt concrete specimens in the uniaxial testing mode, following AASHTO TP 62-03 [27]. Linear variable differential transformers (LVDTs) were attached to the specimen surface with a gauge length of 100 mm. Vertical deformations averaged from

LVDTs were used to calculate the dynamic modulus. Based on the AASHTO TP 62-03, modulus was determined at five temperatures (–10°C, 4.4°C, 21.1°C, 37.8°C, and 54.0°C) and six loading frequencies (25, 10, 5, 1.0, 0.5, and 0.1 Hz). The loading levels were adjusted until the strain level was 0.00005. After that, the frequency-temperature superposition concept was applied to determine the master curve of the dynamic modulus at the reference temperature.

3.5. Indirect Tensile Tests. An indirect tension (IDT) strength was tested under ASTM D 6931 [28]. The peak compressive load (P_{max}) was measured to calculate all the indirect tensile strengths of specimens. The indirect tension strength was estimated using the following equation:

$$\sigma_{IDT} = \frac{2000P_{max}}{\pi t D}, \quad (3)$$

where σ_{IDT} is indirect tensile strength (kPa), P_{max} is the peak load (N), t is the sample thickness (mm), and D is the sample diameter (mm).

Retained tensile strength ratio (TSR) determined from the IDT tests was used to examine the moisture susceptibility of HMA. The specimens of every testing mixture were prepared and divided into two groups. The first group of specimens was placed in an environmental chamber at 25°C for two hours to measure the dry condition tensile strength. The second specimen group was immersed in water at 60°C for 24 h before the specimens were put in water at 25°C for two hours. The IDT tests were conducted on the dry and wet specimens at a displacement rate of 50 mm/min, under a temperature condition of 25°C, using a servohydraulic testing system.

$$\text{TSR} = \frac{\sigma_{IDT_{wet}}}{\sigma_{IDT_{dry}}} \times 100\,(\%), \quad (4)$$

where $\sigma_{IDT_{wet}}$ is the indirect tensile strength under the wet condition (kPa) and $\sigma_{IDT_{dry}}$ is the indirect tensile strength under the dry condition (kPa).

Besides, the retained Marshall stability test was determined to evaluate the effect of the filler on the loss of compressive strength of asphalt mixes after water immersion [29]. Therefore, the MSR was computed as follows:

$$\text{MSR} = \frac{\text{MS}_{wet}}{\text{MS}_{dry}} \times 100\,(\%), \quad (5)$$

where MSR is the Marshall stability ratio (%), MS_{dry} is the Marshall stability of the specimen under dry condition (kN), and MS_{wet} is the Marshall stability of the immersed specimen (kN).

3.6. Fatigue Tests. DTS-30, a Pavetest hydraulic universal testing machine (Figure 2(a)) equipped at HCMUTE, was utilized to test the fatigue resistance of asphalt mixture samples. The applied standard was EN 12697-24, Annex E (Indirect tensile test on cylindrical-shaped specimens) [30]. The fatigue tests were conducted in the indirect tensile mode when temperature and frequency were fixed at 20°C and 10 Hz, respectively. The applied load was a haversine wave with a 0.1 s loading time without rest periods. The load repetition number corresponding to the stiffness decreases to 50% of the original stiffness value and is defined as the fatigue life of the specimen. The fatigue coefficients a and b shown in equation (6) were estimated through a regression analysis of the test data.

$$N_f = a(\varepsilon_0)^b, \quad (6)$$

where N_f is the fatigue life of the asphalt mixture, ε_0 is the initial tensile strain, and a and b are fatigue coefficients.

3.7. Wheel Tracking Tests. The wheel tracking tester developed by Hamburg Wheel Tracker made in Germany was used according to the AASHTO T324-04 [31] test procedure. Steel wheels were used for experiments in water. The wheel diameter and width were 203 mm and 50 mm, respectively. The wheel load of 0.7 MPa was applied to the 320 mm × 260 mm × 50 mm slab specimens immersed in water. The wheel passes 50 times per minute through the center of the specimen. The wheel tracking tests were conducted at a water temperature of 50°C to evaluate the permanent deformation characteristics of asphalt mixtures.

The dynamic stability (DS) index was used to evaluate the rutting resistance characteristics of asphalt mixture. A higher DS value represents a higher rutting resistance ability of the asphalt mixture. The dynamic stability was estimated based on the rutting depth data at 45 and 60 minutes and is calculated by the following equation:

$$\text{DS} = \frac{(t_2 - t_1)}{(d_2 - d_1)} \times N \times C_1 \times C_2, \quad (7)$$

where d_1 is the rutting data (mm) corresponding to the time t_1, d_2 is the rutting data (mm) corresponding to the time t_2, C_1 is the test machine correction factor, C_2 is the specimen coefficient, and N is the number of applied loads in a minute.

4. Optimum Filler Rates

4.1. Finding Limestone Filler Rates. Mixtures were prepared with LS filler of 4, 5, 6, and 7% by weight of the total mix. These mixtures were tested with the Marshall test for determining the amount of optimum bitumen based on six different bitumen contents (4, 4.5, 5, 5.5, and 6%). As a result, the optimum binder content (OBC) percentages of 5.18, 5.07, 5.13, and 5.22% were found for the mixture with 4, 5, 6, and 7% LS filler, respectively. Figure 5(a) shows that all Marshall stability values were more considerable than the limit value of 8 kN [13]. If the saving material is based on choosing the filler rate, the 5% mineral powder was chosen. Besides, the 5% mineral powder was chosen for the asphalt concrete mix from the following analysis:

(i) Figure 5(d) shows that the air void was 3.33% if the mineral filler was 5%, while the air void was 4.84% if the mineral filler was 7%. Suppose the target design air void was 4%. In that case, the 5% mineral powder

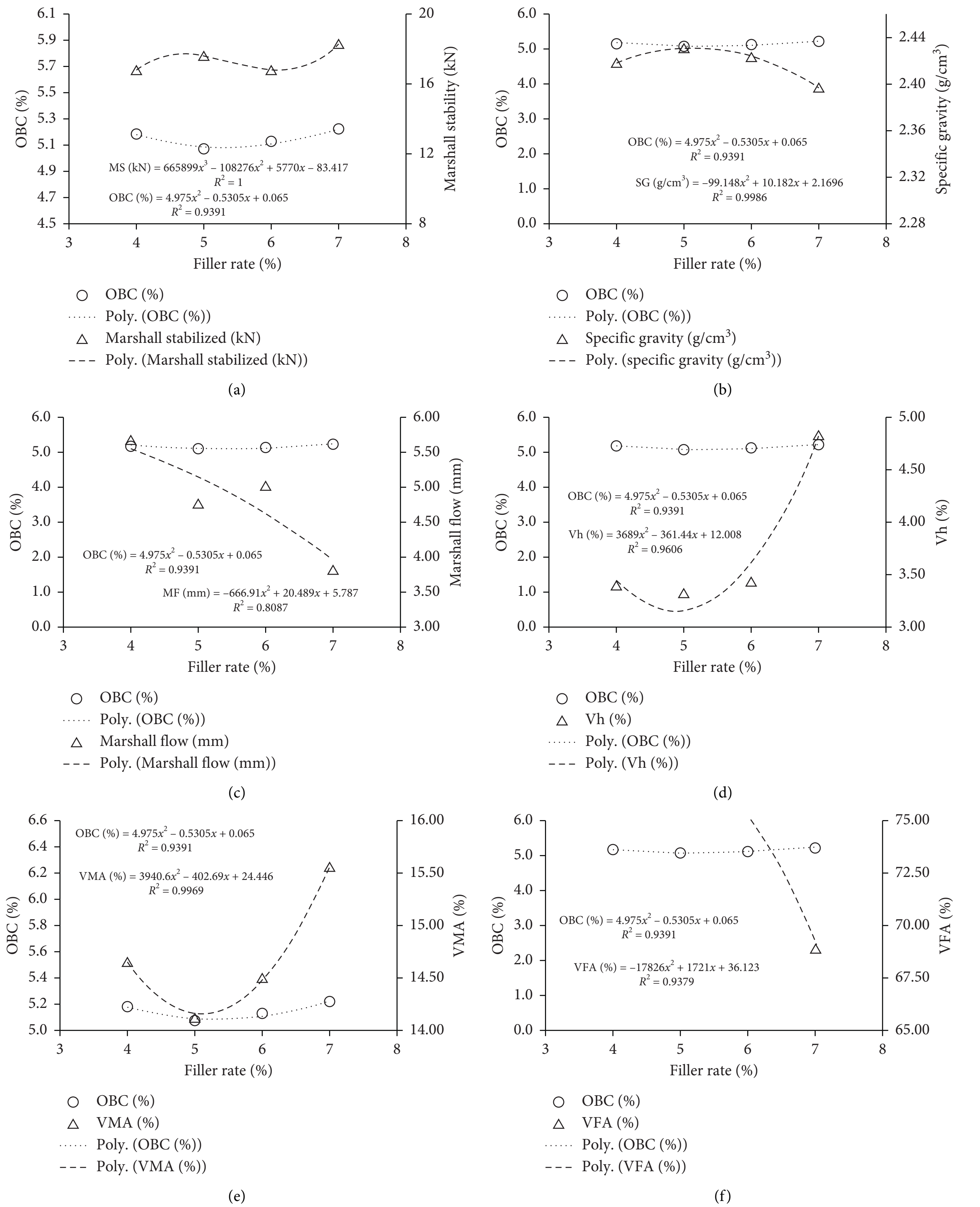


Figure 5: Relationship between the rates of the LS filler and OBC and (a) Marshall stability, (b) specific gravity, (c) Marshall flow, (d) design air voids, (e) VMA, and (f) VFA.

rate could be selected because the 3.33% is closer to 4% than the value of 4.84%.

(ii) Figure 5(e) shows that VMA varies from 14.12 mm to 15.55 mm. These values were higher than the lower bound value of VMA (14%) [13]. Based on OBC, an LS filler rate of 5% was selected because the required OBC was the lowest.

(iii) Figure 5(b) shows that the maximum bulk specific gravity was 2,431 Mg/m^3, corresponding to an LS filler rate of 5%. Figure 5(c) shows a Marshall flow of 4.75 mm in the case of 5% LS. The value was higher than the acceptable value of 3.5 mm [13]. With a filler rate of 5% in Figure 5(f), the VFA value was 76.5%. Although VFA was little (2%) higher than the VFA upper limit of 75% [13], the mineral powder rate of 5% could be selected based on the bulk specific gravity, Marshall flow, and VFA.

The asphalt concrete mix with 5% LS filler, which had high Marshall stability, and many other good Marshall test properties, was chosen as the control mixture.

4.2. Finding SFCC Filler Rates. Mixtures were prepared with SFCC filler rates of 2, 3, 4, 5, and 7% by weight of the total mix for determining the amount of optimum SFCC. The mixture with 2, 3, 4, 5, and 7% SFCC filler had the optimum binder content (OBC) percentages of 4.8, 5.11, 5.16, 5.56, and 6.09%, respectively. Figure 6 presents the OBC and other properties of the mixture varying with filler rates. The optimum SFCC filler rate was selected from 4% to 5% based on the analysis results from Figure 6.

Figure 6(a) presents that the OBC increased with an increase in the SFCC filler rate. Besides, the chart shows that all Marshall stability values were higher than the limit value of 8 kN, and the Marshall stability achieved the highest values at the filler rates from 4% to 7%. Thus, the SFCC filler rate from 4% to 5% could be selected for the asphalt concrete mix if the filler rate was chosen based on the reduction in the asphalt binder content.

Furthermore, the selected SFCC powder rate was from 4% to 5% based on bulk specific gravity (Figure 6(b)), Marshall flow (Figure 6(c)), the air void of mixtures (Figure 6(d)), and VFA (Figure 6(f)). The mixture with 4 and 5% SFCC having the Marshall flow was in the acceptance range from 2 mm to 3.5 mm [13]. In addition, the air void values of asphalt concrete mixtures were near to the designed air void of 4% with the SFCC rate varying from 4 to 5%. The air void corresponding to the 4% SFCC was 3.47%, while the air void corresponding to the 5% SFCC was 4.08%. The VFA values of mixtures having 4 and 5% SFCC filler rates were in the specified range of VFA (from 65 to 75%). The VFA values were 72.95 and 71.29% for mixtures with filler rates of 4 and 5%, respectively.

The difference between the mixtures with 4% SFCC and 5% SFCC is shown in Figure 6(e). VMA of mixtures with a 4% SFCC is lower than 14%, the required value of VMA, while the VMA of mixtures with a 5% SFCC is higher than 14%. The asphalt concrete mixtures with 4% SFCC filler have a high Marshall stability and a low value of OBC. However, VMA, which is related to the HMA pavement durability, is lower than the lower limit of VMA.

In the next section, the asphalt concrete mixtures with both 4 and 5% SFCC filler are compared to the control mix with LS filler in Table 4.

4.3. Optimum Asphalt Content. The selected filler rates of both SFCC filler and LS filler were analyzed to determine the optimum asphalt content. As a result, the 5% LS filler gave the percentage optimum bitumen content of 5.07. In the SFCC filler case, 4% SFCC and 5% SFCC gave the percentage optimum bitumen content of 5.16 and 5.56, respectively. Other Marshall properties corresponding to the optimum bitumen content are summarized in Table 4.

Table 4 shows the Marshall properties corresponding to the optimal filler and binder content rate. The acceptance values are obtained according to MS-2 asphalt mix design methods [13]. Asphalt concrete mixes using 5% LS have two Marshall properties that did not meet the specification requirements. They were Marshall flow and VFA. The percentages of Marshall flow and VFA that exceeded the acceptable upper limit were 35.7% and 2%, respectively. Besides, the Marshall stability of mixtures containing SFCC is higher than the mix containing LS. Higher ratios were 36% and 41%, respectively, with an SFCC content of 5% and 4%. The air voids of the mixtures containing SFCC were more approximate to 4% than the mix containing LS.

The asphalt concrete mixture using 5% SFCC had all the properties that met the specification requirements, while those mixtures using 4% SFCC had a property under minimum specification values. For example, the VMA value under the lower limit value of 14% was about 5.7%. Thus, the asphalt concrete mix having 5% SFCC filler and 5.56% bitumen content was the optimum mix. These mixture components were used to make specimens for further testing.

5. Exploring the Effect of SFCC on Asphalt Concrete Mix

5.1. Mixtures with the Same Aggregate and Various SFCC Filler Rates. Figure 7 shows the influence of Marshall properties due to the variation in both asphalt binder contents and filler rates. The limestone aggregate and aggregate gradation were kept unchanged, while the filler powder rates varied. The percentage of the SFCC filler varied from 2 to 7%. The reference mixture was the asphalt concrete mixture with 5% LS filler, which was chosen above.

Figure 7(a) shows that all samples gave a Marshall stability value higher than the lower limit of 8 kN. The Marshall stability decreased when the asphalt binder content increased. The Marshall stability of mixtures containing the SFCC filler was higher than the mixtures containing the LS filler at the same percentage of the asphalt binder content. It proves that the SFCC filler affected the strength of the asphalt concrete. With the increase in the SFCC filler rates, the stability value increased, as shown in Figure 7(a). At the

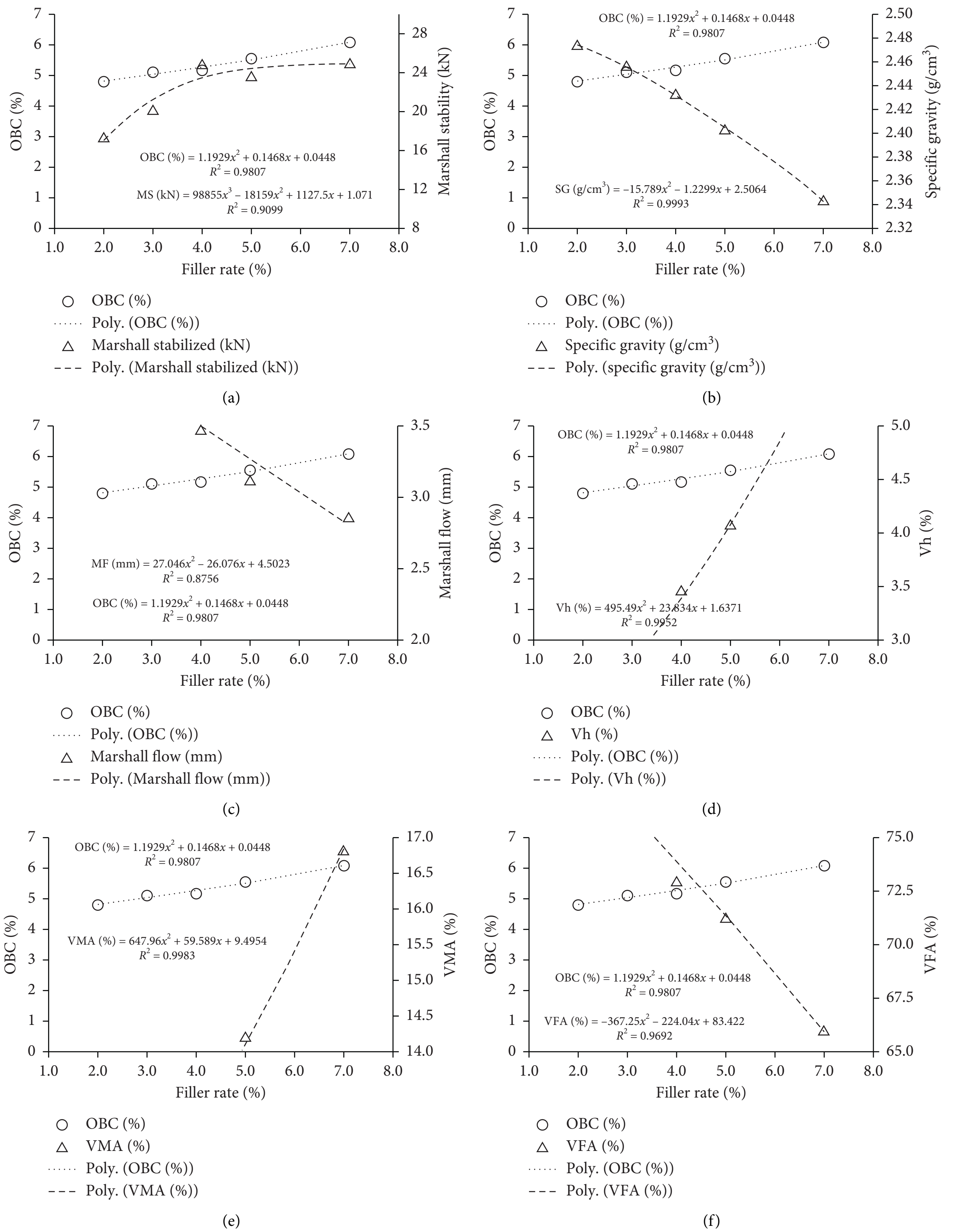


Figure 6: Relationship between rates of the SFCC filler and OBC and (a) Marshall stability, (b) specific gravity, (c) Marshall flow, (d) design air voids, (e) VMA, and (f) VFA.

Table 4: HMA mixture properties corresponding to the optimum bitumen content.

Properties	SRCC (4%)	SRCC (5%)	LS (5%)	Acceptance values
Bulk specific gravity (g/cm^3)	2.43	2.40	2.43	Max.
Marshall stability (kN)	24.90	24.03	17.63	>8 kN
Marshall flow (mm)	3.47	3.05	**4.76**	2–3.5
Air void (%)	3.47	4.04	3.33	3%–5%
VMA (%)	**13.25**	14.48	14.12	>14%
VFA (%)	73.94	72.07	**76.50**	65%–75%

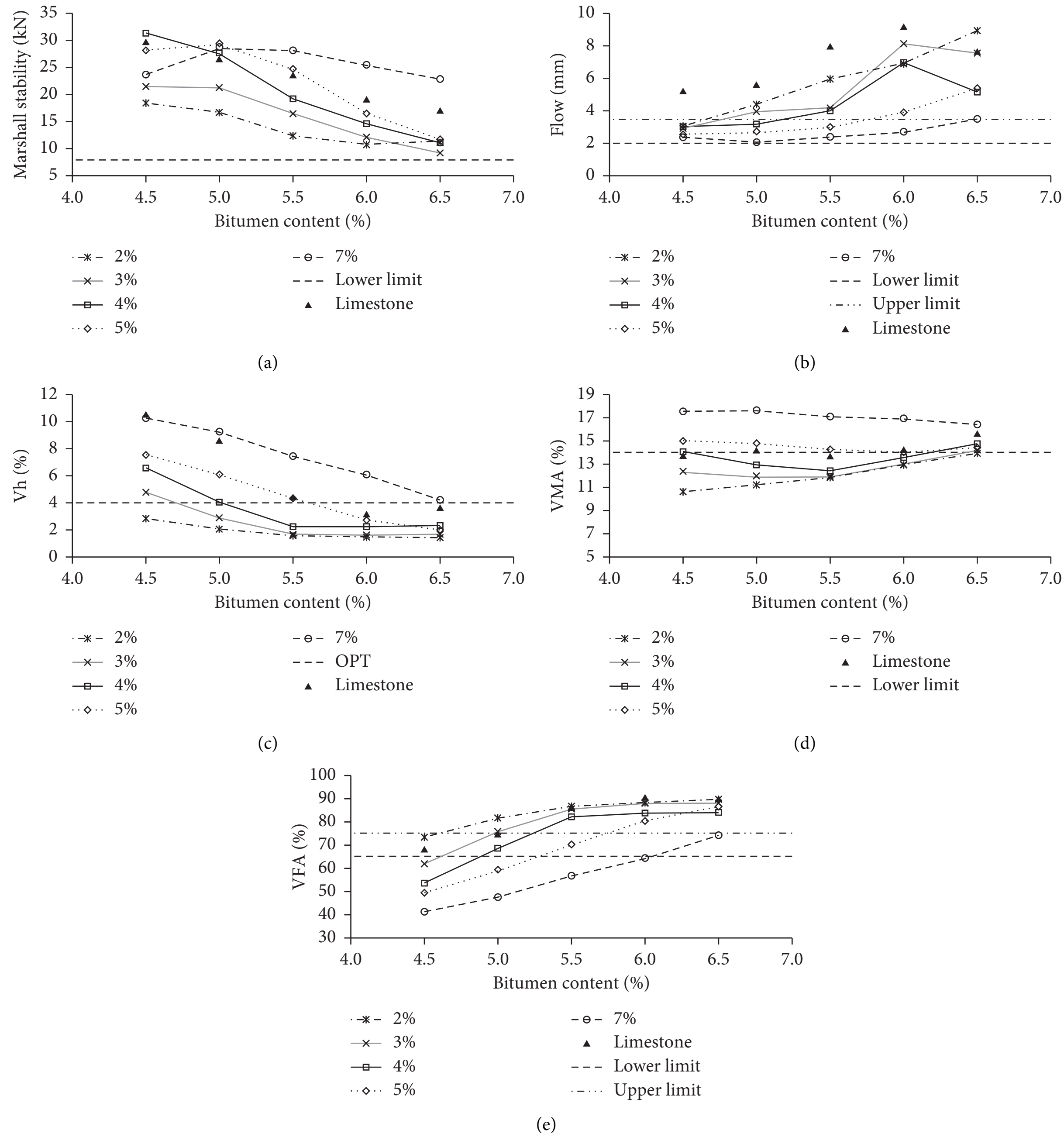


Figure 7: Test property curves for hot-mix design data by using the Marshall method.

proper filler rate of SFCC, the Marshall stability value of the asphalt concrete mixtures was higher than that of the mixture with the optimum LS filler rate.

All asphalt mixes containing SFCC showed a lower Marshall flow than those containing the LS filler, as shown in Figure 7(b). The asphalt concrete mixture is too plastic or unstable if the flow at a certain optimum binder content is above the specified upper limit. It is too brittle if the flow is below the lower specified limit. The LS filler may cause the mix to be too brittle, while the SFCC filler can help reduce the Marshall flow of the asphalt mixture to an acceptable range. If the Marshall flow is considered related to the internal friction coefficient, the SFCC filler could increase the internal friction coefficient. Thus, SFCC could increase resistance to rutting occurring on the asphalt pavement surface.

The mixture flow with different filler rates showed a nonlinear relationship (Figure 7(b)). The Marshall flow value decreased as the SFCC rate increased, while the Marshall flow value increased as the asphalt binder content increased. Besides, if the filler rate of SFCC was 7%, the Marshall flow of the mixtures with the asphalt binder content varying from 4.5 to 6.5% was entirely within the specified limit, from 2 mm to 3.5 mm.

Figure 7(c) shows that the air void value of the asphalt concrete samples with the same SFCC rate was reduced as the asphalt binder content increased. Besides, the air void in asphalt concrete samples with the same asphalt binder content increased as the content of SFCC increased. To reach the design air void of 4%, asphalt concrete mixtures needed increasing asphalt binder content as the content of SFCC increased (Figure 7(c)). It indicates that the asphalt concrete mix using SFCC requires more asphalt binder to achieve the design air void.

Researchers always consider the adequate film thickness for any given type of asphalt and aggregate mixture. The attained film thickness relates to the durability of HMA pavement. The adequate film thickness reflects the VMA property. Voids in mineral aggregate (VMA) should be adequately established during mix design and in the field. It helps in enhancing the pavement performance without excessive asphalt bleeding or flushing [13]. VMA was relatively stable in samples with the LS filler and reached the minimum value specified for VMA, as shown in Figure 7(d). When using SFCC as the filler in the mix, the VMA value was not stable. However, VMA exceeded the minimum value of VMA for all asphalt binder contents when the percentage of SFCC in the asphalt concrete mix was higher than 5% (Figure 7(d)).

VFA relates to the film thickness, which reflects the effective asphalt content. Several research results show that the film thickness could be greater if the aggregate is the coarser gradation. In other words, the film thickness increases by decreasing or minimizing the percentage of fine particles. As the SFCC content in the mix increases, the percentage of fine particles increases, and VFA is affected. Figure 7(e) shows that increasing the SFCC rate decreased the VFA value in the asphalt concrete mixtures having the same asphalt binder content. Meanwhile, the VFA value in the asphalt concrete mix having the same SFCC filler rate increased with increasing asphalt binder content. Therefore, it is necessary to increase the asphalt binder content so that VFA could be in the acceptable range. As a result, the SFCC filler content increased in the mix; and the amount of asphalt binder required for controlling the VFA value in the acceptable range also increased.

5.2. Mixtures with the Same Bitumen Content and Various Filler Rates. The properties of the asphalt concrete mixture depend on the amount and the size of the mineral powder, with the same percentage of the asphalt content. The mixture becomes dry and unstable as the filler rate increases. Thus, the asphalt concrete mixture requires additional asphalt binder. Besides, a small decrease in the powder filler content causes the opposite effect. Too low filler rate results in an asphalt concrete mixture required rich in asphalt binder for filling the air voids. On the other hand, the SFCC filler has an abundance of tiny particles and is expected to result in an asphalt concrete mixture that seems to have more asphalt.

Various filler contents result in mixes with too little or too much asphalt. Two different terms of the asphalt content mentioned in the asphalt mix technology are the total asphalt content and the effective asphalt content. The amount of asphalt required for a mixture to produce the desired mix quality is the total asphalt content. The total and effective asphalt contents are considered in this section. For this purpose, asphalt concrete mixtures with the same bitumen content and various filler rates are considered. Mixtures with 5% asphalt binder content were prepared with 2, 3, 4, 5, and 7% SFCC filler and 5% LS filler. An asphalt binder content of 5% is the optimized asphalt binder content of the asphalt concrete mix with 5% LS filler.

With the same asphalt binder content and compacting energy, the bulk specific gravity decreased as the SFCC rate increased, as shown in Figure 8(a). The relationship between the SFCC filler content and the bulk specific gravity is a quadratic function, a convex parabolic curve. Compared to the 2% SFCC rate mixture, the mix with a 7% SFCC rate had bulk specific gravity decreased by 7%. The reducing bulk specific gravity of asphalt concrete samples as the SFCC filler rate increases was due to the increased air voids inside the samples. The relationship between the SFCC filler and the air void was also a quadratic function, a concave parabolic curve (Figure 8(b)). The increase in air voids in the samples with SFCC rates of 2% and 7% was 4.5 times. Thus, the SFCC powder played the filler role and absorbed the asphalt binder and caused a significant increase in the air void volume when the SFCC rate was too high in the asphalt concrete mix.

Although the air void in the asphalt concrete samples significantly increased in the HMA with an SFCC rate of 7%, Marshall stability was still higher than the Marshall stability of the asphalt concrete mixture containing an optimum LS filler rate (Figure 8(c)). The increase in Marshall stability can be attributed to SFCC, which improves the adhesion between the aggregate and bitumen. Generally speaking, SFCC helped in improving the Marshall stability markedly. The relationship between the SFCC filler rates and Marshall stability was a parabolic curve. Marshall stability increased with the increase in SFCC, with a maximum value at an SFCC rate of 5%, and decreased at an SFCC rate of 7%. This trend has obeyed the rule of filler rates in HMA discussed above.

Besides, SFCC also helped in improving the Marshall flow significantly. With the same asphalt binder content, the Marshall flow decreases linearly when the SFCC content

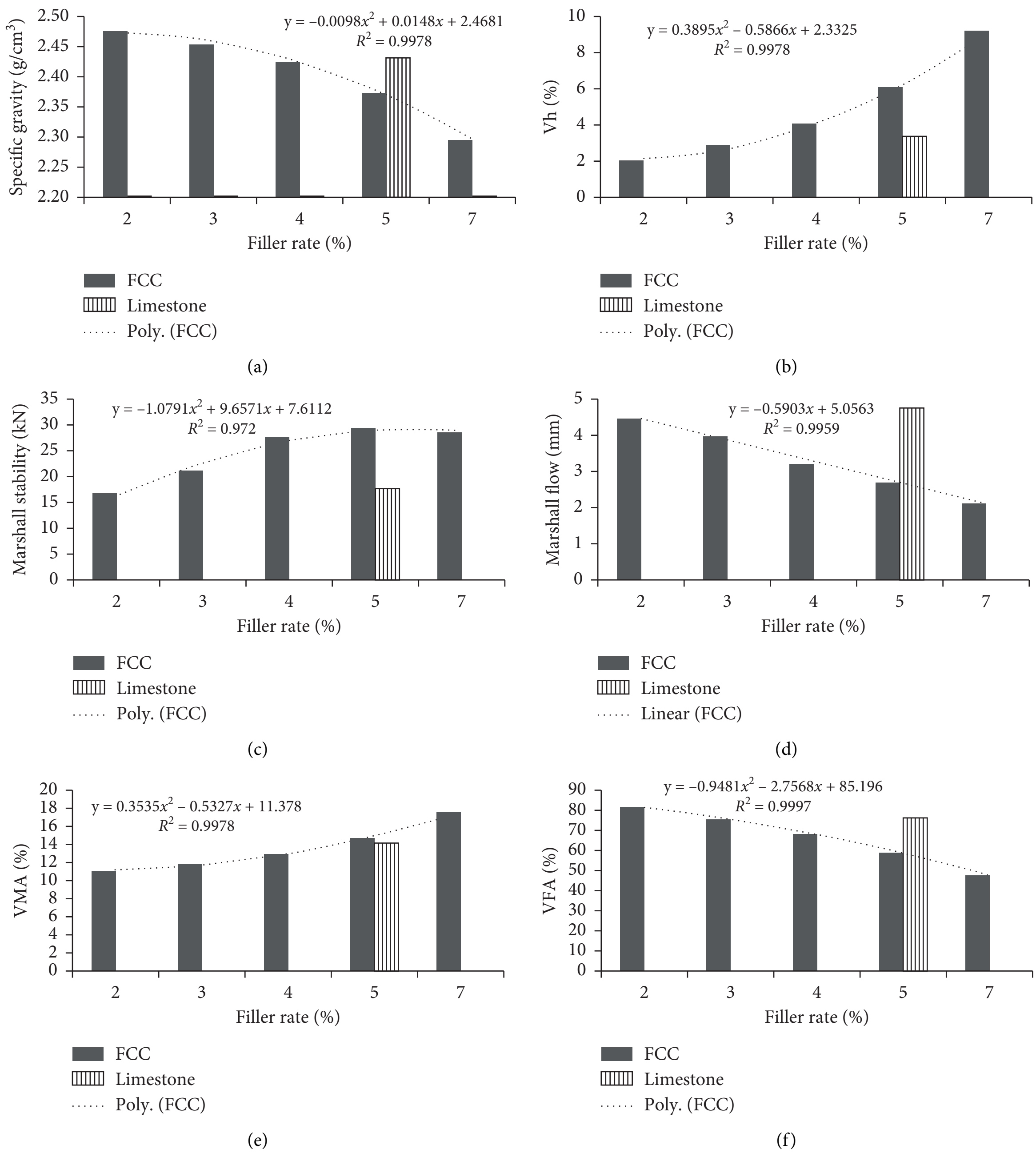


Figure 8: Relationship between the mineral filler ratio and (a) bulk specific gravity, (b) air voids, (c) Marshall stability, (d) Marshall flow, (e) VMA, and (f) VFA.

increases, as shown in Figure 8(d). The Marshall flow reduction ratio of the mixture with SFCC rates of 2 and 7% was about two times. Generally speaking, SFCC could efficiently adjust the Marshall flow. The more the SFCC, the more the ability of the asphalt concrete to improve the deformation.

The relationship between VMA and the rate of SFCC is the concave parabolic curve (Figure 8(e)). Meanwhile, the relationship between the VFA and SFCC rate is a convex curve (Figure 8(f)). With the same percentage asphalt binder content, the relationship between VMA and the SFCC powder rate was contrary to the relationship between VFA and the SFCC powder rate. This trend indicates that SFCC significantly affected the adequate asphalt film thickness. In addition, VMA and VFA could meet the specified VMA and VFA if the SFCC rate is appropriately chosen. In this case, an appropriate SFCC rate is 5%.

5.3. Dynamic Modulus Test. Figure 9 shows the dynamic modulus master curves at the reference temperature of 20°C. The master curve was constructed by shifting the individual dynamic modulus data at various temperatures horizontally along the frequency axis based on the time-temperature superposition principle. In Figure 9, the experimental results

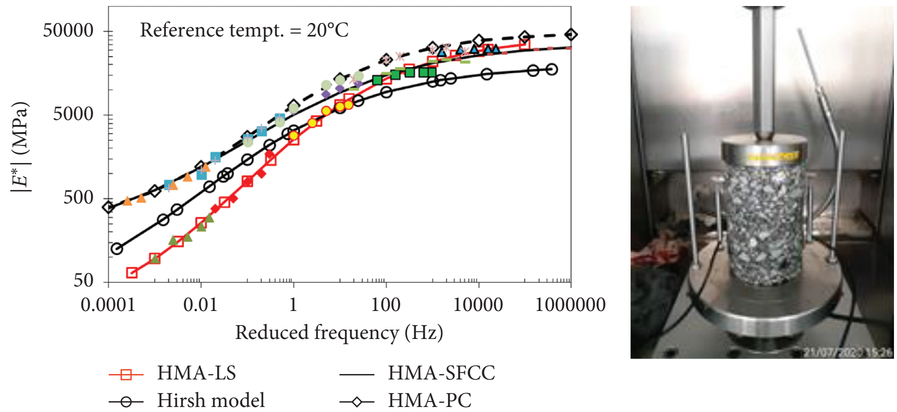


Figure 9: Comparison of the dynamic moduli.

are compared to the Hirsch model. The Hirsch model generally underpredicted the moduli [32]. In general, the test results agreed with that of the predicting model that was verified by several common cases. The figure shows that the Hirsch model underpredicted the dynamic modulus in HMA with SFCC.

The figure shows that the dynamic modulus of the HMA with SFCC is higher than the conventional mixture with LS, especially at low frequencies. Besides, according to the time-temperature superposition principle, the asphaltic concrete behavior at low frequency corresponds to the high-temperature behavior. Thus, it could be said that the HMA with SFCC has a higher dynamic modulus at high temperatures compared to the conventional mixture.

The increase in the dynamic modulus of the HMA with SFCC at high temperatures may be due to the effects of SFCC. Therefore, the SFCC could increase the stiffness of the mix at high temperatures and could reduce the rutting depth in a tropical country such as Vietnam. This point was checked in the wheel tracking test.

Comparing the dynamic modulus of the HMA with PC, the dynamic modulus of the HMA with PC is higher than the mix with SFCC at high frequencies or low temperatures. However, the dynamic modulus of the HMA with SFCC is equivalent to the mix with PC at low frequencies or high temperatures. Thus, the SFCC filler effect in HMA is similar to that of the PC filler at high temperatures.

5.4. Static Modulus Test. The static compressive moduli of HMA at 15, 30, and 60°C were determined to compare three different filler types in the asphalt mixture. They include SFCC, LS, and Portland cement (PC). Cement is a typical selection for replacing the LS filler in Vietnam.

The asphalt mixture is a thermo-viscoelastic-plastic material. Thus, the mechanical properties are susceptible to temperature. The stiffness of the asphalt mixture decreases with the increase in temperature, resulting in the decreased modulus. As a result, the sample manifests as being soft. Figure 10 shows that the static asphalt mixture compressive modulus decreases with increase in temperature.

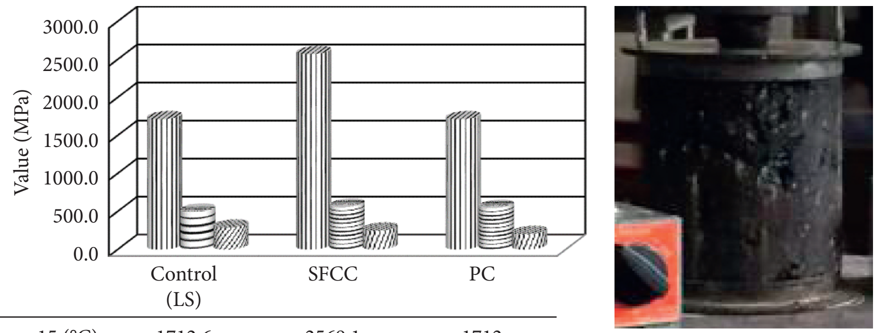
At the temperature of 15, 30, and 60°C, the static moduli of HMA with SFCC are 1.5, 1.1, and 0.9 times the values of HMA with LS, respectively. Compared to HMA with PC, static moduli are 1.5, 1.0, and 1.2 times higher (Figure 10). The static moduli of HMA with SFCC are better than those of HMA with LS and HMA with PC. The improvement in the static modulus of HMA with SFCC was more striking at temperature of 15°C and 30°C. This is because the grading of HMA with SFCC is better than those of HMA with LS and HMA with PC, and the improvement in the static modulus of HMA with SFCC is better than those with LS and PC.

5.5. Wheel Tracking Test. Table 5 summarizes in detail the wheel tracking test results. Besides, the dynamic stability (cycle/mm) was determined. The dynamic stability of the HMA with SFCC had the highest value. Thus, the HMA with SFCC has a great potential to reduce permanent deformation.

Figure 11 shows the rut depth versus loading cycles of the control mixture, HMA of the polymer modified asphalt binders (PMB-I) [24], and asphalt mixture using SFCC. The conventional mix has a maximum rut depth of about 8.66 mm at 15,000 cycles. On the other hand, the maximum rut depth of the HMA with SFCC is about 2.5 mm, while the maximum rut depth of the HMA of PMB-I with LS is about 4.67 mm at 15,000 cycles. Therefore, using the SFCC to replace the LS filler can significantly improve the rut resistance of asphalt mixtures under high-temperature conditions.

Some of the factors that cause the rutting depth include aggregate gradation, aggregate surface texture, air voids in the asphalt mixture, VMA, type of binder, and temperature. HMA with SFCC and HMA with LS are optimized designs with the same aggregate gradation and asphalt binder grade. Besides, these mixtures have air voids in the asphalt mixture and VMA satisfying the required values. The rutting resistance of HMA with SFCC is higher due to the action of SFCC. SFCC has high moisture absorption and have components similar to that of Portland cement. SFCC could enhance the adhesion between the asphalt binder and the aggregate. The reason for this trend could be the same as that for Marshall stability.

5.6. Fatigue Test. Figure 12 shows the fatigue test results without rest periods. In addition, the model regression coefficients of equation (6) are summarized in Table 6. The



	Control (LS)	SFCC	PC
Modulus – 15 (°C)	1712.6	2569.1	1712
Modulus – 30 (°C)	496.8	560.29	546
Modulus – 60 (°C)	286.9	246.97	202

FIGURE 10: Comparison of the static modulus at several temperatures.

TABLE 5: Results of the wheel tracking test.

Results of the wheel tracking test	Binder 60/70, LS	Binder 60/70, SFCC	Polymer PMB-I
Rut depth (mm)	8.66	2.16	4.67
Number of load application (cycles)	15000	15000	15000
Load level (N)	0.7	0.7	0.7
Dynamic stability (cycles/mm)	1875	5357	3000

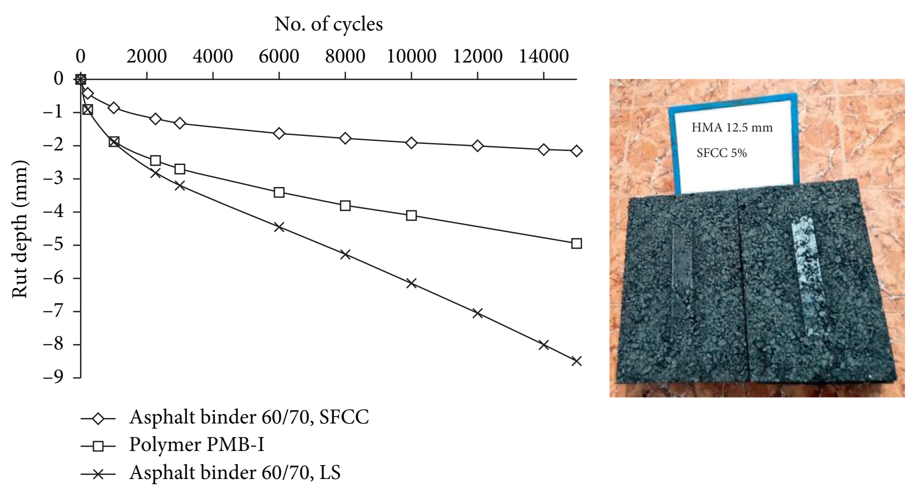


FIGURE 11: Comparison of the wheel tracking test (experimental results of the asphalt binder 60/70 with SFCC filler, LS filler, and PMB-I).

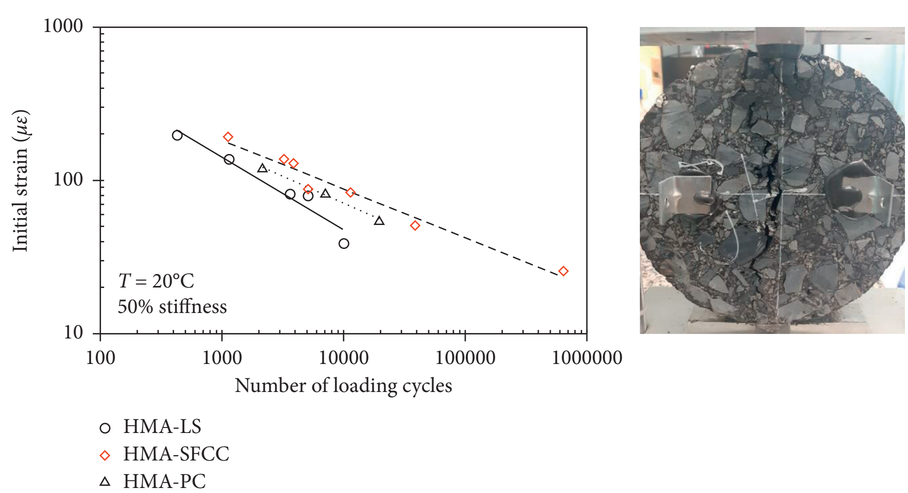
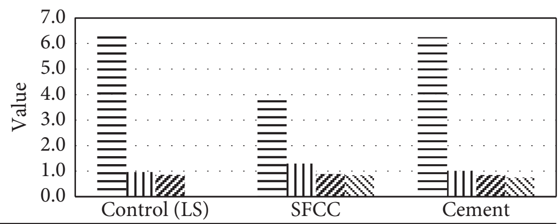


FIGURE 12: Comparison of the dynamic moduli (experimental results of HMA with SFCC filler, LS filler, and PC filler).

Table 6: Fatigue coefficients for tested mixtures.

Mixture	Average air void (%)	Fatigue coefficient		
		a	b	R^2
HMA-SFCC	4.04	8×10^9	−3.045	0.967
HMA-LS	3.33	2×10^7	−1.981	0.942
HMA-PC	4.00	2×10^9	−2.829	0.994



	Control (LS)	SFCC	Cement
Cantabro (%)	6.4	3.8	6.26
IDT (MPa)	0.97	1.3	1.02
TSR	0.86	0.89	0.85
MSR		0.84	0.76

Figure 13: Comparison of Cantabro, IDT, TSR, and MSR for asphalt concretes with variations in filler types.

fatigue results shown in the figure directly represent the effects of SFCC used in the mixes. The fatigue life of HMA with SFCC was higher than that of LS and PC. It indicates that SFCC could considerably improve the asphalt mixture fatigue life. Maintaining the adhesion between the asphalt binder and aggregate under the application of cyclic loading, which was enhanced due to the action of SFCC, could explain this trend.

The tensile strain values at the asphalt layer bottom are lower than 200 microstrains [33] for typically thick asphalt pavements. With the tensile strain lower than 200 microstrains, Figure 12 shows that the fatigue life of HMA with SFCC is higher than that of other mixtures. Thus, the fatigue resistance of HMA with SFCC is better than that of the conventional mixture with LS and PC, especially for the thick asphalt pavements.

5.7. Strength Tests. Figure 13 shows the Cantabro mass loss, the indirect tension strength (IDT), the retained tensile strength ratio (TSR), and the retained Marshall stability ratio (MSR) values of considered HMA mixtures. The weight loss of HMA with SFCC was 3.8% in the surface abrasion resistance test. This value was smaller than those of HMA with LS and PC. However, the difference values among them were too small. Therefore, it indicates that the SFCC filler does not significantly affect the surface abrasion resistance of HMA.

The IDT value of HMA with SFCC increases 34% and 27.4% compared to HMA with LS and PC, respectively. Both IDT and Marshall stability tested under wet conditions of HMA with SFCC are higher than that of the compared mixtures. However, the TSR and MSR of the HMA mixtures in Figure 13 are equivalent, and the values are higher than the required value of 80% [34, 35].

Generally speaking, the samples of HMA with SFCC have the highest IDT, MSR, and TSR values. This result indicates that the SFCC filler can enhance the resistance against the tension force, moisture susceptibility, and stripping in asphalt concrete. The reason for this trend could be the same as that for Marshall stability, fatigue, and rutting resistance. SFCC is an active filler that creates multiple benefits for pavements. SFCC acts as a mineral filler, stiffening the asphalt binder and asphalt concrete. Besides, SFCC could improve resistance to fracture growth at low temperatures and improve moisture stability and durability.

6. Conclusions

The effect of spent fluid catalytic cracking (SFCC) used as mineral fillers in asphalt concrete mixtures was investigated in this study. The mixtures having the LS filler rate of 5% with 5.07% bitumen content showed the best Marshall properties. The mixture with the optimum bitumen and optimum LS filler rate was utilized as a control mix to find the best mix in the mixtures having various SFCC filler rates.

The trial SFCC filler rates were 2, 3, 4, 5, and 7%. It could be found that the mixtures of the 5% SFCC filler with 5.56% bitumen content showed the best with all Marshall properties in the specified limits. Based on the Marshall experiments, the crucial results are summarized as follows:

(i) SFCC affected the Marshall stability of the asphalt concrete mix. The Marshall stability value increased with the increase in the SFCC filler rates. At the proper filler rate of SFCC, the Marshall stability value of asphalt concrete mixtures was 41% higher than that of HMA with optimum LS filler.

(ii) SFCC could efficiently adjust the Marshall flow. The more the SFCC, the more the ability of the asphalt concrete to improve the deformation. In other words, SFCC could help in increasing the internal friction coefficient of the asphalt concrete mixture.

(iii) SFCC significantly affected the adequate asphalt film thickness and improved the adhesion between the aggregate and bitumen.

SFCC may cause a harder HMA. The dynamic modulus of the HMA with SFCC is higher than the conventional mix with LS or PC, especially at low frequencies or higher temperature. Therefore, the HMA with SFCC has a great potential to reduce permanent deformation. The rutting resistance may be comparable to polymer asphaltic concrete. Besides, the fatigue resistance of HMA with SFCC was not reduced compared to that of the conventional mixtures with LS and PC, especially for the thick asphalt pavements. The SFCC filler can enhance the resistance against the tension strength, moisture susceptibility, stripping in asphalt concrete, and the surface abrasion resistance of HMA.

There were disadvantages in the asphalt concrete mixture caused by the SFCC filler. The bulk specific gravity of the asphalt concrete samples decreased as the SFCC filler content increased. As the SFCC rate was too high in the asphalt concrete mix, the SFCC powder absorbed the asphalt binder and caused a significant increase in air voids.

SFCC can be used instead of limestone powder in asphalt concrete mixtures as mineral fillers. SFCC could be utilized in areas close to the oil filtering company when transportation costs of SFCC subtracting the cost for SFCC landfilled do not exceed the cost of the limestone filler.

Abbreviations

CL: Cantabro loss
DS: Dynamic stability
FR: Filler rate
HMA: Hot-mix asphalt
IDT: Indirect tension
LS: Limestone
MF: Marshall flow
MS: Marshall stabilization
MSR: Marshall stability ratio
OBC: Optimum binder content
PC: Portland cement
PMB-I: Polymer-modified asphalt binders graded I
SFCC: Spent fluid catalytic cracking
TSR: Tensile strength ratio
Vf: Void percentages
VFA: Voids filled with asphalt
Vh: Void volume values
VMA: Voids in mineral aggregate.

Data Availability

The experiment data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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