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Research Article

Reinforcement of Recycled Foamed Asphalt Using Short Polypropylene Fibers

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This paper presents the reinforcing effects of the inclusion of short polypropylene fibers on recycled foamed asphalt (RFA) mixture. Short polypropylene fibers of 10 mm length with a 0.15% by weight mixing ratio of the fiber to the asphalt binder were used. The Marshall stability test, the indirect tensile strength test, the resilient modulus test, and wheel tracking test of the RFA mixtures were conducted. The test results were compared to find out the reinforcing effects of the inclusion of the fiber and the other mixtures, which included the conventional recycled foamed asphalt (RFA) mixtures; the cement reinforced recycled foamed asphalt (CRFA) mixtures; the semihot recycled foamed asphalt (SRFA) mixtures; and recycled hot-mix asphalt (RHMA) mixtures. It is found that the FRFA mixture shows higher Marshall stability than the RFA and SRFA mixtures, higher indirect tensile strength than the RFA mixture, and higher rut resistance than the RFA, SRFA, and RHMA mixtures as seen from the wheel tracking test.

1. Introduction

In recent years, pavement researchers are refocusing their efforts on using foamed asphalt due to environmental issues such as air pollution and recycling. The use of foamed asphalt as a recycling method for using reclaimed asphalt pavement (RAP) was once popular in the early of the 1980s in the United States, European countries and is still popular in African countries. However, the mixtures using the foamed asphalt method have been limited to low traffic volume roads due to lack of the strength and durability of the mixtures. Two reinforcing methods were used in order to improve the strength and durability of the foamed asphalt and recycled foamed asphalt (RFA). One is the use of the Portland cement as an additive, and the other is semihot RFA method [1]. It has been reported that both reinforcing methods provide a consistent quality of the mixture that is comparable to hot-mix asphalt (HMA) mixture. One of the important advantages of RFA is its ability to store the mixture at ambient temperatures for weeks. However, the inclusion of the Portland cement and the semihot method limits the storage time to only a few hours. The use of the polypropylene fibers is expected to increase the strength and durability of the RFA mixture as found in the both hot- and cold-asphalt mixtures [2–5] and would also maintain its longer storage time. This study presents the mechanical properties and the enhanced performance of RFA mixtures when polypropylene fibers were included in the RFA mixtures. Four different kinds of RFA mixtures and a hot recycling asphalt mixture were tested and compared. The enhanced performance of the RFA mixture with fiber is discussed in terms of the Marshall stability, the indirect tensile strength, resilient modulus, the moisture susceptibility, and the dynamic stability.

2. Literature Review on Recycled Foamed Asphalt and Fiber Reinforced Asphalt Mixtures

2.1. Recycled Foamed Asphalt (RFA) Mixtures. The first foamed asphalt processes were introduced by Lee [6]. The

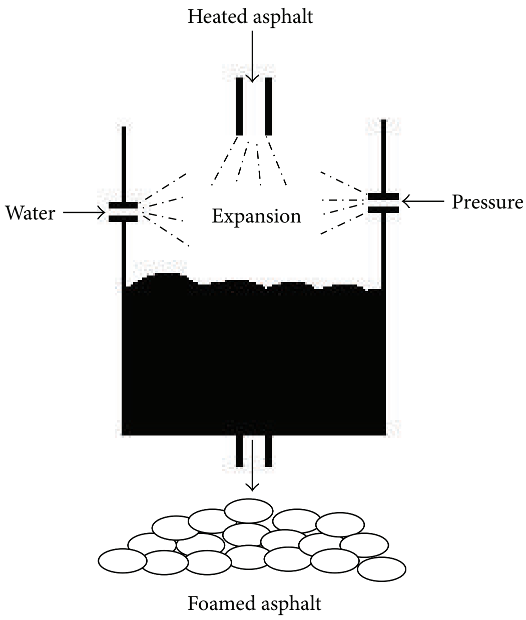

Figure 1: Schematic diagram of foaming system.

foamed asphalt technology has been used for low-volume roads and soil stabilization for many years in the past. The foaming technology has been continually developed using a low-pressure and cold-water system to improve the quality of the foamed asphalt mixture. Figure 1 is the schematic diagram of the foaming system.

Wijk and Wood [7], Brennen et al. [8], Roberts et al. [9], and Tia and Wood [10] have studied the use of foamed asphalt in recycling of an asphalt pavement. These studies demonstrated the feasibility of using RAP to produce a RFA mixture with new materials, such as new aggregates and binder. Portland cement was used as an additive to increase the strength of the RFA and decrease the curing time of the RFA. However, the inclusion of the Portland cement resulted in limiting of the storage time to one hour or so. Jenkins et al. [1] have developed the semihot treatment for the foamed asphalt. The treatment is that RAP and aggregate are heated to between 80°C and 95°C. The water and filler are added to the mixture during mixing. The process improves the binder coating of the RAP and aggregate, and the performance of the RAP is comparable to hot-mix asphalt (HMA). This process can significantly improve the quality of the RFA; however, the separate heating system is required to heat the RAP and aggregate and the storage time of the mixture cannot be kept as long as that of the conventional RFA mixture. Marquis et al. [11], Mohammad et al. [12], Loizos and Papavasiliou [13], and He and Wong [14] reported the performance in the field for medium- and low-volume roads. Kim and Lee [15] and Kim et al. [16] addressed a new mix design method and validation of the foamed asphalt mix. However, these studies did not address the reinforcing methods of the foamed asphalt mix.

2.2. Fiber Reinforced Asphalt (FRA) Mixtures. The previous studies showed that the use of polypropylene improved the performance and the crack resistance of both hot mix and cold mix, with most application in HMA. The use of short polypropylene fibers in the HMA mixture showed that the strain energy measured at a low temperature (0°C and −18°C) was increased [2]. According to Button and Epps [17], small quantities of certain polypropylene fibers with good tensile properties can effectively retard reflective cracking in HMA mixture. Mills and Keller [18] also stated that the addition of polypropylene fibers does offer some improvement in the performance of the asphalt mixture by retarding the reflective crack. They emphasized the importance of the denier (a measurement that is used to identify the fiber thickness of individual thread), surface finishing, and the optimum fiber concentration for paving mixture.

Epps et al. [19] have conducted various tests and the test results showed that fibers in properly designed asphalt mixture have the potential to increase overall service life. The addition of fibers resulted in a decreased susceptibility to moisture damage [4]. Based on the results from the previous studies, with appropriate fiber quantities and distribution of fibers in the mixture, asphalt mixtures can resist cracking by redistributing stresses. The inclusion of the fiber in asphalt mixtures resulted in an increase in the optimum asphalt contents of between 0.5% and 1.0% [4].

3. Description of RFA Mixtures Evaluated

Four different types of RFA mixtures and a recycling HMA mixture were prepared to conduct mechanical laboratory tests. The descriptions of each mixture are as follows.

(1) Conventional RFA mixture without the inclusion of fiber or additive and without heating; the mixture is named RFA.

(2) RFA mixture including 2.0% of cement by the volume of the weight of the total mixture. The ratio of cement was adjusted to find the optimum ratio; 1.0%, 2.0%, and 3.0% were tried, and 2.0% was found to be the optimum ratio using the unconfined compression test: 3 days cured at 60°C as suggested by Bowering and Martin [20]. Lewis and Collings [21] and Marquis et al. [11] recommended the 2.0%–4.0% and 1.5%, respectively, the mixture is named CRFA.

(3) Semihot RFA: the RAP and the virgin aggregate were heated to 90°C. (90°C was found as an optimum heating temperature at 60, 70, 80, 90, 100°C as a result of the aggregate coating) the mixture is named SRFA.

(4) Mixture 1 (RFA) + polypropylene fiber (0.15% by the weight of asphalt mixture was used): the indirect tensile strength tests were used to find out the optimum contents of the fiber [19]; the mixture is named FRFA.

(5) Recycling hot-mix asphalt: the mixture is named RHMA.

4. Selection of Materials Used in Mix Design

4.1. Polypropylene Fiber. Polypropylene fiber was used in this study having a singular shape and white to light gray color (Figure 2). The physical properties of the fiber are shown in Table 1. The 0.15% of the fiber by the weight of asphalt

Table 1: Physical properties of short polypropylene fiber used in the study.

Physical properties	Value	Test procedures
Denier	0.00189 ± 0.004 mm	ASTM D 1577
Length	10 ± 2 mm	—
Crimps	None	ASTM D 3987-82
Tensile strength	2,812 Kg/cm^2 min.	ASTM D 822-83
Elongation	33%, min.	ASTM D 2256-80
Specific gravity	0.91	—
Alkali resistance	99% strength retained	40% NaOH solution at 21°C for 1,000 hours
Acid resistance	99% strength retained	95% HCI solution at 21°C for 1,000 hours
Moisture regain at 70% and 65% relative humidity	Less than 0.1%	ASTM D 2654-76

mixture was used and the fiber was integrated while the RAP, aggregate, and the asphalt are mixing.

4.2. Additive. Portland cement was used as an additive. According to Bowering and Martin [20], Castedo et al. [22], Lewis and Collings [21], and Marquis et al. [11], the Portland cement can be used for reducing the curing times and increasing the marginal strength of foamed asphalt mixtures. The amount of 2.0% by the total weight of foamed asphalt mixture was used.

4.3. Reclaimed Asphalt Pavement (RAP). The RAP materials are collected from a 10-year-old pavement, which contains 5.3% asphalt content, with a penetration of 27 and viscosity of 6,860 Poise. The gradation of the RAP is within the specification; however, it is close to the upper limit in the coarse part and to the lower limit in the fine part of the specification. The gradation for the mix design was controlled by adding new aggregate bringing the gradation curve to the center portion of the specification limits. Figure 3 shows the gradation of the RAP and aggregate mixture.

4.4. New Aggregates and Asphalt. The specific gravity of fine aggregate is 2.71 and that of coarse aggregate is 2.64. A PG 64-22 asphalt binder is used to produce the foamed asphalt.

5. Mix Design

A Wirtgen laboratory scale unit manufactured in Germany was used to produce the foamed asphalt in this study. Foamed asphalt was produced by injecting cold water and hot asphalt with varying the air pressure in the air chamber. Expansion ratio and half-life were measured upon varying the temperature and chamber pressure. The temperature of the asphalt was varied between 160°C and 180°C. The foaming water content was varied between 1.0% and 3.0% by the volume of asphalt to find the optimum foaming asphalt moisture content. The air pressure was 179 kPa in this study.

5.1. Determination of Optimum Moisture Content. A unique procedure for the mix design of foamed asphalt is the determination of the optimum moisture contents for both aggregate and foamed asphalt binder. The optimum moisture content for the aggregate and binder was determined in accordance with the South African specification [23]. The following procedures were used to determine the optimum foaming moisture contents for the production of the foamed asphalt binder:

(1) asphalt binder was prepared to be produced at moisture contents ranging from 1.0% to 3.0% in an increment of 0.5%.

(2) For each sample, allow the foam to discharge for 5 seconds into 20 liters steel drum and mark the maximum volume to which the foam expands. The time was measured in seconds that the foam takes to dissipate to half of its maximum volume (half-life).

(3) The expansion ratio of the foamed asphalt was calculated by dividing the maximum foamed volume by the volume of asphalt in the drum after the foam has completely dissipated.

Using the expansion ratio and half-life relationship, the optimum foaming moisture content was determined to be 1.4% of the volume of asphalt. Figure 4 shows the relationship between the expansion ratio and the half-life of foamed asphalt in this study. The maximum dry density of the RAP and virgin aggregate is 2.1 g/cm^3 and the optimum moisture content is 5.9% using the modified proctor test [24].

5.2. Optimum Foamed Asphalt Content. In the past, Muthen [23] recommended that the optimum foamed asphalt content should be selected based on the relationship between indirect tensile strength and foamed asphalt content. Mohammad et al. [12] also determined the optimum foamed asphalt content based on the asphalt content that produced the maximum retained indirect tensile strength. To determine the optimum foamed asphalt content, the Basic Asphalt Recycling Manual [25] recommended the following test results: Marshall stability in dry and wet conditions and indirect tensile strength in dry and wet conditions. In this study, the average optimum foamed asphalt content (OFAC) was calculated by averaging four optimum foamed asphalt contents determined at highest Marshall stability and indirect tensile strength.

The OFAC was varied due to the inclusion of the fiber and also the different producing method of the recycled foamed

Figure 2: Picture of short polypropylene fibers.

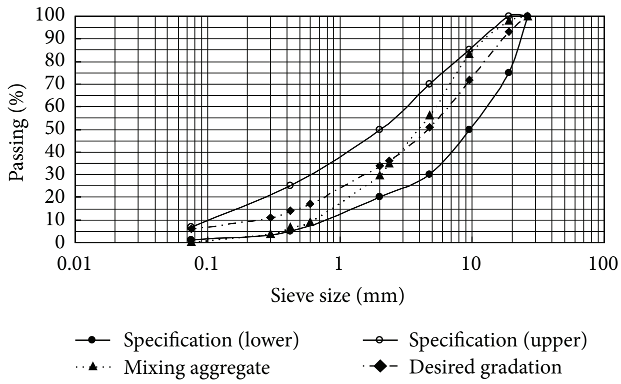

Figure 3: Gradation of RAP and aggregate mixture.

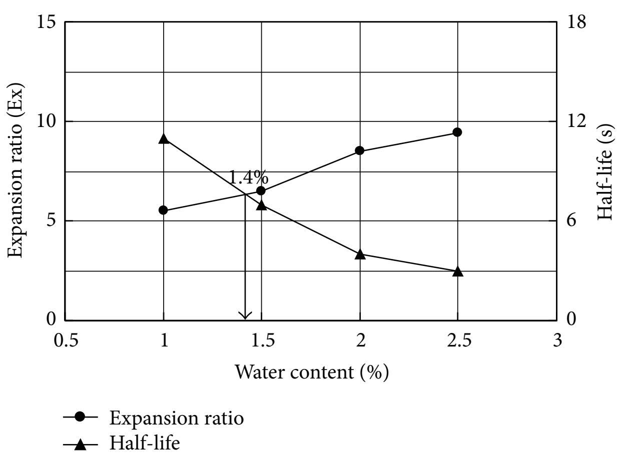

Figure 4: Expansion ratio and half-Life of foamed asphalt.

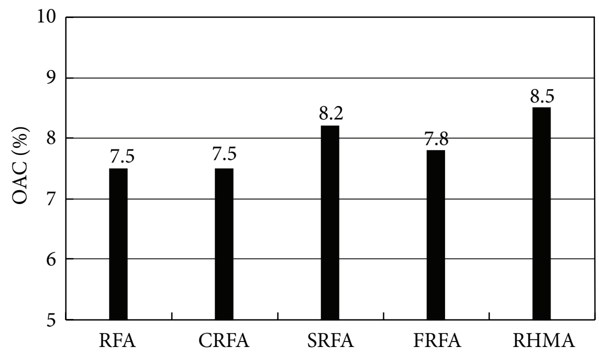

Figure 5: Optimum asphalt content of each mixture.

asphalt (RFA). Figure 5 shows the OFAC for each sample. The inclusion of the fiber in FRA mixture increased the OFAC slightly. It has been reported that the inclusion of the fiber in asphalt mixture resulted in an increased to optimum asphalt contents 0.5% to 1.0% [4].

5.3. Sample Preparation. The specimens for the Marshall stability, the indirect tensile strength, and the resilient modulus test were compacted 75 blows of both sides using the mechanical Marshall compactor. The standard 100 mm diameter mold was used. The samples were cured in the 60°C oven for 72 hours. This curing condition was followed in accordance with the recommendation of South African specification [23]. Five specimens were produced for each test and sample. The specimens for wheel tracking test were compacted using the CRP-RC25V by Cooper slab compactor (305 mm × 305 mm), and five slab specimens were produced for each mixture.

5.4. Evaluations. The Marshall stability tests were performed to find the optimum foamed asphalt content and to compare the stability of the mixtures at both of 25°C in dry condition and 60°C in wet condition [24]. The indirect strength tensile tests were also conducted to determine the optimum foamed asphalt content and evaluate the crack potential and the moisture susceptibility both in the dry and wet conditions at 25°C [26]. The indirect tensile test was performed by loading a cylindrical specimen with a single compressive load which acts parallel to and along the vertical diametral plane. Resilient modulus tests were performed at three different temperatures (5°C, 25°C, and 40°C) to analyze the temperature susceptibility and investigate the elastic properties of RFA mixtures [27]. A CRP-WTEN2 by Cooper wheel tracking test at 40°C was conducted to investigate the permanent deformation using dynamic stability (number of wheel pass (cycle) per mm deformation). The target for good mixture of resistance to the permanent deformation was set to 750 cycle/mm [28].

6. Test Results and Summary

6.1. Marshall Stability Test Results. Marshall stability is commonly used to evaluate the resistance to plastic flow of cylindrical specimens of an asphalt mixture loaded onto the lateral surface. For this study, Marshall stability values were measured for five different recycled mixtures, which were conditioned in water bath at 25°C and 60°C. Figure 6 shows

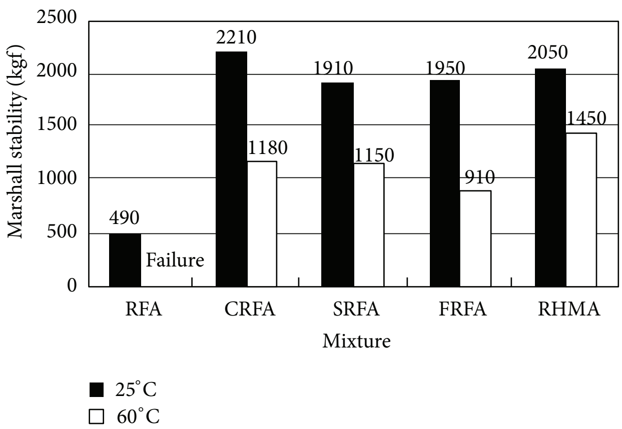

Figure 6: Marshall stability test results at 25°C and 60°C.

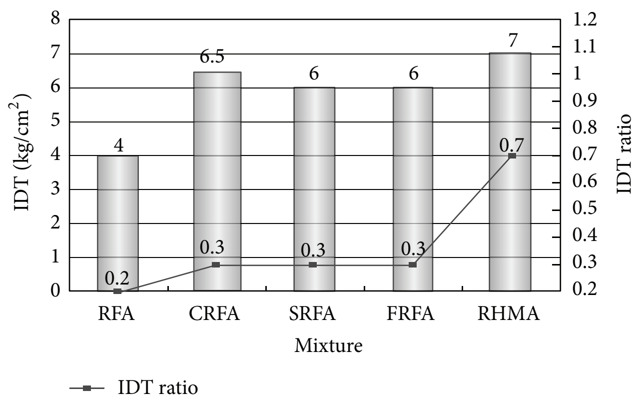

Figure 7: Indirect tensile strength test results and IDT ratio.

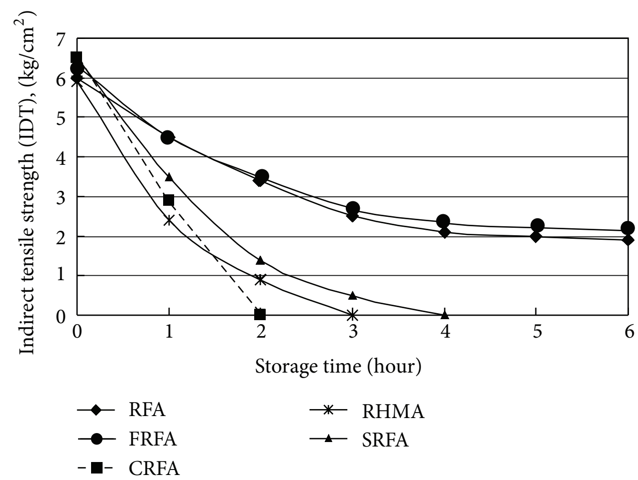

Figure 8: Effect of storage time on indirect tensile strength.

the Marshall stability test results. Based on the test results, the inclusion of the fiber resulted in the increase in the Marshall stability of the FRFA compared to that of the RFA mixture which failed at 60°C and that of SRFA and RHMA is comparable.

6.2. Indirect Tensile Strength Test Results. Indirect tensile strength is commonly used to characterize the crack resistance of hot-mix asphalt (HMA) pavement. For this study, indirect tensile strength values were measured for five different recycled mixtures in dry and wet conditions at 25°C. Figure 7 shows the indirect tensile strength test results. As shown in Figure 7, the indirect tensile strength is affected by the inclusion of the fiber and the cement as well as the semihot process. The effectiveness of the fiber is significant when the samples were in dry condition; however, such is not the case when the samples were tested in the wet condition. Because foamed asphalt mixture is susceptible to failure by moisture intrusion, it is postulated that moisture sensitivity is one of the major drawbacks of the RFA mixture. The wet and dry ratio of the indirect tensile strength of the FRFA mixtures improved compared to that of the RFA mixtures and less comparable to the other RFA mixtures. In comparison, the indirect tensile strength of RHMA mixture is superior to the all RFA mixtures tested in this study.

In Figure 8, the variation of the indirect tensile strength is shown as the storage time is increasing. The indirect tensile strength of the FRFA is dependent upon the storage times. However, that of the CRFA, SRFA, and RHMA mixtures is significantly decreased as the storage time is increased. It should be noted that the indirect tensile strength is strongly dependent upon the storage times and the reinforcing method of the RFA.

6.3. Resilient Modulus Test Results. Resilient modulus test is the most common method of measuring stiffness modulus for HMA. It has been shown that stiffer mixtures at low temperatures trend to crack earlier than more flexible mixtures. Figure 9 shows resilient modulus of five different recycled asphalt mixtures as a function of the testing temperature. The interesting finding of Figure 9 is the difference in the shape of the curves for the mixtures. All RFA mixtures are less susceptible to the temperature changes except the RHMA mixture. The inclusion of the fiber in RFA increased the resilient modulus.

6.4. Wheel Tracking Test Results. Permanent deformation is an issue of critical distress in asphalt pavement and is defined as the accumulation of a small amount of unrecoverable strains due to traffic loading. It typically occurs under higher temperature when the pavement under traffic loading consolidates and/or there is a lateral movement of the HMA. Lateral movement is a shear failure and typically occurs in the upper portion of the pavement surface layer. As a result of permanent deformation, the pavement service life cycle is reduced due to vehicle hydroplaning at rutting area. The wheel tracking test was conducted to evaluate rutting resistance of five different recycled asphalt mixtures at 40°C. The results of the wheel tracking tests were evaluated in terms of the dynamic stability (cycle/mm). The dynamic stability defines the number of wheel paths that reach the 1 mm deformation (permanent deformation) in the mixture.

TABLE 2: Mean of three test properties and T-test analysis results.

Mean property	RFA	CRFA	SRFA	FRFA	RHMA	Prob. > $\|t\|$ RFA versus CRFA	RFA versus SRFA	RFA versus FRFA	RFA versus RHMA	CRFA versus SRFA	CRFA versus FRFA	CRFA versus RHMA	SRFA versus FRFA	SRFA versus RHMA	FRFA versus RHMA
Marshall stability (Kgf)	490	2210	1910	1950	2050	0.0001	0.0001	0.0001	0.0001	0.023	0.01	0.108	0.221	0.004	0.070
Indirect tensile strength (Kg/cm^2)	4.0	6.5	6.0	6.0	7.0	0.0003	0.0006	0.0002	0.0009	0.086	0.079	0.092	0.5	0.017	0.013
Dynamic stability (cycle/mm)	800	1500	950	1200	350	0.0011	0.0674	0.0005	0.0005	0.0001	0.005	0.0001	0.003	0.0001	0.0001

Table 3: Summary of t-test results for the three properties.

Property	Method	RFA	CRFA	SRFA	FRFA	RHMA
Marshall stability (Kgf)	RFA	—	S	S	S	S
	CRFA		—	S	S	NS
	SRFA			—	NS	S
	FRFA				—	NS
	RHMA					—
Indirect tensile strength (Kgf/cm^2)	RFA	—	S	S	S	S
	CRFA		—	NS	NS	NS
	SRFA			—	NS	S
	FRFA				—	S
	RHMA					—
Dynamic stability (cycle/mm)	RFA	—	S	NS	S	S
	CRFA		—	S	S	S
	SRFA			—	S	S
	FRFA				—	S
	RHMA					—

S: significant; NS: not significant.

Table 4: Analysis of variable result for Marshall stability.

Source	DF	Sum of squares	Mean square	F value	Pr > F
Mixture	4	9754400	2438600	220.09	<0.0001
Error	20	221600	11080		
Corrected total	24	9976000			

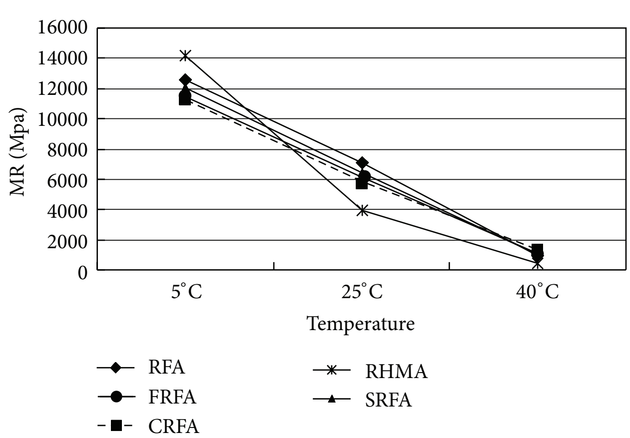

Figure 9: Resilient modulus test results at three different temperatures.

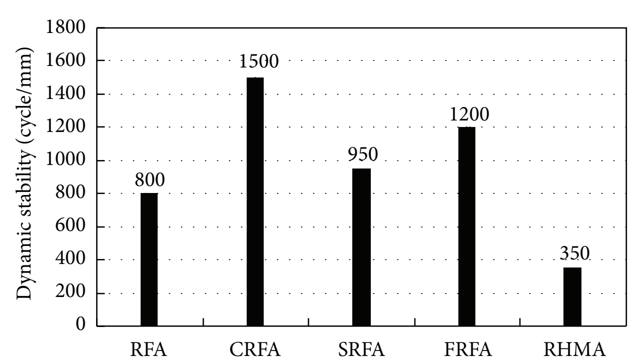

Figure 10: Wheel tracking test results.

Figure 10 shows the dynamic stability values for five different recycled asphalt mixtures. All RFA mixtures are resistant to the permanent deformation, and the CRFA and FRFA mixtures show the highest resistance to permanent deformation. On the other hand, the permanent deformation of the RHMA mixture is significantly higher than that of the RFA mixtures.

6.5. Summary. The inclusion of short polypropylene fibers improved the Marshall stability and the indirect tensile strength. When the fiber is dispersed in the recycled foamed asphalt (RFA) mixture, the structure of foamed mixture is internally reinforced. However, the structure of the RFA and FRFA is weakened by water intrusion. Therefore, the improvement of the stability and the indirect strength was not significant when the samples were tested in a wet condition. Resilient modulus of FRFA mixture is increased with the inclusion of the polypropylene fiber. Button and Epps [17] have addressed the same results on the resilient modulus test. Resistance to permanent deformation of the FRFA mixture is another finding. All RFA mixtures showed good resistance to permanent deformation except semihot

Table 5: Analysis of variable result for the indirect tensile strength.

Source	DF	Sum of squares	Mean square	F value	Pr > F
Mixture	4	25.9816	6.4954	37.46	<0.0001
Error	20	3.4680	0.1734		
Corrected total	24	29.4496			

Table 6: Analysis of variable result for dynamic stability.

Source	DF	Sum of squares	Mean square	F value	Pr > F
Mixture	4	3845404.16	961351.04	138.54	<0.0001
Error	20	138778.80	6938.94		
Corrected total	24	3984182.96			

mixture and RHMA mixture. According to Ruckel et al. [25], this property is likely due to the discontinuous nature of the foamed-asphalt binding mechanism; that is, the binder formed a discontinuous random matrix of primarily fines and asphalt.

7. Statistical Analysis

The reinforcing effect of fiber on the recycled foamed asphalt mixtures was analyzed statistically. The statistical analysis was made in terms of the significance of the inclusion of the fiber and the improvement of performance in the laboratory for each mixture. Typical Student's t-test was conducted. The average of the three properties and results of Student's t-test at = 0.05 level were shown in Table 2. The mean data obtained were from equal number of samples (i.e., five each). If Prob. > $|t|$ is lower than 0.05, the significant difference exists statistically. On the basis of Table 2, the significant difference was evaluated and summarized in Table 3. Table 3 showed that the inclusion of the fiber in RFA mixture had significant effect on the Marshall stability, the indirect tensile strength, and the wheel tracking (dynamic stability). When the performance of the FRFA mixtures was compared to that of the RFA and other RFA mixtures, the FRFA mixture showed statistically significant difference from the RFA mixture in Marshall stability and indirect tensile strength at = 0.05. The FRFA also showed a significantly higher rut resistance, measured by wheel tracking, from the RFA mixture at the same significant level. From this analysis, it was proved that the FRFA was improved statistically significantly in Marshall stability, tensile property, and permanent deformation resistance.

Tables 4, 5, and 6 show analysis results of variance (ANOVA) for the Marshall stability, the indirect tensile strength, and the dynamic stability, respectively. In all three properties, the probability of F value (Fisher statistics) shows highly significant level ("Pr > F" less than 0.0001 in each table) among five mixtures. This means that five mixtures made of different additive materials have different property levels and show statistically significant difference in each strength property.

8. Conclusions

Based upon the test results in the laboratory study using various recycled foamed asphalt (RFA) methods, the following conclusions can be made. The inclusion of the polypropylene fibers in the RFA mixture is a viable method to improve the performance of the RFA mixture. Particularly, the Marshall stability and the indirect tensile strength of RFA mixture show higher values due to the inclusion of the polypropylene fiber. The temperature susceptibility of fiber-recycled foamed asphalt (FRFA) mixture is decreased. The permanent deformation resistance of FRFA mixture is another advantage when it is compared with that of recycling hot-mix asphalt (RHMA). Typical statistical analysis supports these findings. The inclusion of Portland cement and semihot method seems to provide the reinforcing effects to RFA mixture; however, the storage time is limited only to an hour or so. The FRFA mixture is equally susceptible to moisture as the other foamed asphalt mixtures. The fiber reinforcement did not make it more moisture susceptible though it did not improve the indirect tensile ratio.

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