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Production of Polypropylene-reinforced Asphalt Concrete Mixtures Based on Dry Procedure and Superpave Gyratory Compactor

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ABSTRACT

Scientists and engineers are constantly trying to improve the performance of asphalt mixtures. Modification of the asphalt binder is one approach used to achieve good mixtures. Fibres and polymers are generally two important modifiers in improving pavement performance, though fibres have received much attention for their enhancement effects among other modifiers for asphalt. In this study, therefore, polypropylene (PP) fibres were selected as fibre modifier because of their low-cost and consistency with asphalt pavement. Asphalt specimens were made by a Superpave gyratory compactor (SGC), analyzed by both Marshall and Superpave methods and tested by Marshall stability apparatus. PP Fibres of two different lengths, i.e., 6 and 12 mm were used at four different percentages of 0.1%, 0.2%, 0.3% and 0.5%, by the total weight of the asphalt concrete. The dry procedure was used to blend fibres with aggregates at the optimized dosage of bitumen, i.e., 4.2%, by weight of the total mix. The experimental results show that adding PP fibre increases the Marshall stability (26%) and the air voids (67%) while reducing the flow (38%) properties. The "law of mixtures" was used for composite materials to study the fitness of specific gravity of the fibre-reinforced asphalt concrete mixtures with the theoretically calculated values. Thus, it was revealed that the fitness of the real results with the theoretically calculated values is considerable, especially at low percentages of fibres, e.g., 0.1% and 0.2%. It became evident that the existence of voids in all modified and/or neat asphalt-concrete treatments leads samples to completely unfit with the “law of mixtures”. Finally, the analysis of variance (ANOVA) method and Dennett's test were used to check the accuracy of the results which significantly demonstrates the advantages of using PP fibres in AC mixtures.

Key Words:

polypropylene fibres;
composite;
fibre reinforcement;
asphalt concrete;
Marshall stability.

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INTRODUCTION

Asphalt concrete (AC), a mixture of bitumen and aggregates, is a sensitive material compared to other configurations used in civil engineering [1]. Therefore, scientists and engineers are constantly trying to improve the performance of the flexible pavements [2]. Modifying the asphalt binder is one approach to improve the pavement's performance [3].

Fibres and polymers are generally two important modifiers used for increasing pavement's performance [4] though the most popular bitumen modification technique is polymer modification [5]. However, fibres have acquired much attention for their improvement effects among other asphalt modifiers [4].

In pavement engineering, fibre reinforcement can be achieved in two ways. One method involves the random inclusion of fibres directly into the matrix, i.e., asphalt concrete and/or Portland cement concrete slabs. Another way comprises the oriented fibrous materials, e.g., geo-synthetics family. The former concept is not as well-known as the latter, not only in optimizing fibres properties, diameter, length, or surface texture, but also in reinforcing mechanism. Obviously, if the fibres are too long, it may create the so called "balling" problem, i.e., some of the fibres may lump together, and the fibres may not blend well with the asphalt. In the same way, too short fibres may not provide reinforcing effect at all. They may just serve as expensive fillers in the mix [6].

Fundamentally, fibres increase the viscoelasticity [7], dynamic modulus [8], moisture susceptibility [9], creep compliance, rutting resistance [10] and freeze-thaw resistance [11] of the modified asphalt, while reducing the reflective cracking of its mixtures and pavements [12,13]. It is important to know that there are two potential methods to introduce the fibres into the AC mixture: the wet process and the dry process. The wet process blends the fibres with the asphalt cement prior to incorporation of the binder into the mixture. The dry process mixes the fibres with the aggregate before adding the asphalt.

In the case of wet base modification, different approaches have been adopted by some researchers, e.g., Al-Hadidi et al. [14] and Tapkin et al. [15,16]. For instance, the former group concluded that with increased stability there are decreases in both flow and air voids as a result of polypropylene modification. They found optimal amount of 5% polypropylene by weight of asphalt in their study [14]. In other attempts, higher stability and percentage of air voids accompanied with flow reduction are reported by the latter groups. In their approach, an amount of 3% by weight of the aggregates of 3 mm PP fibres was determined to be the optimal fibre dosage [15].

Generally, the dry process is preferred for a number of reasons. Experimentally, the dry process is the easiest to perform and allows for the best fibre distribution in the mixture. Also, because the fibres do not melt in the asphalt, there are no other apparent special benefits to the wet process. In addition, the field work done on fibre reinforced asphalt mixtures has generally adopted the dry process [6,11,17-19] possibly due to the production problems of introducing fibres directly into the asphalt. Another reason for using the dry process is that it minimizes the major problems of clumping or balling together of fibres in the mixture [18].

Abtahi et al. reported that there is no difference between two procedures, i.e., the wet and the dry processes, in Marshal properties (stability and flow) when the nylon 6.6 fibres of 12 mm length were used in fibre reinforced asphalt concrete (FRAC) mixtures [20]. A comparative study carried out by Abtahi et al. showed that the performance of PP fibres, 0.125% by total weight of the mix and 12 mm length, is statistically more desirable than styrene-butadiene-styrene (SBS) fibres. The tests included Marshall and resilient modulus [21].

Another research work illustrated that PP fibres perform advantageously due to their low melting point, i.e., 162°C. Consequently, as a complement a property known as "tackiness" glues the fibres to the AC matrix. This achievement has been approved by an artificial neural network (ANN) analysis and has been viewed through the experiments [22].

As demonstrated by the cited studies, the use of PP fibres in AC mixtures is common. However, it is necessary to determine the best fibre parameters, e.g., length and dosage, to be included in the dry procedure. Moreover, preparing the FRAC specimens by superpave gyratory compactor (SGC), a new production method, can be considered as a novel method because of the lack of research in this area, and due to its high accuracy in preparing specimens in a laboratory which simulates field conditions in a much more accurate way than any previous mix design methods, e.g., Marshall procedure. Therefore, the main aim of this study is to produce PP-reinforced AC mixtures based on dry procedure and to prepare samples by using Superpave gyratory compactor method.

EXPERIMENTAL

Materials and Methods

For this study, continuous aggregate gradation was

Table 1. Physical properties of bitumen.

Properties	Test value	Standard
Penetration at 25°C, 1/10 mm	89	ASTM D 36 - 06
Penetration index	0.48	--
Ductility at 25°C (cm)	> 100	ASTM D 113 - 07
Softening point	41.7	ASTM D 36 - 06
Flash point	278	ASTM D 92 - 05
Specific gravity at (25°C) (g/cm^3)	1.0029	ASTM D 70 - 09

used according to the Turkish Highway Standard for binder course, Type 1 [23].

The aggregate type was a crushed-calcareous stone obtained from a local quarry in North Cyprus. The bitumen (50/70) used in this study was obtained from a local refinary plant. The physical properties of the asphalt binder and the aggregate gradation are given in Tables 1 and 2, respectively. Aggregate's physical properties are also provided in Table 3.

Table 2. Gradation of the aggregate.

Range of Standards		
Sieve size (mm)	Passing (%)	Retained (%)
25	100	0
19	82-100	9
12.5	68-87	13
9.5	60-79	8
4.75	46-65	14
2.36	34-51	13
0.425	17-29	20
0.180	9-18	9
0.075	2-7	9
Pan	0	5

Physiochemical properties of PP fibres are shown in Table 4. The mix was designed according to the procedure in ASTM D 1559 - 89. Aggregates were heated to 170°C and mixed with 3.5, 4.0, 4.5, 5.0, and 5.5% of bitumen by the total weight of the mixture under neat treatment, i.e., AC without any PP fibres. Then, according to Superpave mix design, mixtures were left in the oven at 135°C for 4 h for short term aging which simulates the delays that can occur in actual construction process. After short term aging, asphalt mixtures were placed in another oven to reach the compaction temperature of 150°C-160°C not longer than 30 min. The compaction moulds and base/top plates were also placed at the same temperature for 45-60 min before compaction. Since mixtures were supposed to be tested with Marshall stability, the moulds with 100 mm (4 inch) diameter were used. After 24 h, the prepared specimens were brought to the specified temperature at 60 ± 1°C by placing in water bath for 30 to 40 min to be tested with Marshall stability apparatus [24].

In this study, the dry base approach was selected, i.e., first polypropylene fibres and aggregates were mixed together for approximately 30 s, and then they were introduced into asphalt. PP fibres with two

Table 3. Physical properties of aggregates.

	Coarse	Fine
Average bulk specific gravity (dry) (g/cm^3)	2.79	2.73
Average bulk specific gravity (SSD) (g/cm^3)	2.81	2.77
Average apparent specific gravity (g/cm^3)	2.84	2.85
Average absorption (%)	0.61	1.57
Los Angeles abrasion value	33.65	

Table 4. Physical properties of polypropylene fibres.

Properties	Specification data
Specific gravity	0.91 g/cm^3
Diameter	22 μm
Cross section	Round
Tensile strength	350 - 400 MPa
Melting point	160-170
Acid and salt resistance	High
Alkali resistance	Excellent
Water absorption	0
Thermal conductivity	Low
Electrical conductivity	Low
Fibre length	6 mm and 12 mm

different lengths, i.e., 6 and 12 mm were selected at four different percentages of 0.1%, 0.2%, 0.3% and 0.5%, by total weight of the asphalt concrete. The mixture of fibres and aggregates were blended with the optimized dosage of asphalt. According to the Marshall procedure, the optimum asphalt which in this study was 4.20% by weight of the total mixture was specified for 4.0% air void.

Figures 1 and 2 show Marshall stability and flow, respectively. The Marshall Quotient (MQ) values have been calculated for different treatments which are shown in Figure 3. This parameter is calculated as the ratio of stability to flow. The specific gravity of neat and PP reinforced AC samples were measured and are presented in Figure 4.

Samples were also analyzed using the Superpave method. Notability of densification data in Superpave

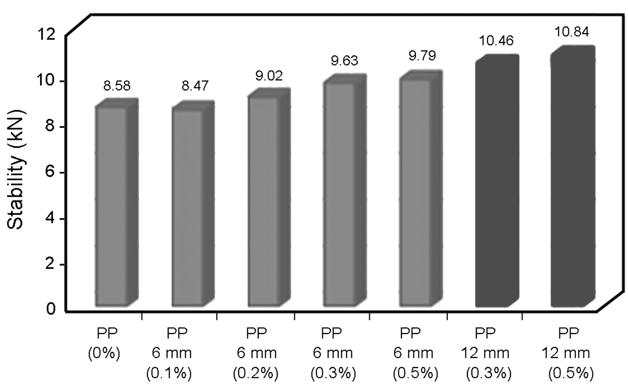

Figure 1. Marshall stability at optimum bitumen content of 4.20%.

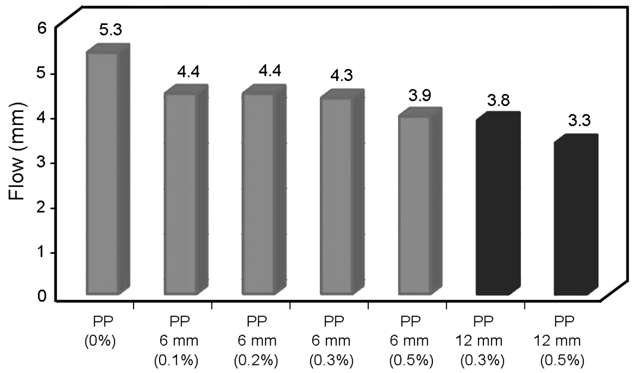

Figure 2. Flow at optimum bitumen content of 4.20%.

procedure expressed in percentage of theoretical maximum specific gravity (G_{mm}%) is dependent on three parameters. First, the initial number of gyration (N_{ini}) which is the maximum allowable mixture density that should be 89%. It means that the percent of air void at N_{ini} must be at least 11.0%. The second parameter was the number of design gyration (N_{des}) which all the calculations (percentages of air voids, voids in the mineral aggregate (VMA%), voids filled with asphalt (VFA%), etc.) are calculated by the percentage of G_{mm} in this level of gyration, and finally, the last parameter is the maximum number of gyration (N_{max}). The maximum allowable mixture density should be 98% which means that the percentage of air void in N_{max} must be at least 2.0% [24].

Table 5 indicates G_{mm}% at the initial and maximum allowable mixture densities. As it is illustrated in Table 5, the maximum mixture density fluctuates between 85.3% and 88.0% when N_{ini} aquals 8 gyrations and between minimum 93.3% to

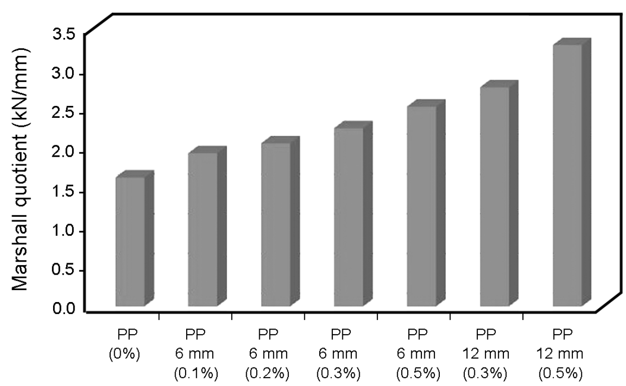

Figure 3. Marshall quotient at optimum bitumen content of 4.20%.

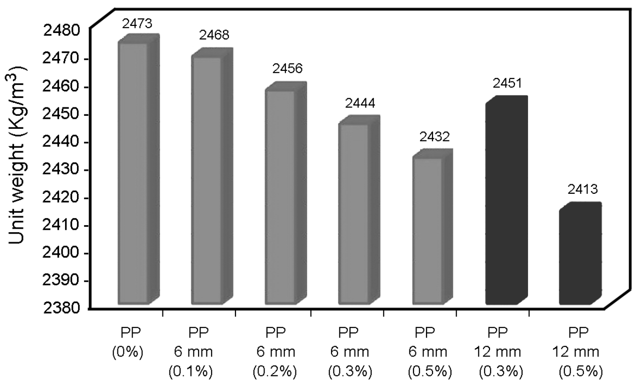

Figure 4. Unit weights at optimum bitumen content of 4.20%.

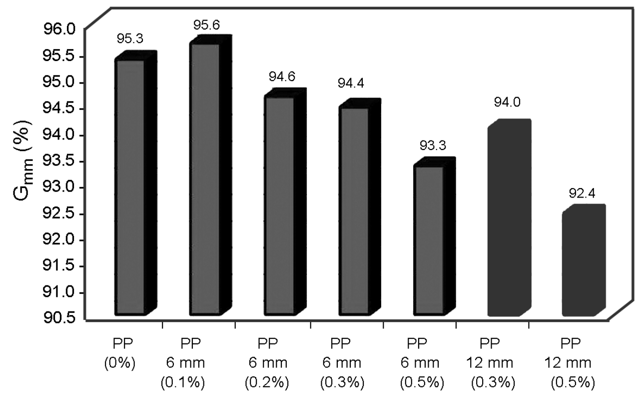

Figure 5. Percentage of G_{mm} at N = 95 and optimum bitumen content of 4.20%.

the maximum of 96.4% when N_{max} equals 150 gyrations. N_{max} is used as the number of gyrations to which test specimens should be compacted where an estimation of this compatibility is determined by N_{ini}.

Figure 5 demonstrates the G_{mm}% at the design level. As it was mentioned earlier, the maximum allowable mixture density at N_{ini} is equal to 89.0% which according to Table 5, all the calculated G_{mm}% for different mixes are lower than specified N_{ini} indicating no problem during construction. The same argument is applicable to N_{max} with having the maximum of 96.4% which has lower mixture density than maximum allowable amount of 98.0%. This indicates that there is not any problem under traffic regarding air voids. As it can be seen all the obtained data are within acceptable range. These findings substantiate the existence of an adequate air void which prevents possible distresses imposing in this manner.

Moreover, in pavement engineering, the volumetric design of asphalt mixtures requires consideration of air voids, voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA). VMA is defined as the sum of the volumes of the air voids and the unabsorbed binder in the compacted specimen. VFA is the percentage of VMA containing asphalt binder [25]. Figures 6-8 illustrate the values of percentage of air voids, VMA% and VFA% for different treatments, respectively.

Finally, the analysis of variance (ANOVA) method was used to check the accuracy of Marshall stability, flow and unit weight results. Data analyses show that the changes in the results are significant. To find the best percentage, the least significant difference (LSD) and Dunnett tests were performed on output data. Principally, in many experiments, one of the treatments includes control test, and the analyst is interested in comparing each "a - 1" treatment with the control. Thus, there are only "a - 1" comparisons to be made.

A procedure for making these comparisons has been developed by Dunnett (1964). More details about Dunnett test is available elsewhere [26]. In this study, the neat treatment (AC sample without PP) was considered as the control treatment while the PP modified samples were compared with it. By using the statistical analysis software, statistical package for social sciences (SPSS) version 17, a one-way

Table 5. Percentage of G_{mm} at optimum bitumen content of 4.20%.

Number of gyration (N)	PP (0%)	PP (6 mm)* (1%)	PP (6 mm) (2%)	PP (6 mm) (3%)	PP (6 mm) (5%)	PP (12 mm) (3%)	PP (12 mm) (5%)
Initial (8)	87.8	88.0	86.8	87.1	86.1	86.8	85.3
Maximum (150)	96.2	96.4	95.6	95.0	94.2	94.9	93.3

(*) Length of polypropylene fibre

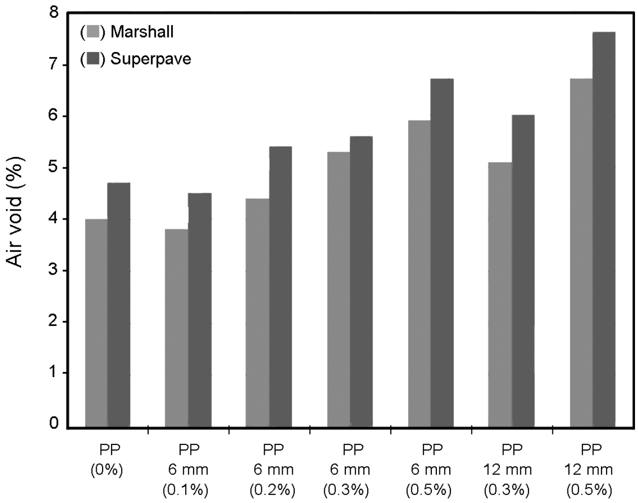

Figure 6. Percentage of air void at optimum bitumen content of 4.20% derived by Superpave method and Marshall procedure.

ANOVA with a confidence coefficient of 95% ($\alpha = 0.05$) was performed. Table 6 shows the ANOVA results where the stability, flow and unit weight are the response variables. The table indicates that the P-value (last column in the table) is less than 0.05 for changes in response variables regarding mixes with polypropylene additive compared with control sample. This certifies the significant effects of polypropylene fibres on mechanical properties, e.g., Marshall stability, flow and unit weight.

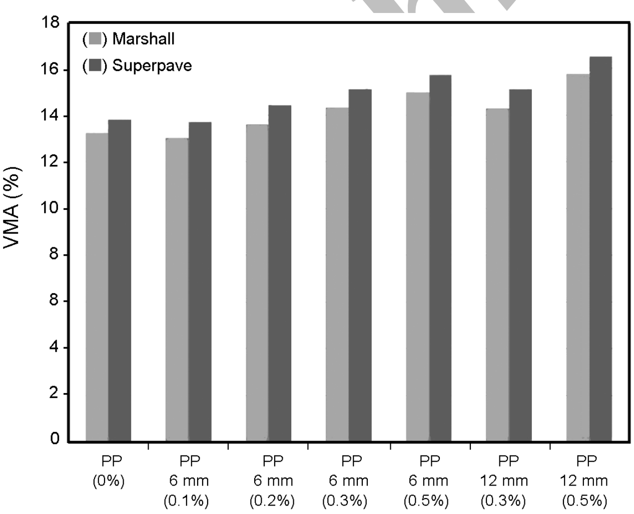

Figure 7. Percentage of VMA at optimum bitumen content of 4.20% derived by Superpave method and Marshall procedure.

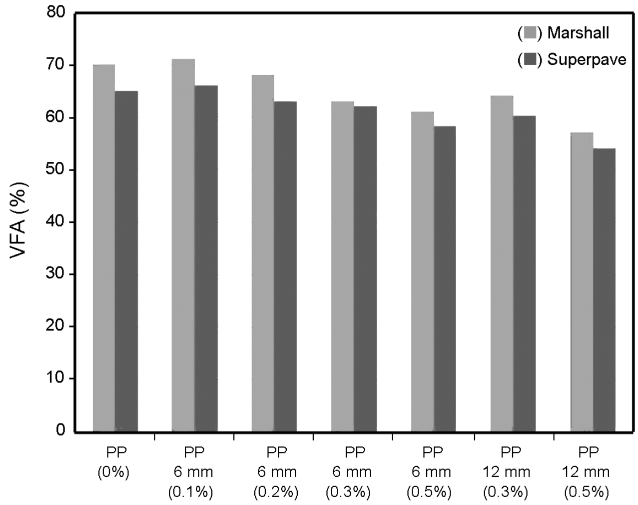

Figure 8. Percentage of VFA at optimum bitumen content of 4.20% derived by Superpave method and Marshall procedure.

Besides, in this study, Fisher's least significant difference (LSD) comparison with "$\alpha = 0.05$" was implemented for Marshall response. The Fisher LSD procedure is a commonly used statistical analysis tool, and it is defined as the observed difference between two sample means necessary to declare the corresponding differences between population means. If the difference between two population means is found to be greater than the least significant difference, then the population means may be declared statistically different [27]. Table 7 illustrates the significant differences for 0.5% PP fibres of 12 mm in both LSD and Dunnett procedures. It is evident that stability of 0.5% polypropylene with 12 mm length is significantly better than the rest of the lengths and percentages values that have been also approved by Dunnett test.

RESULTS AND DISCUSSION

It is evident in Figure 1, that the stability of the modified samples is increased, as the fibre length and percentage are increased. The stability starts from 8.58 kN for neat asphalt and jumps to 9.79 kN and 10.84 kN for 6 mm and 12 mm PP fibres, respectively. There are more than 14 and 26 percentage increases for 0.5% PP fibres of 6 and 12 mm length,

Table 6. ANOVA data obtained for Marshall stability, flow and unit weight.

Response: Stability					
	Sum of squares	df	Mean square	F	Significant
Between groups	432622.232	6	72103.705	179.505	0.000
Within groups	5623.520	14	401.680		
Total	438245.752	20			
Response: Flow					
	Sum of squares	df	Mean square	F	Significant
Between groups	6.744	6	1.124	6.812	0.002
Within groups	2.315	14	0.165		
Total	9.059	20			
Response: Unit weight					
	Sum of squares	df	Mean square	F	Significant
Between groups	0.025	6	0.0041	2.733	0.05
Within groups	0.021	14	0.0015		
Total	0.046	20			

respectively. The same trend was repeated for air void and consequently for VMA. Air void percentage starts from 4.0% and climbs to 5.9% and 6.7% for 6 and 12 mm PP fibres, respectively (47.5% growth for 6 mm and 67% for 12 mm PP fibres). In contrast, reduction in flow (Figure 2) and unit weight (Figure 4) is observed as the percentage of PP fibres is increased. Flow dropped for more than 37% and unit weight for more than 2.0%.

It seems that increase in stability and reductions in flow and unit weight could be related to the penetration of fibres between particles and enhancement of interlocking of the aggregates [28]. Therefore, the concept of "fibre interlocking effect" may result in increase in stability and accordingly decrease in flow. This phenomenon has been generally explained for short fibres composites, e.g., soil composite [29,30] and fiber reinforced asphalt concrete (FRAC) [31].

The increase in Marshall stability is also due to the fibre reinforcement effect, i.e., according to the law of mixtures composites, it can be derived as fallows [32]:

$$\sigma_c = v_f \times \sigma_f + v_m \times \sigma_m \qquad (1)$$

where, the indexes of c, f and m are the initials of composite, fibre and matrix, respectively. Ultimate strength and volume fraction are represented by σ and v, respectively. Consequently, eqn (1) implies that increasing the fibre volume fraction results in increasing the composite strength. Stability, fundamentally, is the compressive strength of the AC sample. The same equation is used for the modulus of composites. That is why flow is decreased by an increase in fibre volume (Figure 2). On the other hand, Figures 6-8 state that the air void has been increased by the fibres content increment. It is clear that when the air void increases, the G_{mm}% and unit weight are decreased (Figures 4 and 5). The "law of mixtures" can explain this phenomenon as fallows [32]:

$$\rho_c = v_f \times \rho_f + v_m \times \rho_m \qquad (2)$$

where, ρ denotes the density. Since, density of PP fibres is low (0.92 g/cm^3) compared to AC density, the specific gravity of the modified samples would be decreased. That is why the air void has been raised and consequently, G_{mm}% has been failed.

Table 7. Least significant difference (LSD) and Dunnett results for Marshall stability (0.5% and 12 mm PP fibres).

Test type	Polypropylene (%)	Polypropylene (%) (12 mm)	Mean difference	Standard error	Significant
LSD	0.0 (6 mm)	0.5	-384.4667	16.36420	0.000
	0.1 (6 mm)	0.5	-414.4000	16.36420	0.000
	0.2 (6 mm)	0.5	-307.8000	16.36420	0.000
	0.3 (6 mm)	0.5	-210.5333	16.36420	0.000
	0.3 (12 mm)	0.5	-69.6667	16.36420	0.001
	0.5 (6 mm)	0.5	-192.0000	16.36420	0.000
	0.5 (12 mm)	0.5	+192.0000	16.36420	0.000
Dunnett t (2-sided)	0.0 (6 mm)	0.5	-384.4667	16.36420	0.000
	0.1 (6 mm)	0.5	-414.4000	16.36420	0.000
	0.2 (6 mm)	0.5	-307.8000	16.36420	0.000
	0.3 (6 mm)	0.5	-210.5333	16.36420	0.000
	0.3 (12 mm)	0.5	-69.6667	16.36420	0.004
	0.5 (6 mm)	0.5	-192.0000	16.36420	0.000

In this way, Figure 9 shows the fitness of the unit weight experimental results with the values obtained through the law of mixtures in accordance with eqn (2). As it is observed the fitness of the real results with the theoretically calculated values is considerable, especially at low percentages of fibres contents, e.g., 0.1% and 0.2%. It is clear that the existence of voids in all modified and/or neat AC treatments leads samples not quite fit with the law of mixtures, the concept that is well-known in composite science.

Another interesting outcome is that by increasing the PP dosage in the AC mixture, air voids in the FRAC composites will be increased (Figures 6-8). Accordingly, the unfitness of the experimental results with the theoretical calculated values has been enhanced. From another point of view, it has been accepted that fibres reduce the viscosity of the asphalt binder [6]. That is why increasing fibres dosage decreases VFA% (Figure 7). As it was mentioned above, VFA is the percentage of the voids in the compacted aggregate mass that are filled with asphalt cement.

The Marshall quotient (MQ) calculated as the ratio of stability to flow and thereby representing an approximation of the ratio of load to deformation under the particular conditions of the test can be used as a measure of the material's resistance to permanent deformation in service [33]. Figure 3 presents MQ values for different treatments stating that the greater the fibre length and dosage, the more MQ value would result. Since, MQ is an indicator of the resistance against the deformation of the asphalt concrete, MQ values are calculated to evaluate the resistance of the deformation of the PP-modified specimens. A higher value of MQ indicates a stiffer

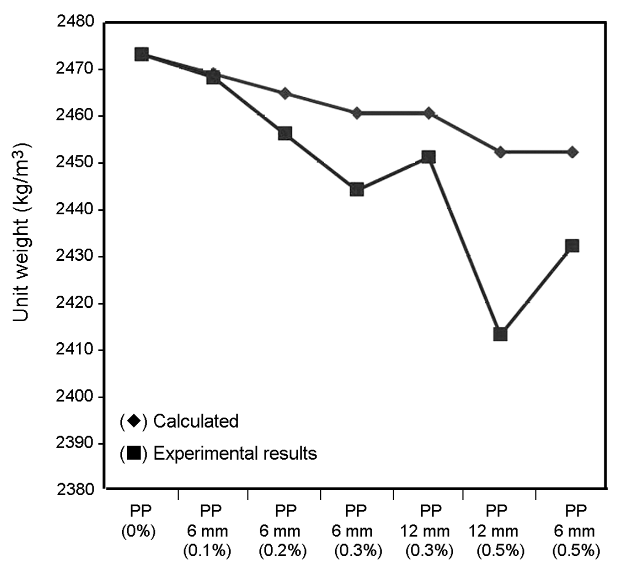

Figure 9. Comparison of the unit weight experimental results with calculated values obtained through the "law of mixtures".

mixture and, hence, indicates that the mixture is likely more resistant to permanent deformation [33]. As it is noticed in Figure 3, the AC specimen reinforced with 0.5% PP fibres of 12 mm presents the highest MQ than other mixtures.

Figure 5 depicts G_{mm}% at N = 95 gyrations (N_{des}) specified according to Superpave mix design (SP-2) [24]. Reduction in maximum theoretical specific gravity was revealed by increasing PP dosage, as it was expected due to lower specific gravity of the modified fibres.

It is interesting to note that both the LSD and Dunnett tests demonstrate that the treatment of AC modified with 0.5% PP fibres of 12 mm length showed a significant difference in Marshall stability and flow among all samples. On the whole, these results support other studies that have shown that PP can be helpful for increasing pavements life [12,14,15]. Moreover, increasing the air void is important for pavements designed to serve in hot regions where flushing and bleeding are one of the main problems which can be avoided by increasing air void [12].

Using the Superpave method showed an increase in the percentage of air voids in comparison to the Marshall method. But, the same trend was observed for both two methods, i.e., Marshall and SGC.

The authors concluded that 0.3% PP fibres of 12 mm length should be preferred to other PP fibres percentages and lengths. Since, at higher percentage of PP fibre contents, the air void would be increased to 6.7%, which can be considered as a disadvantage. There is not any significant difference in stability of PP modified samples, between two treatments of 0.3% and 0.5% PP fibres of 12 mm length (only 3.6% difference) which are approved by LSD and Dunnett test (Table 7).

CONCLUSION

Scientists and engineers are constantly trying to improve the performance of asphalt mixtures by using various methods including asphalt binder modification. In this study, therefore, polypropylene fibres were selected as fibre modifier because of their low-cost and good consistency with asphalt binder. Two lengths of PP fibres including 6 and 12 mm were selected and each used separately at four different percentages of 0.1%, 0.2%, 0.3% and 0.5%, by total weight of the asphalt concrete. The mixture of fibres and aggregates was blended with 3.5%, 4.0%, 4.5%, 5.0% and 5.5% of butmen by weight of the total mix. Asphalt specimens were made by Superpave gyratory compactor (SGC), analyzed by both Marshall and Superpave methods and tested by Marshall stability apparatus. Addition of PP fibres showed an increase in Marshall stability (26.3%), and the percent of air void (67.5%) while decreases in flow property (38.0%). As a result, the data show that PP modified asphalt-concrete samples can be considered as high-performance asphalt-concrete mixtures. Increasing the percent of air void, in modified treatments, they are useful for hot regions where bleeding and flushing are critical distresses. The composite "law of mixture" was used to explain the experimental results. Since the density of PP fibres is low compared to AC density, the specific gravity of the modified samples is decreased. That is why the air void has been raised and consequently, G_{mm}% has failed. In this regard, the fitness of the unit weight experimental results with the values obtained through the "law of mixtures" was investigated. Therefore, it was found that the fitness of the real results with the theoretically calculated values is considerable, especially at low percentages of fibre contents. It is due to the existence of voids in all modified and/or neat AC treatments which leads samples to not fitting completely with the "law of mixtures", the concept that is well-known in composite science. Another interesting outcome is that by increasing the PP dosage in the AC mixture, air voids in the FRAC composite is increased. Accordingly, the unfitness of the experimental results with the theoretical calculated values is enhanced.

Finally, we concluded that 0.3% of polypropylene of 12 mm length is better than other percentages and lengths used in the experiment, because the air void increased to 6.7% at this percentage. The high amount of void is disadvantageous and also there is no significant difference in stability (3.6% difference) at this percentage, which is approved by LSD and Dunnett tests. This study was carried out only on the continuous gradation, with one type of asphalt cement. The dry method with 6 and 12 mm polypropylene fibres was tested. Hence, Superpave-wet modification as a useful procedure is recommended for the future studies. Moreover, modifications with other polypropylene fibre lengths, e.g., 3 mm are also recommended for the future study.

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