A NOVEL SOLUTION TO RUTTING, FLUSHING AND BLEEDING PROBLEMS ENCOUNTERED IN VERY HOT CLIMATES BY THE UTILISATION OF POLYPROPYLENE FIBER MODIFICATION OF DENSE BITUMINOUS MIXTURES

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ABSTRACT

Multifilament 3 mm polypropylene fibers are completely native modifiers that are utilised in modifying the bituminous binder. It has been clearly proven in the time span of more than 14 years that the addition of polypropylene fibers into asphalt mixtures results in the improved Marshall stabilities, reduced flow values and therefore increased Marshall Quotient values. The lives of the polypropylene modified specimens under repeated creep testing increased by 5-12 times versus reference specimens. The decrease of the accumulated strains at the end of the static creep tests correspond to more than 60%. The initial and final creep stiffness values have increased by 129% and 149% correspondingly. The average stability values of the control specimens increase up to more than 70%. Based on the static creep, Marshall Tests and stereo microscopy analyses, the optimal polypropylene addition amount had been determined as 5.5‰ by weight of aggregate. Besides, there is an economy of 30% from bitumen. Altogether the extra cost of using polypropylene fibers as a modifier is only 9.3% but this cost is becoming far more smaller when the dependency to imported expensive modifiers and the know-how being sold besides them. This is a novel solution for countries especially exposed to detrimental effects of high temperatures monitored on flexible pavement systems all throughout the year, which are subjected to rutting, flushing and bleeding. Also there is always no need for very expensive patented modifiers as native modifiers can be a perfect solution to the above mentioned problems for developing countries.

Keywords: Polypropylene fibers, Marshall design, Creep testing, Stereo microscopy, Economy

1. INTRODUCTION

Main applications of polymer fiber reinforcement in the modern era have begun in early 1990s. Brown et al. have enriched the development of this kind or research [1]. Also some other researchers believe that some type of fibers create physical changes to modifiers which has a preferable effect on drain-down reduction than polymer modifiers do [2,3]. In another study, fracture mechanics approach was utilized to assess the effects of fiber reinforced asphalt concrete on resistance to cracking [4]. Simpson et al. conducted another study in which polypropylene, polyester fibers and some other polymers were used to modify the bituminous binder [5]. Huang and White conducted a research on asphalt overlays modified with polypropylene fibers [6]. Ohio Department of Transportation carried out extensive research on the addition of polypropylene fibers to the asphalt mix in a dry basis [7]. In a study carried out by Cleven, fibers (polypropylene, polyester, asbestos and cellulose) appear to increase the stiffness of the asphalt binder resulting in stiffer mixtures with decreased binder drain-down and increased fatigue life [8]. Tapkın has found out that the addition of polypropylene fibers into the asphalt concrete in a dry basis alters the behaviour of the mixture in such a way that, Marshall stability values increase, flow values decrease and the fatigue life increases in a pronounced manner [9]. Tapkın et al. has also worked on the addition of polypropylene fibers to the asphalt concrete on a wet basis, and have shown that the most favourable and suitable polypropylene type was M-03 and the addition of this type of bitumen has increased the Marshall stability values by 20 %. Also the stiffness of the Marshall specimens has increased in a considerable manner, which is also supported by the visible increase in the Marshall Quotient values. By carrying out repeated load creep tests under different loading patterns have also shown that the lives of the fiber modified asphalt specimens under repeated creep loading at different loading patterns increased by 5-12 times vs. reference specimens, which is a very significant improvement [10-12]. In another accompanying study, first of all, the physical and chemical effects of polypropylene fibers on bitumen were investigated. Next, the amount of "optimum" polypropylene fibers that has to be added into mixture was determined. In order to determine it, first, static creep tests and Marshall tests were carried out and then, images of the polypropylene fiber added bituminous binders under fluorescence microscopy were researched. With the application of physical and mechanical tests to the Marshall specimens prepared with the optimum polypropylene amount that was obtained at the end of these three tests, optimum bitumen content was determined and finally economical analyses were carried out. After examining the obtained results, it has been found out that the polypropylene modification of bituminous binders has developed the physical and mechanical properties of the mixture and substantially improved the resistance to permanent deformations. Besides, the polypropylene modification results in 30 % economy from bitumen which is very important for the costly asphalt concrete production in recent times [13]. There are also some more relevant studies in the literature mentioning about the several different applications of polypropylene fiber modification of asphalt concrete in last decade which deserve attention [14-18].

2. Wet basis modification with M-03 type polypropylene fibers and repeated creep tests undertaken

Rutting can result in the loss of pavement serviceability in case when cracking follows the formation of ruts and rapid deterioration of pavement due to accumulation of water on the pavement surface. Under normal service conditions, deformations within the bituminous materials occur more frequently during late spring, summer and early fall because of high temperature conditions. During winter, the subgrade soil may be frozen, so it provides firm support for asphalt pavement and thus reduces pavement deformation. In order to model the rutting susceptibility of bituminous mixtures, universal testing machine UTM-5P, which can carry out static and repeated creep tests has been utilised all throughout the undertaken studies [19].

2.1 Material properties

Continuous aggregate gradation has been used to fit the gradation limits for wearing course [20]. Aggregate was calcareous type crushed stone obtained from a local quarry and 50/70 penetration bitumen was obtained from a local refinery were used for preparation of the Marshall specimens. Physical properties of the bitumen samples are given in Table 1. The physical properties of coarse and fine aggregates are given in Table 2. The apparent specific gravity of filler is 2790 kg/m^3.

Table 1: Physical properties of reference bitumen

Property	Test Value	Standard
Penetration at 25°C, 1/10 mm	55.4	ASTM D 5-97
Loss on heating, %	0.057	ASTM D 6-80
Specific gravity at 25°C, kg/m^3	1022	ASTM D 70-76
Softening point, °C	48.0	ASTM D 36-95
Flash point, °C	327	ASTM D 92-02

Table 2: Physical properties of coarse and fine aggregates (fines written in bold characters)

Property	Test Value	Standard
Bulk specific gravity, kg/m^3	2703, **2610**	ASTM C 127**(128)**-04
Apparent specific gravity, kg/m^3	2730, **2754**	ASTM C 127**(128)**-04
Water absorption, %	0.385, **1.994**	ASTM C 127**(128)**-04

The mixture gradation and gradation limits are given in Table 3.

Table 3: Type 2 wearing course gradation [20]

Sieve size, mm	Gradation limits, %	Passing, %	Retained, %
12.7	100	100	0
9.52	80-100	90	10
4.76	55-72	63.5	26.5
2.00	36-53	44.5	19.0
0.42	16-28	22	22.5
0.177	8-16	12	10.0
0.074	4-10	7	5
Pan	-	-	7

In the wet basis modification procedure of the asphalt concrete specimens, standard 50/70 penetration bitumen was modified by utilising polypropylene fibers. The fibers were premixed with bitumen using a standard mixer at 500 revolutions per minute for two hours. The mixing temperature was around 165-170°C [21]. For the sake of testing reasons, the reference bitumen samples were also subjected to same temperature to equalise the oxidative and aging effects of two hours of heat effect utilised in polypropylene modification. Three types of polypropylene fibers: M-03 (multifilament 3 mm), M-09 (multifilament 9 mm) and waste fibers were used in research. For M-03 type fibers, fiber contents of 3 ‰, 4.5 ‰ and 6 ‰ by weight of aggregate were premixed with bitumen and were used for preparation of standard Marshall specimens [10-12, 22]. For M-09 type and waste fibers only 3 ‰ fiber content was utilized as it was extremely difficult and cumbersome to mix fibers with greater lengths with bitumen using standard mixers other than high shear ones. According to the workability criteria, M-03 type fibers were found to be the best modifiers and, due to the consistency of the Marshall test results, 3 ‰ fiber content was determined as the optimal addition amount. The physical properties of the polypropylene fiber based bitumen samples with 3 ‰ fiber content are given in Table 4.

Table 4: Physical properties of the M-03 type polypropylene fiber modified bitumen

Property	Test Value	Standard
Penetration at 25°C, 1/10 mm	45.5	ASTM D 5-97
Loss on heating, %	0.025	ASTM D 6-80
Specific gravity at 25°C, kg/m^3	1015	ASTM D 70-76
Softening point, °C	52.1	ASTM D 36-95
Flash point, °C	292	ASTM D 92-02

To determine the optimum bitumen content, the bitumen contents corresponding to the mixtures with maximal stability and unit weight, 4% air voids and 70% voids filled with asphalt, were found and averaged according to the acting standard limits [20]. These optimum bitumen contents for various types of polypropylene fibers are represented in Figure 1.

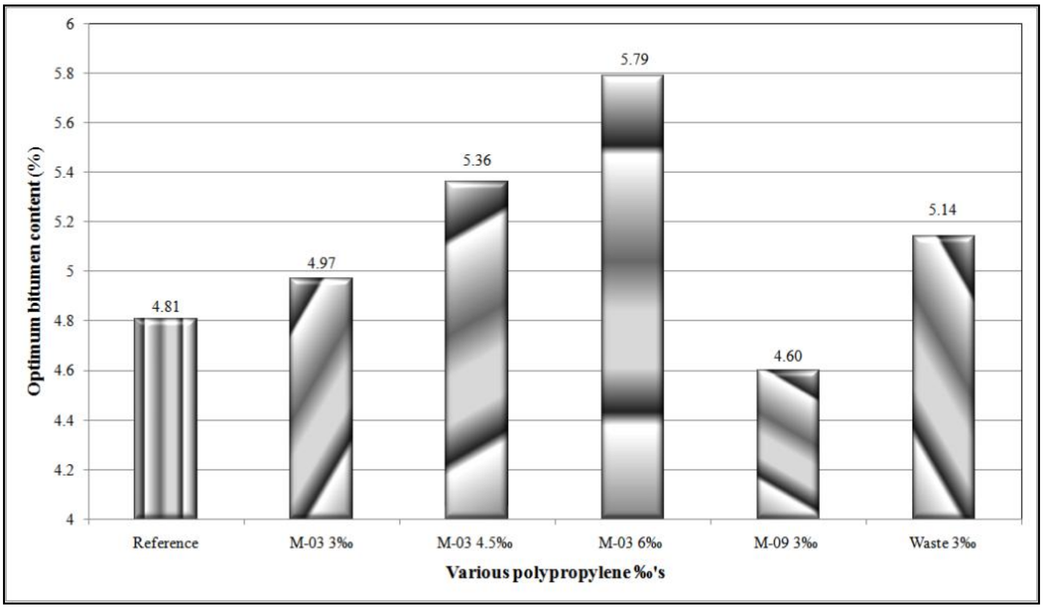

Figure 1: Optimum bitumen contents for different type and amount of polypropylene fibers

As can be seen form Figure 1, based on the performed experiments, the optimum bitumen content varies depending on the type and dosage of fibers. However, the optimal polypropylene amount, the type, the homogeneity in the preparation of the Marshall specimens, the ease in the addition of the polypropylene fibers, the ease in the fabrication of the specimens and the fluctuations of the observed physical and mechanical properties are also very important. For example, specimens prepared with higher dosages of M-03 fibers, mixtures made with M-09 and waste fibers resulted in increased values of optimal bitumen contents. M-09 and waste fibers also had very little workability. The addition of these fibers into bitumen is really difficult and results in very viscous modified bitumen samples that does not allow the fabrication of stable Marshall specimens (these modified bitumen mixtures were in a condition which was nearly impossible to prepare “stable” asphalt specimens via Marshall compaction or any other compaction method). The fluctuations in the stability and flow values and Marshall Quotient values do support the above mentioned observations [22]. Based on these results and years of extensive experience in this kind of modification, M-03 polypropylene fibers at dosage of 3 ‰ by the weight of aggregates were found to be the optimal polypropylene addition amount. Also, it can be seen that the optimum bitumen contents for reference and specimens with 3‰ of M-03 fibers are 4.81% and 4.97%, respectively (Figure 1). For the next step of experiments, these two values were taken as 5% for the sake of ease in preparation of the reference and polypropylene fiber modified asphalt specimens [22].

2.2 Repeated creep tests undertaken

Repeated creep tests have been performed in order to log the accumulation mechanisms of the developing strains in the specimen body, or in other words permanent deformations. Prior to testing, the specimens were put into the chamber for 24 hours in order to have the uniform temperature distribution. All of the tests were carried at 50°C. To understand the behaviour of the asphalt specimens under different loading patterns, different constant stress values were chosen (namely 100, 207 and 500 kPa). As polypropylene modification was carried out, utilizing lower stress values like 100 and 207 kPa was not feasible, since under such loading the tertiary creep region could not be observed within a reasonable period of time. Therefore, in order to be able to differentiate between the reference and fiber-reinforced samples, a real destructive loading level of 500 kPa (approximately 73 psi) was chosen as the standard stress value which is a main departure from the published pioneering literature of the rule of thumbs about creep testing [23-26]. This value very well represents the actual tire pressure of a loaded truck.

The specimen strain during the pulsed loading stage of the test were measured in the same axis as the applied stress using two linear variable displacement transducers (LVDTs). The applied force was open loop controlled and rectangular in shape [10, 22]. Load periods were chosen as 500 ms for all of the specimens and the rest periods were 500, 1000, 1500 and 2000 ms, respectively. Four specimens were tested for each loading pattern. The reference specimens were prepared with 5% bitumen content. The fiber-reinforced (M-03 type with dosage of 3‰ by the weight of aggregate) specimens were also prepared with 5% bitumen content. The repeated creep test results, representing the log of accumulated strains developed in the asphalt specimen bodies versus pulse counts are visualized through Figures 2 to 5.

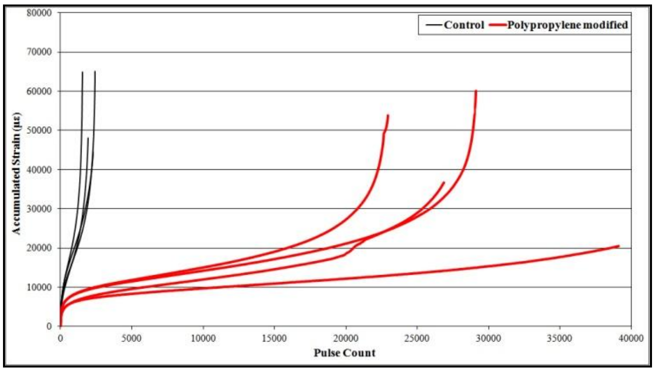

Figure 2: Accumulated strain versus pulse counts of specimens with loading pattern of 500 ms load-500 ms rest period

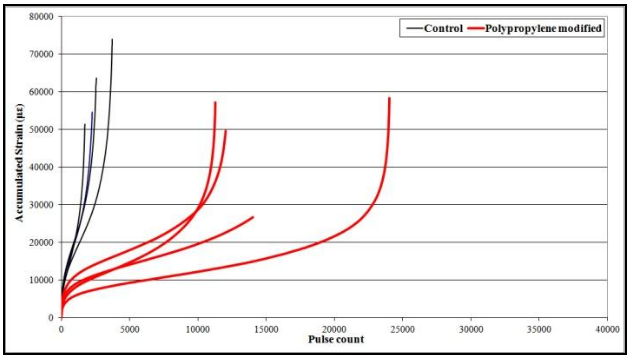

Figure 3: Accumulated strain versus pulse counts of specimens with loading pattern of 500 ms load-1000 ms rest period

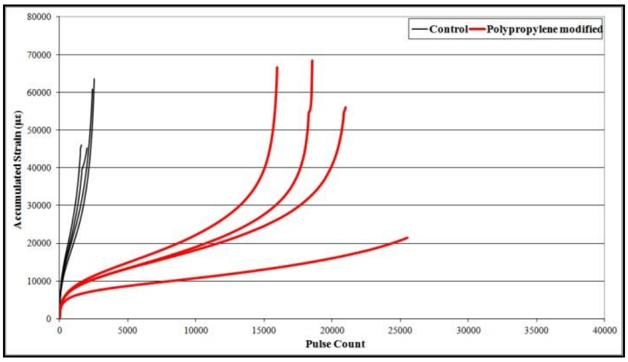

Figure 4: Accumulated strain versus pulse counts of specimens with loading pattern of 500 ms load-1500 ms rest period

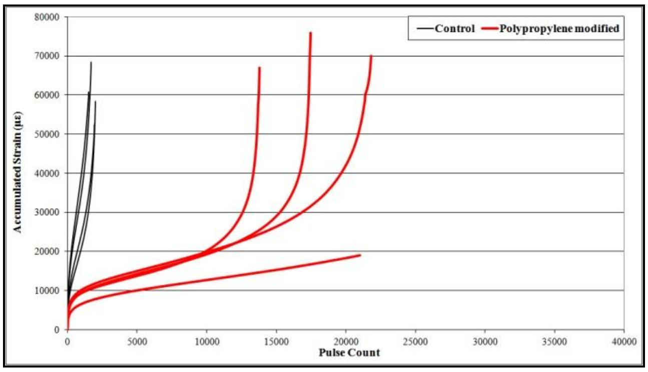

Figure 5: Accumulated strain versus pulse counts of specimens with loading pattern of 500 ms load-2000 ms rest period

As can be clearly seen in Figure 2 (500 ms load-500 ms rest), fiber-reinforced specimens under repeated creep tests show a reaching to failure point pattern which is approximately 12 times longer than the reference specimens under the same loading pattern and temperature. This is a perfect indication of the wet basis modification of asphalt specimens with M-03 type polypropylene fibers. When the reader analyses Figure 2, he/she can see that the reference specimens are entering to the tertiary stage of creep only at around 2000 pulse counts. This point corresponds only to the primary creep stage for the polypropylene fiber modified specimens. Fiber modified specimens reach the tertiary creep stage at the pulse counts of 20000 which is the clear indication of the start of the failure of these specimens. When the reference specimens have a total collapse, the fiber reinforced specimens did not show any sign of failure (they are in fact just in their primary creep stages) [10].

Figure 3 represents the graph of the reference and fiber modified specimens for 500 ms load-1000 ms rest periods. In this graph, it can be seen that the service life of the modified specimens is approximately five times longer than the reference specimens.

Fiber-reinforced specimens under repeated creep tests show a reaching to failure point pattern approximately 7.5 times higher than the lives of the reference specimens under 500 ms load-1500 ms rest period loading pattern (Please refer to Figure 4).

Accumulated strain versus pulse counts and the creep stiffness versus pulse counts of the reference and modified specimens for the 500 ms load-2000 ms rest periods are given in Figure 5. The main difference of this loading pattern when compared to 500 ms load-500 ms rest loading pattern is related to considerably longer rest periods.

2.3 Static creep tests

The test conditions consist of a static axial stress, σ, of 100 kPa being applied to a specimen for a period of 1 hour at a temperature of 40°C. These test conditions were standardized following a seminar in Zurich [27]. This test is inexpensive and easy to conduct but the ability of the test to predict performance is extremely questionable. In place asphalt mixtures are typically exposed to truck tire pressures of approximately 828 kPa (120 psi) and maximum temperatures of 60°C (140°F) or higher [28]. Therefore, the conditions of this test do not closely simulate in-place conditions. The outlet of this part of the study was this major drawback of the static creep tests that have been carried out worldwide up to date [13]. Therefore a completely different loading pattern and testing temperature was adopted all throughout the studies that have been carried out. Because of this fact, in this study, first of all, the test temperature has been chosen again as 50°C to resemble the actual in-situ conditions. To determine the optimum bitumen content of unmodified specimens, Marshall design was utilised. Prior to testing, the specimens were put into an environmental chamber for 24 hours to have uniform temperature distribution. Then, the static axial stress, σ, of 100kPa was applied to the specimens as a preloading for 10 minutes and after on, 500 kPa of loading was applied to the specimens for 1 hour to simulate in-place conditions in a realistic manner.

2.3.1 Polypropylene modification of bitumen

M-03 type fibers had been utilised to modify the bitumen samples [10]. Starting with 0.5 thgiew yb srebif epyt 30-M ‰ erew dna nemutib htiw deximerp neeb dah srebif enelyporpylop ,‰ 0.7 ot pu ‰ 5.0 yb gnisaercni dna ,etagergga fo selpmas nemutib desab rebif enelyporpylop eht fo seitreporp lacisyhP .]31[snemiceps llahsraM fo noitaraperp rof desu .5 elbaT ni nevig era tnetnoc rebif ‰ 0.7-0 htiw

Table 5. Physical properties of control and various percentages of polypropylene modified samples

Polypropylene Amount (‰ of aggregate	**Specific gravity (kg/m^3)**	**Ductility (cm)**	**Softening point (^oC)**	**Penetration (dmm)**	**Penetration Index, PI (unitless)**
0.0	1028	+150	50.7	68.4	-0.26
1.0	1026	69.7	54.3	42.4	-0.545
2.0	1021	57.0	53.7	35.0	-1.10
3.0	1018	56.1	69.3	32.0	1.64
4.0	1017	11.6	105.1	21.7	5.17
5.0	1014	11.1	152.2	28.7	9.13
6.0	1010	5.5	156.6	14.2	8.01
7.0	1008	5.0	156.7	9.4	7.31

The performance characteristics, such as specific gravity, ductility, softening point penetration and penetration index of the fiber modified bitumen samples was greatly improved as compared to control specimens. The specific gravity values have decreased by 1.94 % when the maximum amount of polypropylene is added to the bitumen samples.

Ductility values have dropped to 5.0 cm when 7 ‰ modification has been carried out. The increase in softening point values is 106.03°C when compared to control specimens. This is an enormous increase from the pavement engineering point of view which is showing the clear decrease in the temperature susceptibility of the bituminous binders with polypropylene fiber modification (tests were carried out in glycerine after 3‰ fiber addition). Penetration values have dropped to 9.38 dmm for 7 ‰ modification. These above figures altogether show the very positive effect of polypropylene modification to the physico-chemical properties of control specimens according to the temperature susceptibility criteria [13].

Starting with control specimens (a total of 9 specimens), Marshall specimens have been prepared at the optimum bitumen content (5 %) with changing polypropylene contents of 0.5 ‰ to 7.0 ‰ by aggregate weight with 0.5 ‰ increments. For each polypropylene content, a total of 6 specimens have been fabricated. Therefore, in the end, a total of 84 modified specimens have been tested under the static creep test conditions stated above. In order to give a sample for the accumulated strain versus time graphs of the specimens subjected to creep loading, 6.0 ‰ modified specimens' curves are given below in Figure 6.

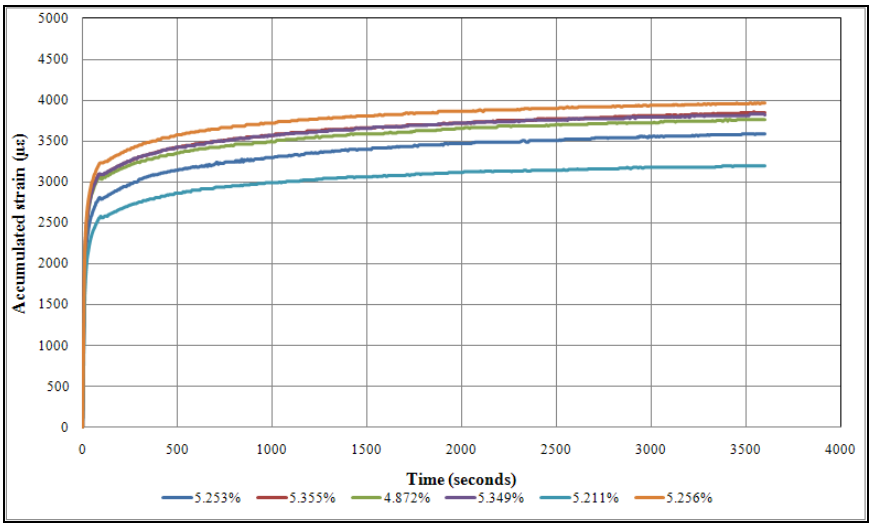

Figure 6: Accumulated strain vs. time graphs of 6.0 ‰ M-03 type polypropylene modified specimens

In order to be able to identify the whole behaviour of the specimens with different amounts of polypropylene modification, the reader may refer to Figure 7. In Figure 7, it can be clearly seen that the accumulated strains at the end of 1 hour of static loading decreases in a noticeable manner due to the addition of polypropylene fibers. Another interesting point is, after 6 ‰ of polypropylene addition with respect to the total weight of aggregate, the accumulated strains start to increase again. This is a perfect notification to be able to determine the optimal polypropylene amount to the designated mixture.

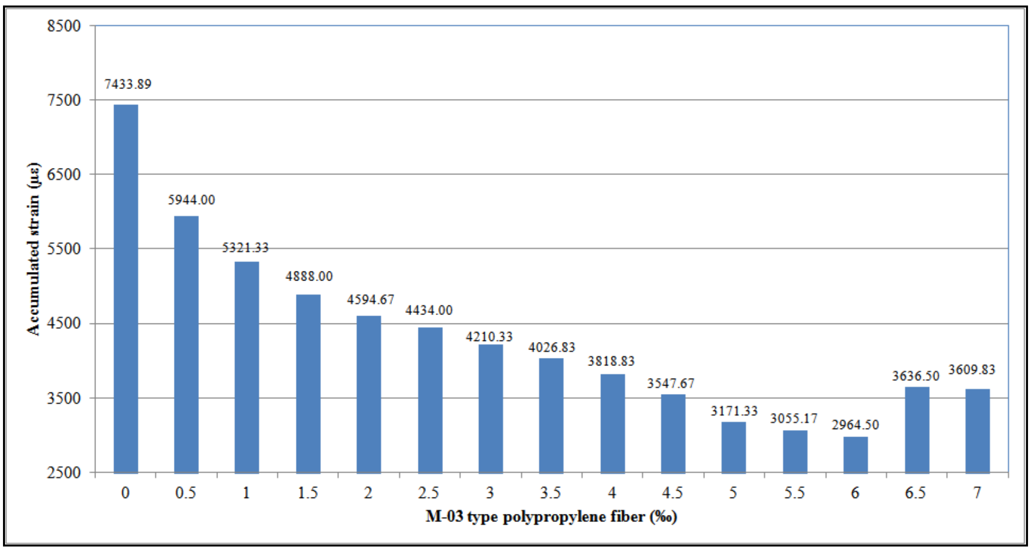

Figure 7: Accumulated strain values for 15 sets of specimens at the end of static creep tests

The initial (at the end of 100 seconds of 500 kPa loading) and final creep stiffness values for the 15 different sets of specimens are drawn correspondingly in Figures 8 and 9. In these graphs, it can again be clearly seen that 5.5 ‰ of polypropylene modification is an optimal amount.

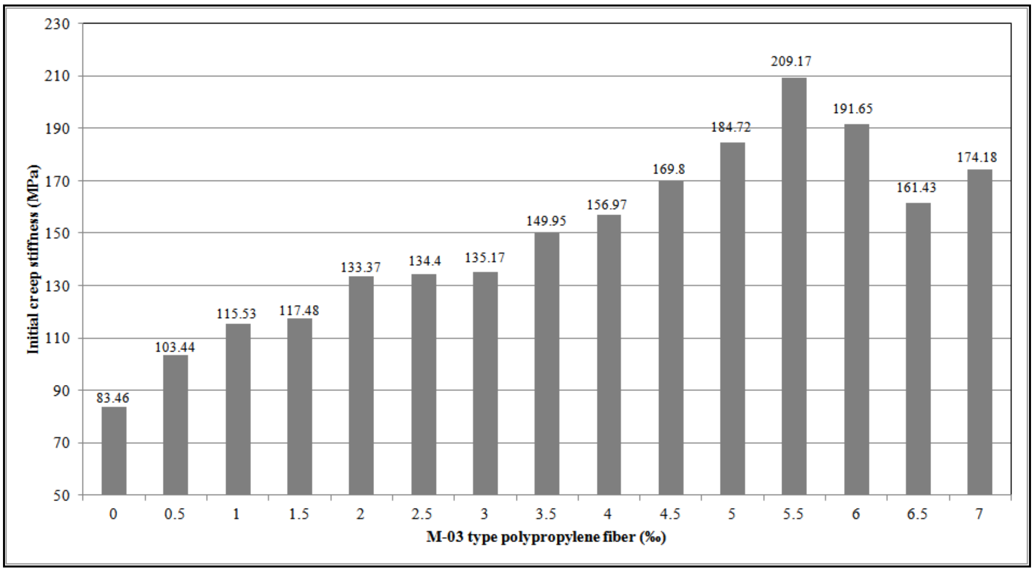

Figure 8: Initial creep stiffness versus time graphs for 15 different sets of polypropylene modified specimens

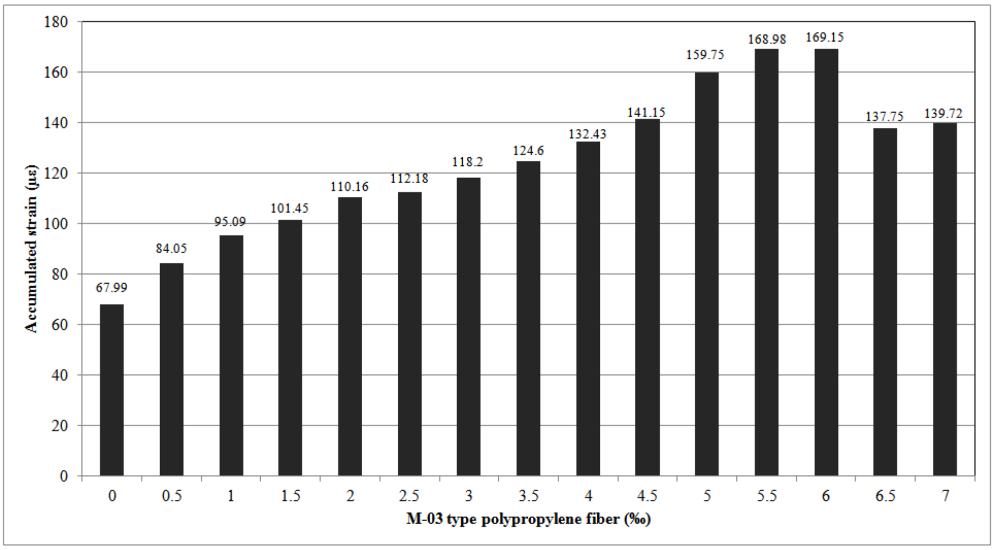

Figure 9: Final creep stiffness versus time graphs for 15 different sets of polypropylene modified specimens

One can easily notice form Figures 7, 8 and 9 that the addition of polypropylene enhances the mixture properties in a very favourable manner. For example, the control specimens have a final accumulated strain value of 7433.89 με. On the other hand, the 6 ‰ polypropylene modified specimens have a final accumulated strain value of 2964.50 με. This corresponds to a decrease of approximately 60 % and deserves great attention. On the other hand, the initial and final stiffness (creep stiffness) values are 83.46 and 67.99 MPa respectively. When the 6 ‰ polypropylene modified specimens are investigated, these values are 191.65 and 169.15 MPa respectively. These values correspond to an increase of 129 % in the initial and 149 % in the final creep stiffness values and must be highlighted.

3. Mechanical testing by the utilisation of Marshall design

The bitumen, aggregate type, properties and characterisation can be found in relevant literature [13]. Only M-03 type fibers were used to modify the bitumen samples according to the workability criteria [10]. In order to give more insight to the investigated problem, Marshall stability and flow tests were performed with 90 more specimens (6 for control and 6 for each proposed amounts of polypropylene addition of 0.5 ‰ to 7.0 ‰). By carrying out these tests, another value for the determination of optimum polypropylene amount is sought. To show this, the stability, unit weight, air voids, voids filled with asphalt, voids in mineral aggregate, flow and Marshall Quotient values have been determined and averaged accordingly for the 15 sets of specimens (Please refer to Table 6).

Table 6: Average physical and mechanical values obtained for 15 sets of specimens

Polypropylene amount (‰)	Unit weight (kg/m^3)	V.M.A. (%)	Vf (%)	Air voids (%)	Flow (mm)	Stability (kg)	Marshall Quotient (kg/mm)
0.0	2465	14.919	76.990	3.443	3.463	1294.355	376.899
0.5	2462	15.029	76.337	3.569	3.416	1355.712	400.559
1.0	2459	15.114	75.828	3.665	3.408	1378.510	405.166
1.5	2452	15.365	74.449	3.949	3.388	1391.292	411.593
2.0	2446	15.581	73.148	4.195	3.233	1453.083	463.103
2.5	2437	15.873	71.555	4.526	3.081	1500.593	490.412
3.0	2432	16.033	70.710	4.707	2.982	1542.140	523.329
3.5	2430	16.131	70.188	4.818	2.826	1626.905	588.954
4.0	2419	16.500	68.340	5.237	2.788	1703.500	618.161
4.5	2406	16.961	66.112	5.761	2.748	1837.763	680.879
5.0	2402	17.080	65.546	5.895	2.628	1971.715	755.850
5.5	2394	17.360	64.261	6.214	2.678	1917.643	724.647
6.0	2414	16.681	67.429	5.443	2.984	1989.972	682.360
6.5	2416	16.607	68.804	5.359	3.169	2113.038	678.393
7.0	2421	16.412	68.760	5.138	3.211	2186.930	683.755

When Table 6 is examined, it can be visualized that the average stability values of the control specimens increase up to 70 % when 7 ‰ polypropylene modification is carried out. This is a dramatic increase when viewed from the pavement engineering point of view. The unit weight values drop by 2.9 % until 5.5 ‰ polypropylene amount is reached and after this point on, tends to increase again. The air voids increase by 80 % until 5.5 ‰ polypropylene amount, and start to decrease from thereon. Voids filled with asphalt values show a similar trend (16.5 % decrease) up to 5.5 ‰ polypropylene addition. The voids in mineral aggregate values increase by 16.4 % up to 5.5 % addition of polypropylene and start to decrease from this point on. The tendency of flow values are similar (23 % decrease). Finally, Marshall Quotient values increase by 92 % which is an indication of pseudo stiffness. At the end of the Marshall stability and flow tests, the physical and mechanical properties of the 15 sets of specimens show the optimal polypropylene addition of 5.5 ‰ in a perfect manner with no doubt. At the end of the Marshall stability and flow tests, the physical and mechanical properties of the 15 sets of specimens show the optimal polypropylene addition of 5.5 ‰.

4. Stereo microscopy analyses

A fluorescence microscope has been used to investigate the morphology of the various polymer modified (in this study M-03 type polypropylene fibers) bitumen samples by investigating the state of dispersion of the polymer within the base bitumen as well as to characterize the nature of the continuous and discontinuous phase. Polypropylene fiber modified samples were examined at room temperature under a Leica DM EP microscope with fluorescent light (generated from a high pressure Xenon lamp) at magnification levels of 100x. The polypropylene modified bitumen samples were prepared by means of a low to high shear laboratory type mixer rotating at 500 rpm and the mixing process continued for two hours at 170°C [21]. The concentrations of polypropylene in the base bitumen were chosen as 0.5 % to 7 % (by 0.5 % increments) by weight of aggregate as can be visualised through Figures 10 to 16.

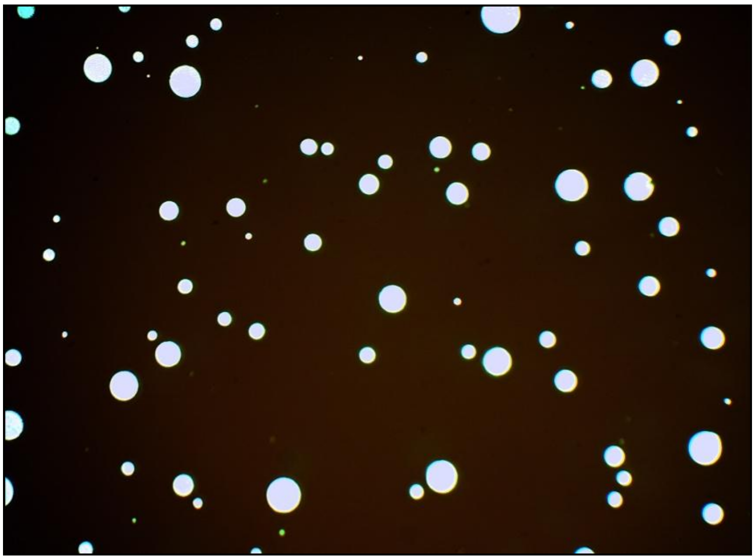

Figure 10: Concentrations of polypropylene in the base bitumen (0.5‰ by weight of aggregate)

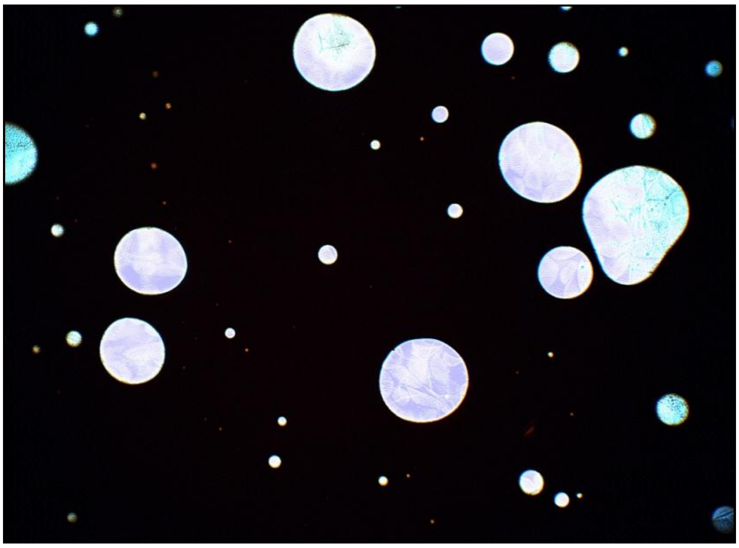

Figure 11: Concentrations of polypropylene in the base bitumen (1.5‰ by weight of aggregate)

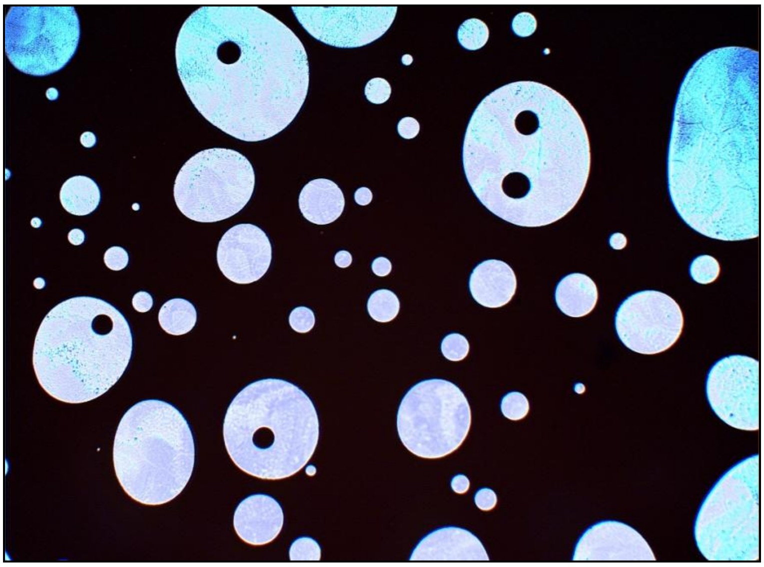

Figure 12: Concentrations of polypropylene in the base bitumen (2.5 ‰ by weight of aggregate)

Figure 13: Concentrations of polypropylene in the base bitumen (3.5 ‰ by weight of aggregate)

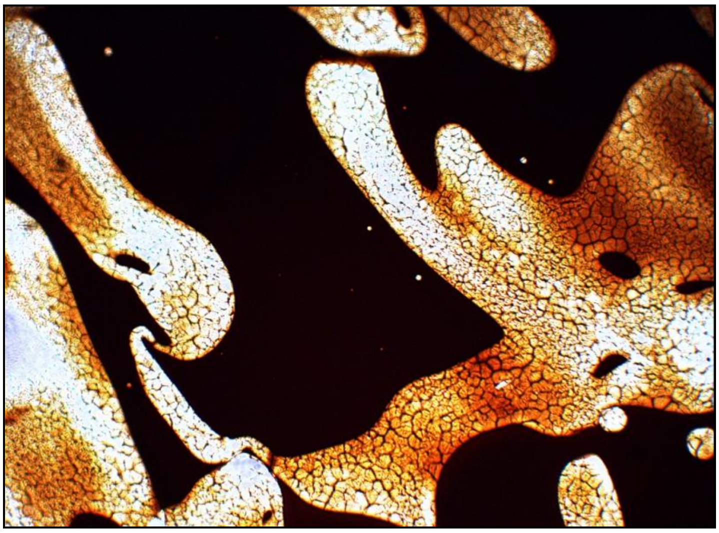

Figure 14: Concentrations of polypropylene in the base bitumen (4.5 ‰ by weight of aggregate)

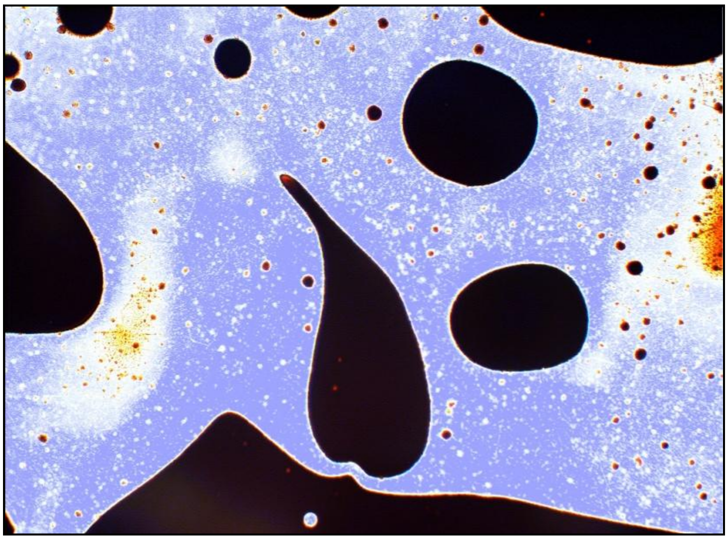

Figure 15: Concentrations of polypropylene in the base bitumen (5.5 ‰ by weight of aggregate)

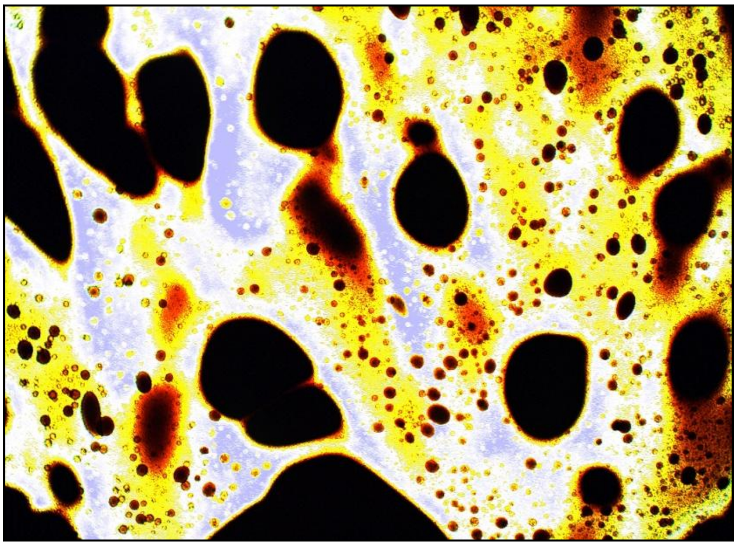

Figure 16: Concentrations of polypropylene in the base bitumen (6.5 ‰ by weight of aggregate)

A distinction can be made between the polypropylene modified bitumen whose continuous phase is a bitumen matrix with dispersed polymer particles and samples whose continuous phase is a polymer matrix with dispersed bitumen globules. In the images, the swollen polymer phase appears (light) while the bitumen phase appears dark. As depicted in Figures 10 to 16, the images show a clear change in morphology of the polypropylene based polymer modified bitumen as polymer content increases. At polymer content below 5.5 ‰ the small polymer globules that are swollen by the base bitumen compatible fractions are spread homogenously in a continuous bitumen phase. At polymer content above 5.5 ‰, a continuous polymer phase with dispersed bitumen phase is observed. In this situation, the properties of the mixture are mainly determined by the polymer phase, therefore by the type of the polymer.

5. Conclusions

In the light of all of the above discussions throughout the paper and after 13 years of extensive research, it can be concluded that, using the multifilament 3 mm (M-03) type of polypropylene fibers as a modifier, on both a dry and a wet basis, will aid in order to be able to solve the distresses occurring at both moderate and high temperatures (such as fatigue cracking and rutting) with very little extra cost (especially with an unpatented modifier like polypropylene fibers). The prevention of flushing and bleeding problems with the help of especially a wet-basis modification is another attractive outcome of this kind of modification, especially for countries subjected to very high ambient temperatures during late spring, summer and early autumn months. But it has to be borne in mind that the engineers working on site must be aware of the benefits of polypropylene modifications. Only in this manner might the detailed laboratory investigations about polypropylene fiber-reinforced bitumen will aid to solve the asphalt modification problem for both developing and developed countries that are prone to the above-mentioned pavement problems. Also by the help of field trials, especially for the high amount of polypropylene fiber modification, the problems of encountering a really “highly viscous” modified bituminous mixture should be investigated in an extensive manner by the prospective studies.

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