



DETERMINATION OF THE OPTIMAL POLYPROPYLENE FIBER ADDITION TO THE DENSE BITUMINOUS MIXTURES BY THE AID OF MECHANICAL AND OPTICAL MEANS

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Abstract. Polypropylene fibers are completely native modifiers and they do not have any dependence on abroad in case of technology. When viewed from this point, the modification of bituminous binders with polypropylene fibers is a very important step for our country's "economical" concerns. In this 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 the 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, optimum bitumen content was determined and finally economical analyses were carried out. By carrying out extensive analyses it was seen that the utilisation of polypropylene fibers improves the physical and mechanical properties of the resultant asphalt mixture mainly by enhancing the permanent deformation resistance. On the other hand, polypropylene modification results in 30% economy from bitumen which is a clear indication of the benefit in the mass production of asphalt concrete.

Keywords: modified bitumen, polypropylene fibers, Marshall design, static creep test, fluorescence microscopy, economical analysis.

1. Introduction

Fiber modification is a type of polymer modification and polypropylene fiber modification is a specialized fiber modification. By the beginning of 1990s, polymer fiber reinforcement had started to being utilised in asphalt concrete mixture designs. Brown *et al.* (1990) have put a lot to the development of fiber reinforcement. Another similar study has indicated that some sort of special fibers create physical changes to modifiers that have been utilised in asphalt mixtures up to date (Maurer, Malasheskie 1989; Wu *et al.* 2006). Jenq *et al.* (1993) investigated the fiber reinforcement techniques from the fracture mechanics point of view. Simpson and Kamyar (1994) carried out a similar study in the subject matter which investigated polypropylene, polyester fibers and some other polymers that were used as polymer modifiers. Cleven (2000) has utilised different fibers (polypropylene, polyester, asbestos and cellulose). These special fibers look as if they increase the stiffness of the asphalt binder which eventually results in stiffer mixtures with an eminent increase of fatigue lives. These mixtures which contained different types of fibers eventually showed less decrease in void content and

a distinguishable resistance to permanent deformation problem. But on the other hand, only polypropylene fibers improved the tensile strength of the resultant mixture. Ohio Department of Transportation (Item 400HS, 1998, *Standard Specification for Asphalt Concrete High Stress using Polypropylene Fibers*, Construction and Materials Specifications, Ohio Department of Transportation, Columbus, OH) has done a considerable amount of research on polypropylene fiber modification of dense bituminous mixtures in a dry basis. Tapkın (2008) has also carried out research on the addition of polypropylene fibers into the dense bituminous mixtures in a dry basis. Polypropylene fibers altered the mechanical behavior of asphalt mixtures by increasing their Marshall stability values, their fatigue life, and decreasing their flow values. Uşar (2007) and Tapkın *et al.* (2009a; 2009b), later on, have worked on wet basis modification of dense bituminous mixtures. They have proven that the most suitable polypropylene fiber type was multifilament of 3 mm (M-03). The modification of reference bitumen by these types of fibers has increased the Marshall stability values by 20% and the stiffness of these specimens in a pronounced manner. Repeated load

creep testing under different loading patterns have also figured out that the lives of the M-03 type polypropylene fiber modified dense bituminous mixtures under repeated creep loading increased by 5–12 times vs. control specimens under different loading patterns which is a very significant improvement from the pavement engineering point of view.

The creep test has been used to estimate the rutting potential of asphalt concrete mixtures. This test is being carried out by applying a static load to an asphalt specimen. In the end of the testing procedure the resultant permanent deformation is being logged. Extensive studies using the simple creep test or uniaxial creep test as a basis of predicting permanent deformation in dense bituminous mixtures has been carried out all throughout the pavement research laboratories around the world up to date. It has been admitted by all of the researchers that creep test must be performed at relatively low stress levels, such as the ones not exceeding 30 psi (206.9 kPa) and low temperatures such as ones again not exceeding 104 °F (40 °C). Otherwise the samples will fail in a premature manner (Hills 1973; Van de Loo 1974; Van de Loo 1976). Testing conditions of static creep test consist of an axial stress (σ) application of 100 kPa being subjected to a specimen for a period of 1 h at a temperature of 40 °C. According to the *Recommendation for the Performance of Unconfined Static Creep Test in Asphalt Specimens* of 1977 the testing conditions were standardized. This test is inexpensive and practically easy to carry out in any pavement research laboratory conditions but the ability of this testing protocol to predict the real performance of asphalt mixtures on site is very questionable. In-place asphalt mixtures are typically exposed to truck tire pressures of approx 120 psi (828 kPa) and sometimes more. Also these mixtures might be subjected to max temperatures of 140 °F (60 °C) or higher (Roberts 1996). Therefore, the conditions of this test do not closely resemble the real in-place conditions (Chen *et al.* 2011; Özcan 2008; Wasage *et al.* 2010).

The outlet of this study was this main drawback of the static creep tests that have been carried out worldwide up to date (Özcan 2008). Therefore, a completely different loading pattern and testing temperature was adopted all throughout the studies that have been carried out. Also, the optimum polypropylene amount that has to be added into the mixture by the percentage of aggregate has been determined for a dense bituminous mixture that is prepared by using local aggregate and bitumen sources.

2. Experimental Program

2.1. Specimen Preparation

Marshall specimens were fabricated by utilising 50 blows on each face (medium traffic conditions). 50/70 penetration bitumen was modified in the laboratory with M-03 type polypropylene fibers. Several Marshall specimens were fabricated and Universal Testing Machine had been utilised to carry out static creep tests. Also stereo micros-

copy techniques were used in order to determine the optimal M-03 polypropylene fiber addition amount on a wet basis.

2.2. Material Properties

Gradation limits for wearing course type 2 set by *Highway Technical Specifications of General Directorate of Turkish Highways* of 2006 had been utilised all throughout the studies. 50/70 penetration bitumen was utilised for the preparation of the Marshall specimens. The used aggregate was calcareous type crushed stone. Physical properties of the bitumen samples are given in Table 1. The physical properties of coarse and fine aggregates are given in Tables 2 and 3. The apparent specific gravity of filler is 2785 kg/m³.

Aggregate gradation had been selected as wearing course type 2 given by *Highway Technical Specifications of General Directorate of Turkish Highways*. The mixture gradation is given in Table 4.

Table 1. Physical properties of the reference bitumen

| Property | Units | Test value | Standard |
|---------------------------|-------------------|------------|---------------|
| Penetration at 25 °C | 1/10 mm | 68.35 | ASTM D 5-97 |
| Penetration Index | - | -0.26 | - |
| Ductility at 25 °C | cm | +150 | ASTM D 113-99 |
| Specific gravity at 25 °C | kg/m ³ | 1028 | ASTM D 70-76 |
| Softening point | °C | 50.67 | ASTM D 36-95 |

Table 2. Physical properties of coarse aggregates

| Property | Units | Test value | Standard |
|--|-------------------|------------|---------------|
| Bulk specific gravity | kg/m ³ | 2705 | ASTM C 127-04 |
| Saturated surface dry specific gravity | kg/m ³ | 2714 | ASTM C 127-04 |
| Apparent specific gravity | kg/m ³ | 2729 | ASTM C 127-04 |
| Water absorption | % | 0.322 | ASTM C 127-04 |
| Los Angeles abrasion coefficient | % | 30 | ASTM C-131-06 |

Table 3. Physical properties of fine aggregates

| Property | Units | Test value | Standard |
|--|-------------------|------------|---------------|
| Bulk specific gravity | kg/m ³ | 2685 | ASTM C 128-04 |
| Saturated surface dry specific gravity | kg/m ³ | 2717 | ASTM C 128-04 |
| Apparent specific gravity | kg/m ³ | 2776 | ASTM C 128-04 |
| Water absorption | % | 1.236 | ASTM C 128-04 |

Table 4. Type 2 wearing course gradation (Highway Technical Specifications, 2006)

| 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 |

The physical properties of the polypropylene fibers used in the experimental program are given in the relevant literature (Özcan 2008; Tapkın 2008).

2.3. Polypropylene modification of bitumen

50/70 penetration bitumen was modified by M-03 type polypropylene fibers. The fibers were premixed with bitumen using a standard mixer at 500 rpm for at least two hours. Mixing temperature was around 165–170 °C (Chen, Lin 2005). Only M-03 type fibers had been utilised to modify the bitumen samples according to the workability criteria (Tapkın *et al.* 2009a). Starting with 0.5% M-03 type fibers by weight of aggregate, and increasing by 0.5% up to 7.0%, polypropylene fibers had been premixed with bitumen and were used for preparation of Marshall specimens (Özcan 2008). Physical properties of the polypropylene fiber based bitumen samples with 0–7.0% fiber content are given in Table 5.

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 which can be seen in Table 5. The specific gravity values have decreased by 1.94 % when the max 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.

2.4. The proportioning of the bituminous mixtures

To find out the optimum bitumen content of reference asphalt specimens, Marshall stability and flow tests were utilised. In order to do this, 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 limits given by the *Highway Technical Specifications of General Directorate of Turkish Highways*. Two different Marshall designs were carried out. In the first design, the optimum bitumen content was found as 5%. Second design was ended with an optimum bitumen content of 4.96%. These two results are very near to each other therefore the optimum bitumen content of the reference specimens has been taken as 5.0%.

3. Experimental setup and tests performed to determine optimal polypropylene addition to the mixture

3.1. Static creep tests performed

In-place asphalt mixtures are typically exposed to truck tire pressures of approx 120 psi (828 kPa) and sometimes more. Also these mixtures might be subjected to max temperatures of 140 °F (60 °C) or higher (Roberts *et al.* 1996). Therefore, the conditions of this test do not closely resemble the real in-place conditions (Özcan 2008).

Because of this fact, in this study, first of all the test temperature has been chosen as 50 °C to resemble the in-situ conditions. The height of asphalt specimens were approx the same for all of the specimens. Prior to testing, the specimens had been placed in an environmental chamber for 24 h to maintain uniform temperature distribution. Then, the static axial stress, σ , of 100 kPa was applied to the specimens as a preloading for 10 min and after on 500 kPa

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

| Polypropylene amount, % of aggregate | Specific gravity, kg/m ³ | Ductility, cm | Softening point, °C | Penetration, dmm | Penetration Index PI, unitless |
|--------------------------------------|-------------------------------------|---------------|---------------------|------------------|--------------------------------|
| 0.0 | 1028 | +150 | 50.67 | 68.35 | -0.262 |
| 1.0 | 1026 | 69.7 | 54.33 | 42.42 | -0.549 |
| 2.0 | 1021 | 57.0 | 53.65 | 34.98 | -1.103 |
| 3.0 | 1018 | 56.1 | 69.30 | 32.02 | 1.639 |
| 4.0 | 1017 | 11.6 | 105.10 | 21.68 | 5.166 |
| 5.0 | 1014 | 11.1 | 152.18 | 28.69 | 9.130 |
| 6.0 | 1010 | 5.5 | 156.57 | 14.15 | 8.008 |
| 7.0 | 1008 | 5.0 | 156.70 | 9.38 | 7.310 |

of loading was applied to the specimens for 1 h to resemble the in-place conditions in a realistic manner. In order to validate this preloading time of 10 min, preloading times of 0 to 10 min, increasing one by one, has been applied to standard Marshall specimens prepared at optimum bitumen content. A total of 11 specimens had been fabricated and subjected to the same loading pressure of 500 kPa for 1 h. At the end of these tests, it has been found out that 10 min of preloading can be accepted as the optimal preloading time for the further studies that will be carried out with no doubt (Özcan 2008).

Starting with control specimens (a total of 9 specimens), Marshall specimens have been prepared at the optimum bitumen content 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 Fig. 1.

In order to be able to identify the whole behavior of the specimens with different amounts of polypropylene modification, another figure is presented below (Fig. 2). In Fig. 2 it can be clearly seen that the accumulated strains at the end of 1 h of static loading decreases in a noticeable manner due to the addition of polypropylene fibers. Another interesting point is that 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.

For the sake of completeness, the creep stiffness versus time graphs of the specimens subjected to creep loading 6.0‰ modified specimens' curves are given below in Fig. 3.

The initial (at the end of 100 s of 100 kPa loading) and final creep stiffness (at the end of 3600 s and 500 kPa loading) values for the 15 different sets of specimens are drawn correspondingly in Figs 4 and 5. In these graphs it can be clearly seen again that 5.5‰ of polypropylene modification is an optimal amount.

It could be easily noticed from Figs 2, 4 and 5 that the addition of polypropylene enhances the mixture properties in a very favorable 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 approx 60% and deserves attention. On the other hand, the initial and final stiffness (creep stiffness) values are 83.46 MPa and 67.99 MPa respectively. When the 6‰ polypropylene modified specimens are investigated, these values are 191.65 MPa 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.

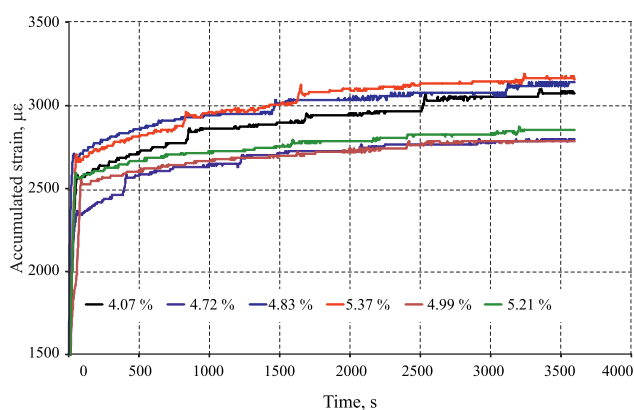


Fig. 1. Accumulated strain versus time graphs for 6.0‰ polypropylene modified specimens

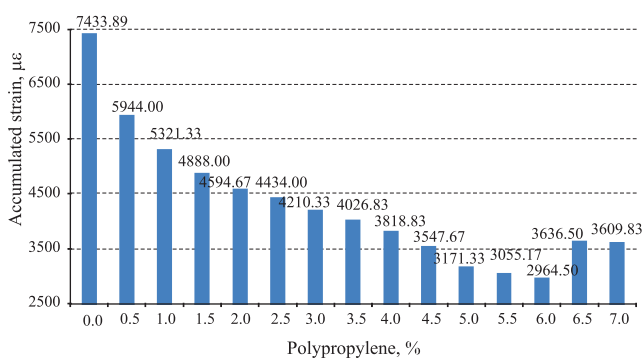


Fig. 2. Accumulated strain values for 15 sets of specimens at the end of static creep tests

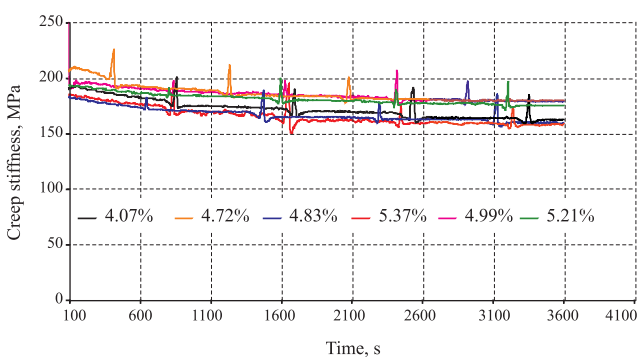


Fig. 3. Creep stiffness versus time graphs for 6.0‰ polypropylene modified specimens

3.2. Marshall stability and flow tests performed

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 criterion for the determination of optimum polypropylene amount is sought. Naturally this value should again have been expected to be

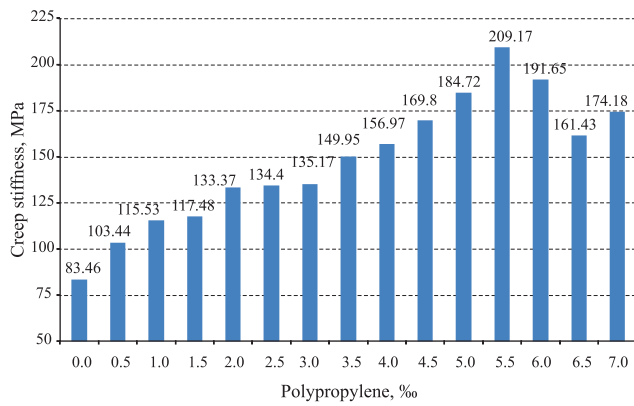


Fig. 4. Initial creep stiffness values for 15 sets of specimens at the end of static creep tests

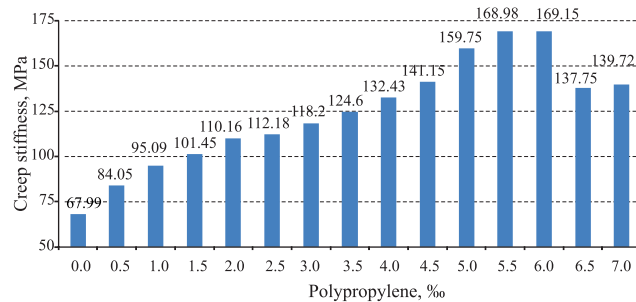


Fig. 5. Final creep stiffness values for 15 sets of specimens at the end of static creep tests

around 5.5%. 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. These values are stated below in Table 6.

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 (Tapkın *et al.* 2010). 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.

3.3. Stereo Microscopy

Polypropylene modified bitumen samples were investigated at room temperature under "MEIJI EMZ-TR" trino/stereo/microscope with fluorescent light at a magnification level of 40 times which can be accepted as quite enough for research purposes. Digital images were taken for 30 sets of

Table 6. The average physical and mechanical values obtained for 15 sets of specimens

| Polypropylene amount, % | Stability, kg | Unit weight, kg/m ³ | Air voids, % | Vf ¹⁾ , % | V.M.A. ²⁾ , % | Flow, mm | Marshall Quotient, kg/mm |
|-------------------------|---------------|--------------------------------|--------------|----------------------|--------------------------|----------|--------------------------|
| 0.0 | 1294.355 | 2465 | 3.443 | 76.990 | 14.919 | 3.463 | 376.899 |
| 0.5 | 1355.712 | 2462 | 3.569 | 76.337 | 15.029 | 3.416 | 400.559 |
| 1.0 | 1378.510 | 2459 | 3.665 | 75.828 | 15.114 | 3.408 | 405.166 |
| 1.5 | 1391.292 | 2452 | 3.949 | 74.449 | 15.365 | 3.388 | 411.593 |
| 2.0 | 1453.083 | 2446 | 4.195 | 73.148 | 15.581 | 3.233 | 463.103 |
| 2.5 | 1500.593 | 2437 | 4.526 | 71.555 | 15.873 | 3.081 | 490.412 |
| 3.0 | 1542.140 | 2432 | 4.707 | 70.710 | 16.033 | 2.982 | 523.329 |
| 3.5 | 1626.905 | 2430 | 4.818 | 70.188 | 16.131 | 2.826 | 588.954 |
| 4.0 | 1703.500 | 2419 | 5.237 | 68.340 | 16.500 | 2.788 | 618.161 |
| 4.5 | 1837.763 | 2406 | 5.761 | 66.112 | 16.961 | 2.748 | 680.879 |
| 5.0 | 1971.715 | 2402 | 5.895 | 65.546 | 17.080 | 2.628 | 755.850 |
| 5.5 | 1917.643 | 2394 | 6.214 | 64.261 | 17.360 | 2.678 | 724.647 |
| 6.0 | 1989.972 | 2414 | 5.443 | 67.429 | 16.681 | 2.984 | 682.360 |
| 6.5 | 2113.038 | 2416 | 5.359 | 68.804 | 16.607 | 3.169 | 678.393 |
| 7.0 | 2186.930 | 2421 | 5.138 | 68.760 | 16.412 | 3.211 | 683.755 |

1) – voids filled with asphalt; 2) – voids in mineral aggregate.

specimens (duplicate specimens, 1 control and 14 with different polypropylene contents) and detailed analyses were carried out on the images. The images for control (with micron bar), for the 3.5%, 5.5% and 7% polypropylene modified specimens are given below in Figs 6 and 7.

When Fig. 6b is examined it can be seen that the polypropylene particles are distributed in a regular pattern in the bitumen phase. Also this can be observed in Fig. 7a but if this figure is examined in a more detailed manner, one can observe that the polypropylene particles tend to become as the dominant phase when compared to bitumen. Finally, Fig. 7b shows that the polypropylene particles have formed an irregular phase and bitumen is somehow scattered in between polypropylene particles. This can further be explained by percolation theory (Zoorob *et al.* 2012). In the light of the stereo microscope investigations, once more, it can be easily concluded that 5.5% polypropylene modification is the optimal value.

4. Determination of the optimum bitumen content of specimens prepared with optimal polypropylene amount

From the carried out analyses the optimum bitumen content has been determined as 5.38%. This value is only 7.6% more than the optimum bitumen content of the control specimens. While preparing the modified specimens, because of the swelling of polypropylene, more bitumen is needed to prepare same kind of specimens. Therefore while preparing specimens for economical analysis the optimum-optimal bitumen content can be taken as 5.0%. This is a very realistic design approach.

4.1. Economical analysis

In this part of the study, with the optimum-optimal bitumen content, new sets of Marshall specimens have been fabricated and static creep and Marshall stability and flow tests were applied to these specimens. In order to be able to investigate the economical concerns 4 different sets of specimens with 3.5%, 4.0%, 4.5% and 5.0% were prepared (6 specimens for each content) and subjected to static creep tests again with a 100 kPa preloading of 10 min followed by 500 kPa loading of 60 min at 50 °C. In order to be able to have better insight to the problem for the six different curves the values at each time interval were averaged accordingly and a single set of curves was drawn once more with the final accumulated strains stated on the corresponding graphs. An example of this study is given in Fig. 8.

As can be seen from Fig. 8 the permanent accumulated strain that is developed in the specimen body is measured as 3055.17 $\mu\epsilon$ for specimens prepared with 5.0% bitumen content (5.5% polypropylene modification). This value is only 5.20% less than the accumulated strain values of specimens prepared with 3.5% bitumen. Again, this value is 1.36% less than the accumulated strain values of specimens prepared with 4.0% bitumen. Besides, this value is 18% higher than the accumulated strain values of specimens prepared with 4.5% bitumen.

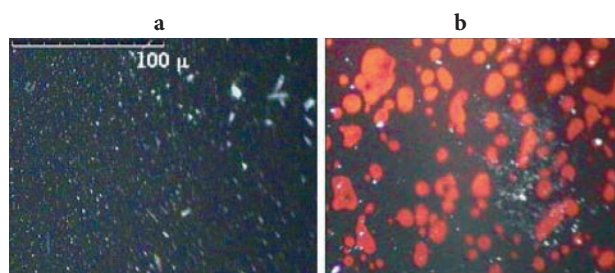


Fig. 6. The stereo microscope image for: a – control specimens with micron bar; b – 3.5 % polypropylene modified specimens

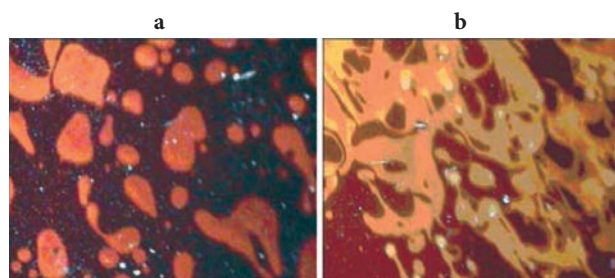


Fig. 7. The stereo microscope image for: a – 5.5 %; b – 7.0 % polypropylene modified specimens

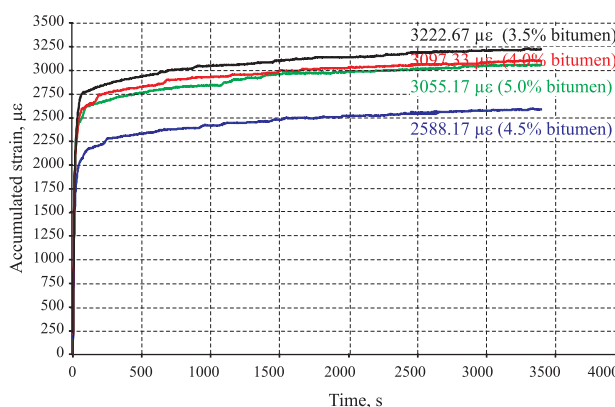


Fig. 8. Average accumulated strain versus time graphs for optimum-optimal polypropylene modified specimens (according to air voids)

In the first glance, one can say that the specimens prepared with 4.5% bitumen behave in a very favorable manner when compared to specimens of 5.0%. But in this case, the economy is only 10%. Thus, all the attention must be focused on the specimens with bitumen content of 3.5%. These specimens, when viewed from the physical properties, have 43% less average air voids contents, 2.7% less average specific gravity values, 5.75% less average voids in mineral aggregate values and finally 53% less voids filled with asphalt values (Özcan 2008). But they behave in a very similar fashion under static creep tests when compared to specimens prepared with 5.0% bitumen content. This really deserves great attention. 3.5% specimens are lighter, having more voids and having much less bitumen than 5.0% specimens which is really a giant step to the way

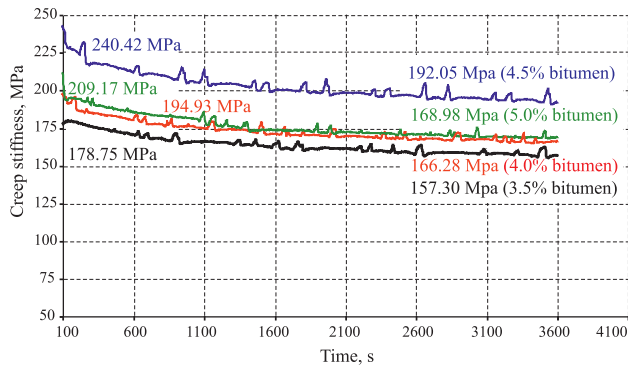


Fig. 9. Average creep stiffness versus time graphs for optimum-optimal polypropylene modified specimens

ahead to new generation of paving products. Altogether, there is an economy of “30%” from bitumen. This is really very important. Finally, the extra cost of using polypropylene fibers as a modifier is only 9.3% (for research purposes only with no addition of technology and know-how of course) but this cost is becoming much smaller when the dependency to imported expensive modifiers and the know-how being sold besides them. This is a very important item for the developing countries like Turkey.

For the sake of completeness, the stiffness (creep stiffness) versus time graphs of the specimens subjected to creep loading are given below in Fig. 9 (the values at each time interval were averaged accordingly and a single set of curves were drawn once more with the initial and final creep stiffnesses).

When Fig. 9 is examined it can be visualized that the initial creep stiffness of the specimens prepared with 3.5% bitumen are 14.5% lesser when compared to the initial creep stiffness of the specimens prepared with 5.0% bitumen. Also the final creep stiffness of the very same specimens is 6.9% lesser when compared to specimens prepared by 5.0% bitumen. These are a very logical and acceptable depending on the above mentioned discussions.

The Marshall test results for specimens prepared with optimal polypropylene amount for economical analysis are given in the relevant literature (Özcan 2008). The physical and mechanical properties of the specimens prepared with 3.5% bitumen content compared with 5.0% bitumen content specimens are as follows: they are lighter, have more air voids and have less asphalt in their structures. Also the Marshall Quotient (a kind of pseudo stiffness) values are approx 17% higher than the 5.0% bitumen samples. In the light of these facts, it can be concluded that 3.5% bitumen specimens can be utilized in the designs in a very favorable way.

5. Conclusions and recommendations

1. The addition of the polypropylene fibers into the asphalt mixture enhances the mixture properties in a very favorable manner. The decrease of the accumulated strains at the

end of the static creep tests corresponds to approx 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 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 is similar (23% decrease). Finally, Marshall Quotient values increase by 92% which is a clear indication of pseudo stiffness.

2. In the light of the stereo microscope investigations, once more, it can be easily concluded that 5.5% polypropylene modification is the optimal value. Based on the static creep, Marshall tests and stereo microscopy analyses that were carried out with M-03 type polypropylene fiber reinforced specimens the optimal polypropylene addition amount was determined as 5.5%. While preparing specimens for economical analysis the optimum-optimal bitumen content can be taken as 5.0%. This is a very realistic design approach. There is an economy of “30%” from bitumen for the 3.5% specimens. This is really very important. Altogether the extra cost of using polypropylene fibers as a modifier is only 9.3% (for research purposes only with no addition of technology and know-how of course) but this cost is becoming much smaller when the dependency to imported expensive modifiers and the know-how being sold besides them. This is a very important item for the developing countries like Turkey.

3. The physical and mechanical properties of the specimens prepared with 3.5% bitumen content compared with 5.0% bitumen content specimens are as follows: they are lighter, have more air voids and have less asphalt in their structures. Also the Marshall Quotient (a kind of pseudo stiffness) values are approx 17% higher than the 5.0% bitumen samples. In the light of these facts, it can be concluded that 3.5% bitumen specimens can be utilized in the designs in a very favorable way.

4. The static creep tests can be carried out on the polypropylene fiber modified specimens at temperatures above or below 50 °C and different loading patterns. Also, polypropylene fiber reinforcement of the bitumen can be examined by the aid of scanning electron microscopy and atomic force microscopy. Further, the thin asphalt mixture films can be examined under scanning electron microscopes to be able to identify the bonding patterns of polypropylene with bitumen and aggregate. Also, gyratory compactors might be utilized in the laboratory environment for a very similar testing pattern and scheme in order to simulate the actual compaction efforts carried out on site.

Finally, a prospective study may focus on the behavior of the polypropylene modified asphalt specimens at lower temperatures below zero.

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