ISSN 1392–1320 *MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 30, No. 1. 2024*

Investigation of Performance Properties of Milled Carbon Fiber Reinforced Hot Mix Asphalt

Ayşe Cansel DURMAZ [1], Nihat MOROVA [2]*

[1] *Civil Engineering Department, Institute of Graduate Education, Isparta University of Applied Sciences, 32100, Isparta, Turkey*
[2] *Civil Engineering Department, Faculty of Technology, Isparta University of Applied Sciences, 32100, Isparta, Turkey*

http://doi.org/10.5755/j02.ms.34075

Received 15 May 2023; accepted 8 August 2023

In this study, the mechanical behavior and resistance to moisture damage of hot mix asphalt (HMA) concrete with the addition of Milled Carbon Fiber (MCF) were experimentally investigated. For this purpose, the gradation curve within the boundaries of the Turkish highway construction specifications (HTS) has been determined. By keeping the determined gradation constant, MCF was added at different rates (1 %, 1.5 %, 2 %, 2.5 %, 3 %) by weight of the mixture. In the study, first, optimum bitumen ratios (*OBR*) of pure control samples (0 %-Control) without MCF and mixtures with MCF additives were determined by using the Marshall design method. To determine the *OBR*, samples were prepared with bitumen content of 3.5 %, 4 %, 4.5 %, 5 %, 5.5 %, and 6 % at each carbon additive ratio. The mixture samples prepared using the specified OBRs were subjected to Marshall stability (*MS*) and flow, as well as to retained Marshall stability (*RMS*), indirect tensile strength (*ITS*), and moisture damage resistance tests. According to the test results, it was observed that the *MS* values of the asphalt concrete with MCF additives increased at certain carbon additive ratios, while the flow values decreased compared to the witness sample. It was determined that the *RMS* and indirect tensile strength ratio (*TSR*) values of hot mixes with MCF-added bitumen increased and the moisture damage resistance of the mixes increased. As a result, when the optimum MCF ratio determined for the wearing course is used, it is thought that the engineering properties of HMA will improve.

Keywords: Marshall design, hot mix asphalt, milled carbon fiber, moisture susceptibility.

1. INTRODUCTION

Hot mix asphalt (HMA) pavement consists of different combinations of aggregate and asphalt. Aggregate serves as the structural framework of the pavement and asphalt cement acts as the adhesive of the mixture. Mineral aggregates consisting of coarse and fine particles occupy approximately 90 % of the volume of HMA. One of the most important factors in the performance of coatings is the properties of the aggregate [1 – 3].

As with any building, asphalt pavements deteriorate over time due to traffic load and adverse environmental effects. The service life of asphalt pavements can be significantly shortened if the aggregate and asphalt used by HMA are not of good quality. Recent studies, it is aimed to improve the performance of asphalt mixture by using different additives. Researchers are trying to increase the service life of the pavement by adding different additives to the asphalt or asphalt mix, improving the properties of asphalt mixes such as durability and stability [4].

Günay et al. [5] in their study, used waste polymers as a modifier in bitumen to improve the performance of binders and reduce plastic pollution. In the study [6] synthesis of a new boron-containing additive and its incorporation into asphalt binder were carried out under chemical laboratory conditions. For this purpose, structural analyses of boron containing additive cyclic borate ester and modified asphalt binders were investigated. In another study [7] low density polyethylene (LDPE) and triethanolamine were used together by applying a different process to obtain a good chemical interaction between LDPE and bitumen in bitumen modification and the effects of this interaction on the performance properties of bitumen were investigated.

As the advantages of carbon fibers (CF), we can list their high specific strength, high specific modulus, high-temperature resistance, and excellent electrical conductivity [8]. Due to these properties, CFs are used in many fields such as the chemical field, the military, and the automotive industry, apart from being used as reinforcement and repair material in civil engineering. Road pavements are also one of the other application areas where CF is used. Due to the genetic compatibility of CFs with asphalt and its superior mechanical properties, it is an excellent modification material for asphalt or mixture [9]. Today, many types of additives are used, including polyester fiber, asbestos fiber, glass fiber, polypropylene fiber, carbon fiber, cellulose fiber, etc [2]. Modifying HMA with carbon fiber is thought to improve mechanical properties and extend pavement life [3].

It is widely believed that the addition of fibers to asphalt enhances material strength as well as fatigue characteristics while at the same time adding ductility. Likewise, carbon fibers may also offer excellent potential for binder modification due to their inherent compatibility with asphalt cement and superior mechanical properties. With new developments in production, carbon modified binder has

* Corresponding author. Tel.: +905324419917
E-mail: *nihatmorova@isparta.edu.tr* (N. Morova)

become cost competitive with polymer modified binders. Further, it was expected that carbon fiber modified asphalt mixtures would increase stiffness and resistance to permanent deformation and, similarly, that the fatigue characteristics of the mixture would improve with the addition of discrete carbon fibers. Because of the high tensile strength of carbon fiber, the cold temperature behavior of the asphalt mixture was also expected to improve [10].

The study [11] examines the influence of different sources and lengths of carbon fiber on the volumetric properties, volume resistivity, and heat-generation efficiency of electrically conductive asphalt concrete. In the article [12] by adding different percentages of carbon fiber with high strength and doing the necessary Marshall tests, it was observed that the Marshall resistance and its flow increased. In a recent study [9] the effects of carbon fibre on improving the performance characteristics of asphalt mixtures were investigated. To this end, four percentages of carbon fibre were used as an additive in asphalt mixtures. The mechanical properties of prepared mixture specimens were investigated using tests such as Marshall stability and flow, indirect tensile stiffness modulus, creep stiffness, indirect tensile strength, and moisture resistance. Experimental results indicated that carbon fibre provided a positive contribution to the performance properties of asphalt pavements. There has been some recent research on the use of CF in HMA [13 – 19].

The main purpose of this study is to evaluate the effect of MCF and asphalt mixtures added in different proportions on Marshall properties, taking into account the RMS Index and TSR values, to avoid the harmful effect of moisture and to show the benefits of the MCF reinforcement effect.

2. MATERIALS

In this section, information about aggregate, asphalt, and carbon microfiber used in experimental studies is given.

2.1. Aggregate

In this study, limestone aggregates (LS), which are frequently used in HMA applications, were obtained from a quarry in the province of Isparta in southern Turkey and used. In terms of gradation of the mixture, 52.6 % coarse aggregate passed through a 25 – 4.75 mm sieve, 42.68 % fine aggregate passed through a 4.75 – 0.075 mm sieve and 4.8% filler material were used. The sieve analysis results of the mixture were within the limits set by Highway General Directorate of Turkey (HTS) [20].

Table 1 shows the sieve analysis results and specification limits of the mixture used in this study. In this study, the recommended maximum aggregate size of 12.5 mm was chosen in the aggregate gradation prepared for the surface layer. Sieve analyses were made and the current gradation curve for the aggregate used in the study was close to the course of the wear layer.

2.2. Bitumen

To prepare the Marshall specimens, the researchers utilized an asphalt binder with a 50 – 70 penetration grade, which was found to be 58 in this study. To assess the basic properties of asphalt cement, conventional asphalt tests were conducted on pure asphalt, including tests for penetration grade, softening point, combustion point, ductility, specific gravity, and flash point. The rheological characteristics of this binder are presented in Table 2.

Table 1. Gradation and specification limits

Sieve diameter		Limit values [16] passing, %	Gradation of mixture passing, %	Weight, g
Inch	mm			
3/4"	19	100	100	0
1/2"	12.5	88 – 100	92.5	86.25
3/8"	9.5	72 – 90	77.7	170.2
No.4	4.75	42 – 52	47.4	348.45
No.10	2.00	25 – 35	31.6	181.7
No.40	0.425	10 – 20	12.3	221.95
No.80	0.180	7 – 14	7.9	50.6
No.200	0.075	3 – 8	4.8	35.65
Filler	-	-	0	55.2
Total		100%	100%	1150

Table 2. Physical properties of the asphalt binder

Test	Average values	Standard
Source	Aliağa/Türkiye	-
Penetration grade	50 – 70	-
Penetration, 25 ºC	59	ASTM D5
Flash point, ºC	290 ºC	ASTM D92
Softening point, ºC Loss on heating, %	51 °C 2.0	ASTM D36 ASTM D6
Ductility (5 cm/minute at 25 ºC)	> 100 cm	ASTM D113
Specific gravity at 25 °C	1.033	ASTM D70
Viscosity at 135 °C	0.408 Pa·s	ASTM D4402-06

Asphalt mixtures were obtained by using crushed LS and aggregate material tests were carried out according to American (ASTM) standards to determine the mechanical and durability properties of these selected materials for these mixtures. The physical and mechanical properties of aggregates used for mixtures are given in Table 3.

Table 3. Physical and mechanical properties of aggregates

Samples	Apparent specific gravity, g/cm^3	Bulk specific gravity, g/cm^3	Water absorption, %	Standard
>Sieve number:4 (coarse aggregate)	2.711	2.686	0.40	ASTM C127
Sieve number: 4-sieve number: 200 (fine aggregate)	2.715	2.662	0.60	ASTM C128
Filler of limestone	2.729	-	-	-
Aggregate tests	Value	Limit	Standard	
Abrasion loss value (Los Angeles), %	22	≤ 27	ASTM C-131-89	
Percent fractured faces, %	100	≥ 100	ASTM D5821	
Polish value	54	≥ 50	ASTM C 3319	
Flatness index, %	19.1	≤ 25	ASTM D 4791	

2.3. Milled carbon fiber

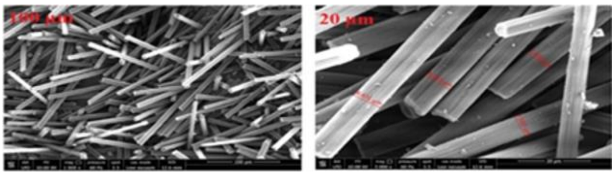
In this study, a commercial milled carbon fiber (MCF) was employed as an additive. Table 4 presents the physical characteristics of the MCF, which have been scarcely investigated in previous studies.

Table 4. Physical properties of MCF

Typical properties	Units	Carbon fiber
Density	g/cm³	1.80
Mean fiber length milled	µm	80
Filament diameter	µm	7
Tensile strength	GPa	3.0
Tensile modulus	GPa	200
Elongation at break	%	1.5
Single filament resistivity	µΩm	22
Bulk density	g/l	380
Sizing type	-	unsized

MCF and its SEM image are given in Fig. 1.

a



b

Fig. 1. a – MCF; b – SEM image of MCF

As observed in Fig. 1 b, carbon fiber has a tube shape with a uniform distribution. The SEM image depicted in Fig. 1 illustrates that the MCF comprises a substantial quantity of micro-sized MCF. Considering this micro-MCF, one of the motivations of this study was that MCF would be a good candidate to be used as a micro filler, potentially improving the performance of asphalt concretes.

3. METHOD

The asphalt mixtures were produced following the construction standards outlined by HTS [20]. A flowchart outlining the experimental procedure is presented in Fig. 2.

In the study, first of all, optimum bitumen ratios (*OBR*) of the control sample and carbon fiber reinforced samples were determined by using the Marshall design method. Samples were prepared using the *OBR* determined for each series of carbon added samples. The prepared samples were subjected to permanent Marshall stability, indirect tensile strength and moisture damage resistance tests, respectively. At the last stage of the study, the results of the experimental studies were evaluated and the optimum MCF additive amount was determined.

3.1. Marshall stability and flow test

Initially developed for airfield pavements, the Marshall mix design method and criteria were subsequently incorporated for use in highway pavements. The simplicity of the Marshall method of mix design made it the preferred choice in the United States before the introduction of the Superpave design system, and it continues to be the most frequently utilized mix design method worldwide [21].

The stability of an HMA pavement is considered to be the most crucial property of the asphalt mixture employed in the wearing course design. The lack of stability in an asphalt mixture causes the unraveling and flow of the road surface.

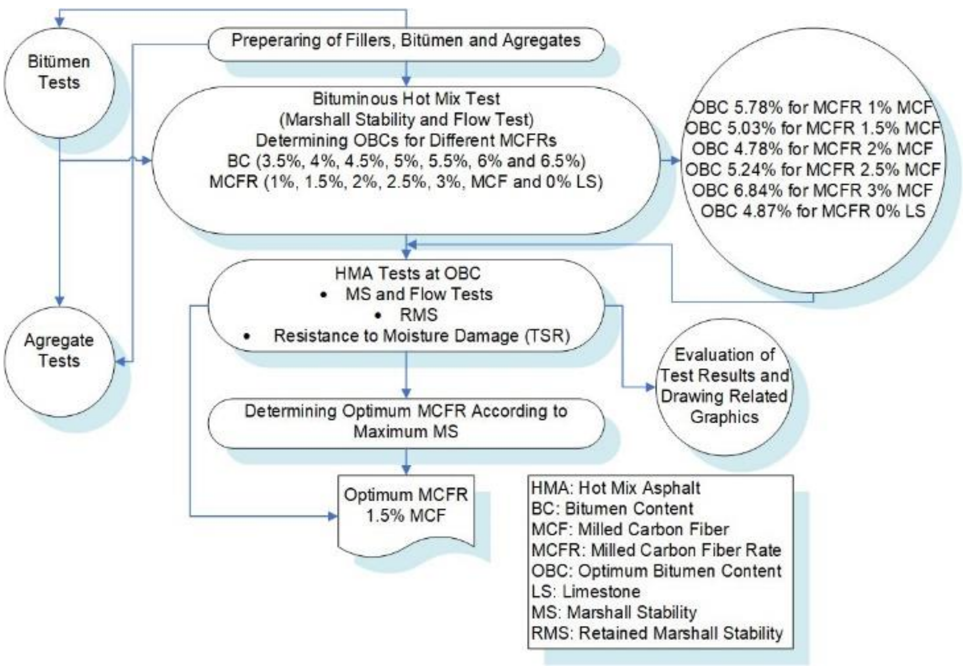


Fig. 2. Experimental work flow chart

Flow, on the other hand, is the pavement's ability to adapt to gradual settlements and movements in the subgrade without fracturing. Flow represents an opposite property to stability and determines the reversible behavior of the wearing course under traffic loads, significantly impacting the plastic and elastic properties of the asphalt concrete [22]. The Marshall Quotient (MQ) is a metric that assesses the stiffness and durability of asphalt concrete by measuring the ratio of its stability to flow. This ratio is used to determine the material's resistance to various forms of stress, including shear stress, permanent deformation, and rutting. By analyzing the MQ, engineers can gain valuable insights into the quality and performance of asphalt concrete, helping them to optimize its composition and ensure its long-term viability [23]. In the study, the MQ was determined using the formula below:

$$MQ = \frac{MS}{F}, \tag{1}$$

where MQ is Marshall Quotient; F is the flow value; MS is Marshall stability.

To determine the ideal amount of asphalt for various aggregate mixtures, Marshall design tests are conducted [17]. To conduct these tests, 1150 g of the dry mixture of aggregates is first measured and then heated up to 160 °C. After heating the aggregate to 160 °C, it is transferred into a pan and mixed thoroughly. Then, a depression or "crater" is formed in the center of the aggregate and 50/70 penetration grade asphalt (also heated to 160 °C) is added. The mixture of aggregate and asphalt is thoroughly blended until the aggregate particles are well coated with the asphalt. The next step is to ensure they are thoroughly cleaned and to heat the sample mold assembly and compression hammer to 160 °C [24].

To prepare the specimen for compaction, filter paper is placed at the bottom of the mold, and the heated mixture of aggregate and asphalt is carefully poured into the mold. A heated spatula is then used to smooth the mixture along the perimeter of the mold. The collar is removed, and the surface of the mixture is further smoothed with a trowel to achieve a slightly rounded shape. It is important to maintain the temperature of the mixture at 150 °C just before compaction to ensure proper and consistent results. After replacing the collar, the mold assembly was positioned on the compaction pedestal and secured in place by the mold holder. The top of the specimen was then subjected to 75 blows using a compaction hammer. Following this, the collar and baseplate were removed, and the sample was inverted. The mold was then reassembled, and 75 additional blows were applied to the inverted face of the specimen. After compaction, the specimen is carefully removed from the mold using a sample extractor and a jack and frame arrangement. After extraction, the specimen was placed on a flat, smooth surface and allowed to cool to room temperature according to established guidelines [24]. Once properly prepared, the samples, which measured 101.6 mm in diameter and 63.5 mm in thickness, underwent a series of tests to determine their density, voids, stability, and flow properties. These tests were conducted using a specialized device known as the *MS* and flow test device [17].

The main goal of the Marshall design procedure is to identify the OBR for the asphalt mixture. To do this, the designer must examine the following values on the test property curves [25]:

a) maximum stability of the asphalt mixture;
b) maximum unit weight;
c) the median value of the acceptable range for percent air voids;
d) the median value of the acceptable range for voids filled with asphalt.

3.2. Retained Marshall stability test

Mechanical tests that involve measuring changes in the properties of a compacted bituminous mixture after immersion in water are commonly used to indirectly assess the degree of stripping. The ratio of the mechanical property after immersion divided by the initial property provides a useful measure of the degree of stripping. One of the most popular tests for this purpose is the Marshall test. The ratio of the *MS* of bituminous specimens after wet conditioning to identical specimens that have not been subjected to the conditioning process is referred to as the RMS, and it is usually expressed as a percentage [26].

To assess the moisture susceptibility of the two mixes, the RMS test was conducted according to the ASTM D-1075 standard. A total of 36 Marshall specimens were prepared, with 6 specimens per MCF. These specimens were divided into two sets: unconditioned and conditioned. The unconditioned specimens were placed in a water bath at 60 °C for approximately 30 – 40 minutes, and their *MS* was measured. The conditioned specimens, on the other hand, were immersed in the water bath for 24 hours at 60 °C, and their *MS* was also determined. RMS was calculated as the MS of the conditioned samples was proportional to the MS of the unconditioned samples and then multiplied by 100, as indicated in the formula below:

$$RMS = \frac{MS_{cond}}{MS_{uncond}} x100, \tag{2}$$

where *RMS* is retained Marshall stability, MS_{cond} is average *MS* for conditioned specimens, kg; MS_{uncond} is average *MS* for unconditioned specimens, kg.

3.3. Indirect tensile strength test

The indirect tensile strength (*ITS*) test is a method used to determine the strength of cylindrical specimens by subjecting them to compressive loads along the vertical diametral plane using Marshall loading equipment. This results in uniform tensile stresses perpendicular to the direction of the applied load and along the vertical diametral plane, leading to the splitting of the specimen along the vertical diameter upon failure. The *ITS* value is calculated by determining the maximum load that the specimen can withstand before failure, using Eq. 3 [26]. The *ITS* test is conducted at a temperature of 25 °C and a loading rate of 50.8 mm/min, utilizing the Marshall apparatus, as per the ASTM D6931-17:2017 standard test method for indirect tensile (IDT) strength of asphalt mixtures. To compare mean ITS values, 24 samples (three per MCF) were prepared.

$$ITS = \frac{2P_{max}}{\pi t d}, \tag{3}$$

where *ITS* is the indirect tensile strength, kPa; P_{max} is the ultimate applied load required to fail specimen, kN; t is the thickness of the specimen, mm; and *d* is the diameter of specimen, mm.

3.4. Moisture damage resistance test

Moisture sensitivity refers to the resistance of plastic coatings to internal moisture movement enclosure damage after contact with water. The presence of water or moisture in the coating weakens the bond between the asphalt and aggregate and causes deterioration in the coating. Moisture sensitivity in hot mix coatings is determined by the AASHTO T283 standard. According to the standard, hot mix samples are evaluated by dividing them into two groups as "unconditioned" and "conditioned". Unconditioned samples are kept in a water bath at 25 °C for 2 hours. Conditioned samples, on the other hand, are subjected to vacuum treatment so that the air spaces of the samples are filled with 60 – 80 % water. After that, the samples are wrapped with cling film and kept in the freezer at -18 °C for 16 hours, and at the end of the time, these samples are kept in a water bath at 60 °C for 24 hours. At the end of the time, the samples taken from the bath are kept in the bath at 25 °C for 2 hours. After these procedures, unconditioned (ITS_{dry}) and conditioned (ITS_{wet}) samples are subjected to the *ITS* test using the Marshall device. As a result of the test, the indirect *TSR* values of the mixture samples are calculated with the help of Eq. 4. *TSR* values of HMA samples are required to be more than 80 % in terms of their resistance to moisture damage caused by water [27].

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} * 100, \quad (4)$$

where ITS_{wet} is the *ITS* for soaked specimens kPa; ITS_{dry} is the *ITS* for dry specimens, kPa.

4. TEST RESULTS AND DISCUSSION

4.1. Marshall test results

In the study, apart from the control sample (0 % control) produced with LS, 1 %, 1.5 %, 2 %, 2.5 %, 3 % of MCF reinforced hot mix asphalt samples were prepared. To identify the optimum asphalt content for various mixture groups, the Marshall test was conducted. For this purpose, asphalt mixture samples were prepared at the asphalt ratios of 3.5 %, 4.0 %, 4.5 %, 5.0 %, 5.5 % and 6.0 % for each MCF additive ratio. The hot mix asphalt specimens were prepared in accordance with the specified limit gradation curves for the HTS [20] wearing course. The tests were conducted for each 0.5 % increase in asphalt ratio.

For each level of asphalt ratio, three HMA specimens were prepared and subjected to Marshall tests. The weight, weight in water, and surface dry-saturated to water measurements were taken for all the samples. Based on the data obtained, curves were plotted to examine the relationships between the percentage of asphalt content and *MS*, *Dp*, Vf, and Vh. OBR levels were then determined from these curves for each of the design groups, resulting in OBR of 4.87 %, 5.78 %, 5.03 %, 4.78 %, 5.24 %, and 6.84 % for design groups 0 %, 1 %, 1.5 %, 2 %, 2.5 %, and 3 %, respectively. The correlation between the *MS* and asphalt content can be seen in Fig. 3. The maximum *MS* values of the samples with 0%, 1%, 1.5%, 2%, 2.5% and 3% MCF added were primarily determined as 1171, 1192, 1270, 1168, 1146 and 971 kg.

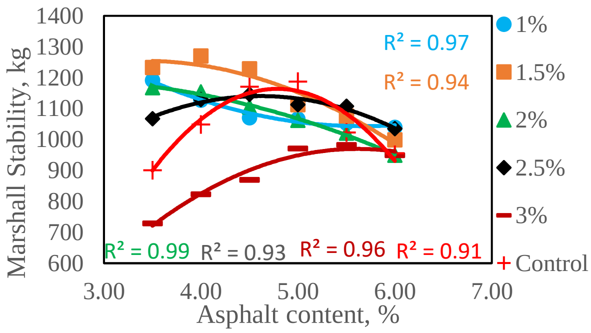


Fig. 3. Relationship between MS and percentage of asphalt

The results show that the highest durability wears are obtained from the figures with an MCF addition of 1.5 %. It was determined that the 1 % and 1.5 % MCF added samples had higher stability values than the control sample, while the 2 % and 2.5 % and 3 % carbon added samples were found to have lower values than the control sample. It is seen that the stability results are above the minimum stability value determined in the HTS wear layer in all samples. While the stability values increased up to 1.5 % carbon additive ratio, they showed a linear decrease after this value. It was observed that the 1 % and 1.5 % MCF added samples had higher stability values than the control sample, while the 2 % and 2.5 % and 3 % carbon added samples were found to have higher stability values. It was determined that it took lower values than the control sample. It is seen that the stability results are above the minimum stability value determined in the HTS wear layer in all samples. While the stability values increased up to 1.5 % carbon additive ratio, they decreased linearly after this value.

Density is one of the most important properties of HMA. As the density of HMA increases, physical properties such as durability and stability also improve [28].

The highest practical specific gravity (*Dp*) values were obtained as 2.404, 2.388, 2.396, 2.391, 2.367 and 2.333 g/cm^3 for 0 %, 1 %, 1.5 %, 2 %, 2.5 % and 3 % series, respectively. The highest *Dp* value was obtained in the samples of the control series (0 % control). Considering the samples with MCF addition, it was observed that the highest *Dp* value was obtained from the 1.5 % series and as expected, the MS value was the highest in the 1.5 % series. The relationships between the percentage of bitumen versus the change in *Dp* values are quite stable (Fig. 4).

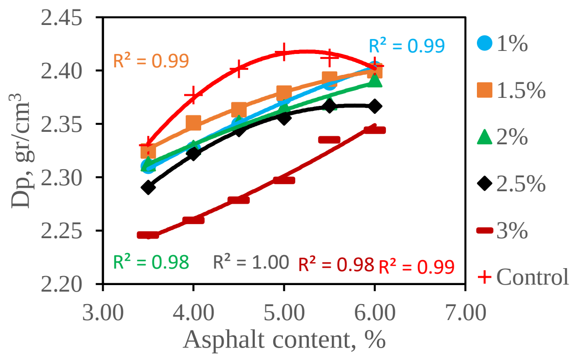


Fig. 4. Relationship between *Dp* and percentage of asphalt

The amount of 'Void filled with asphalt' (Vfa) plays a crucial role in determining the plasticity, durability, and friction coefficient of asphalt mixtures. It also helps in providing a protective asphalt coating around the aggregate particles. In case the Vfa is insufficient, the overall durability and stability of asphalt concrete tend to get compromised [29].

According to the HTS [20], the amount of asphalt filled voids should be between 65 % and 75 %. While determining the optimum amount of asphalt for hot mixes with MCF additives, the asphalt ratio with a void ratio of 70 % was chosen (Fig. 5). In the mixtures with 0 %, 1 %, 1.5 %, 2 %, 2.5 % and 3 % MCF addition, the percentage of asphalt filled voids corresponding to the OBR were obtained as 72.8 %, 78.84 %, 70.71 %, 65.14 %, 71.36 % and 88.11 %, respectively. 0 %, 1.5 %, 2 % and 2.5 series are within the limit values specified in the HTS. It is seen that 1 % and 3 % series exceed the limit value (75 %) of the void ratio filled with asphalt.

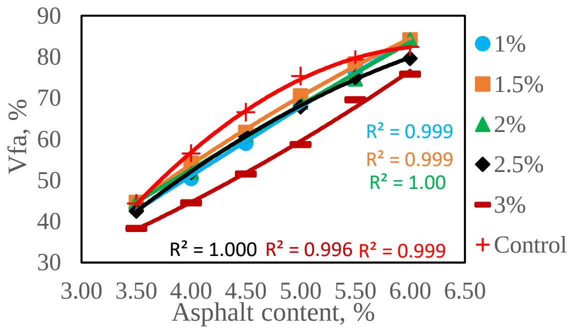


Fig. 5. Relationship between Vfa and percentage of asphalt

The void percentage (Vh) is an important property for hot bituminous mixes. In the HTS, the lower and upper limit for the vacancy rate is determined as 3 – 5 %. The purpose of determining these limit values is to prevent possible vomiting deterioration. The reason for determining the upper limit for the void percentage is to ensure the layer's water impermeability and sufficient stability [28].

While determining the OBR of MCF-added bituminous hot mixes, the asphalt ratio corresponding to 4 % void ratio was chosen. The changes in the percentage of voids versus the percentage of asphalt by weight in the samples belonging to all series are shown in Fig. 6.

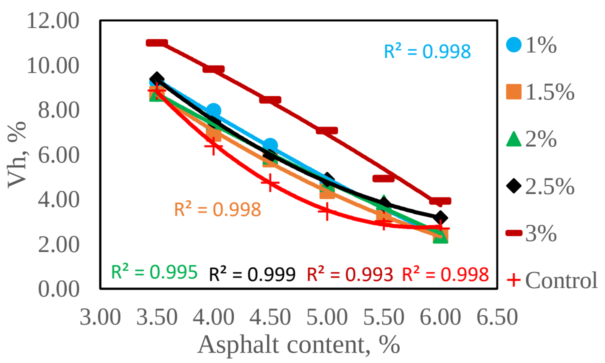


Fig. 6. Relationship between Vh and asphalt content

It is seen that the relations between the percent of asphalt by weight and the void are stable. The void percentage corresponding to the OBR was obtained as 3.78 %, 3.22 %, 4.29 %, 5.28 %, 4.28 % and 1.78 %, respectively, in the mixtures with 0 %, 1 %, 1.5 %, 2 %, 2.5 % and 3 % MCF.

According to the test results, it is seen that the void amounts of all samples are within the specification limits, except for the sample series with 2 % and 3 % milled carbon addition. It was determined that the void amount in the 0 %, 1 %, 1.5 % and 2.5 % carbon added series was very close to the ideal void amount of 4 %.

According to the HTS [20], it is foreseen that the flow value for the HMA to be used in the wear layer is between 2 and 4 mm. OBR of MCF-added HMA the asphalt ratio corresponding to 3 % void ratio was chosen. The changes in the percentage of voids versus the percent of asphalt by weight in the samples belonging to all series are shown in Fig. 7. The flow values corresponding to the OBR in the mixtures with 0 %, 1 %, 1.5 %, 2 %, 2.5 % and 3 % MCF were obtained as 3.44 %, 2.30 %, 2.23 %, 3.40 %, 1.95 % and 2.41 %, respectively. When the test results are examined, it is seen that all samples comply with the HTS, except for the series with 2.5 % milled carbon addition. However, it was determined that the flow value of the control sample was higher than the series using MCF.

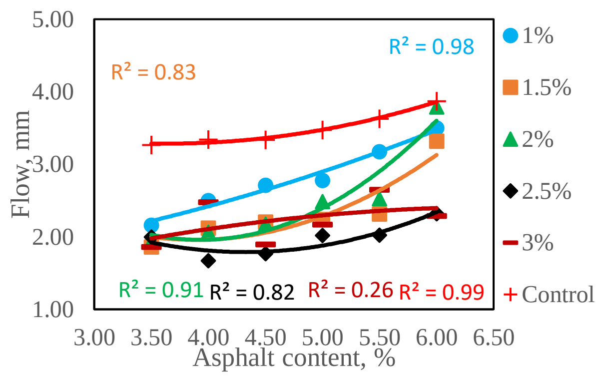


Fig. 7. Relationship between flow and asphalt content

Durability is enhanced by obtaining a sufficient film thickness for any asphalt and aggregate mixture. Larger film thickness in the sense of effective asphalt content will result from coarser aggregate gradation. Reducing or minimizing the percentage of fines is the most effective strategy to accomplish this. To achieve a sufficient film thickness without excessive asphalt bleeding or flushing, adequate Voids in Mineral Aggregate (VMA) must be established both during the mix design process and in the field [30].

For the reasons stated above, the minimum void percentage value between mineral aggregates for aggregates to be used in the wear layer is defined as a minimum of 14% in the HTS. The relationship between the voids between mineral aggregates and the percent by weight of asphalt is given in Fig. 8.

In the mixtures with 0 %, 1 %, 1.5 %, 2 %, 2.5 % and 3 % MCF addition, the void values between mineral aggregates corresponding to the OBR were obtained as 14.04 %, 15.28 %, 14.76 %, 15.15 %, 15.11 % and 15.93 %, respectively. When the test results are examined, it is seen that all series comply with the HTS. However, it was determined that the void values between the mineral aggregates of the control sample were lower than the series using MCF.

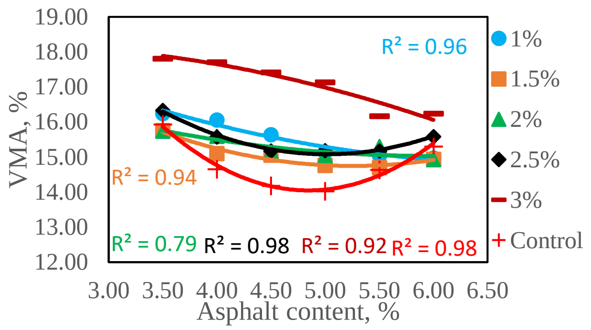


Fig. 8. Relationship between VMA and asphalt content

The relationship between the *MQ* and the percentage of asphalt is given in Fig. 9. *MQ* values of the produced bituminous hot mix samples were determined as 3.32, 3.07, 4.88, 4.67, 5.69 and 3.44 kN/mm, respectively, in the mixtures with 0 %, 1 %, 1.5 %, 2 %, 2.5 % and 3 % MCF (Fig. 10).

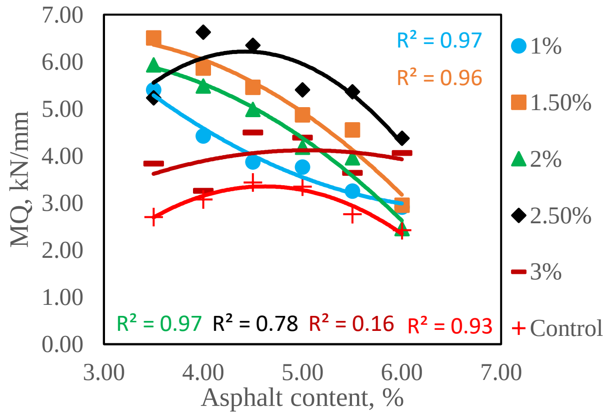


Fig. 9. Relationship between *MQ* and asphalt content

When the *MQ* values are examined at the OBR, it is seen that there are changes in the *MQ* values with the contribution of MCF. These changes are 7.5 % decrease and 46.9 %, 40.7 %, 71.4 % and 3.61 % increase compared to the control sample. According to these results, it will be possible to say that the highest increase is seen in the mixture samples with 2.5 % milled carbon and therefore the mixtures with 2.5 % milled carbon additives are the most resistant to shear stresses.

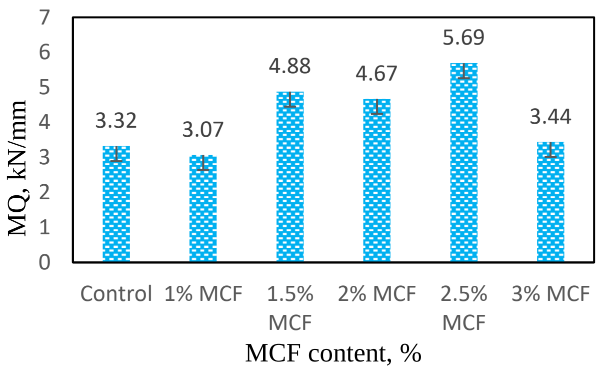


Fig. 10. Relationship between *MQ* and MCF content

4.2. Retained Marshall stability test results

When Fig. 11 is examined, as the MCF additive ratio increased, significant increases occurred in the RMS values of the modified mixtures compared to the control mixture. These increases are 3.97 %, 15.28 %, 13.91 %, 15.17 %, and 13.45 %, respectively. When the RMS results are examined, it is seen that all series with milled carbon added have higher values compared to the control sample. The highest RMS value was obtained from 95.19 % and 1.5 % milled carbon added samples. Therefore, it is understood that the bituminous hot mixtures with the least sensitivity to moisture are the mixtures with 1.5 % milled carbon. It can be concluded that the MCF strengthens the relationship between aggregate and asphalt, resulting in an increase in the resistance of bituminous hot mixes to water-induced deterioration.

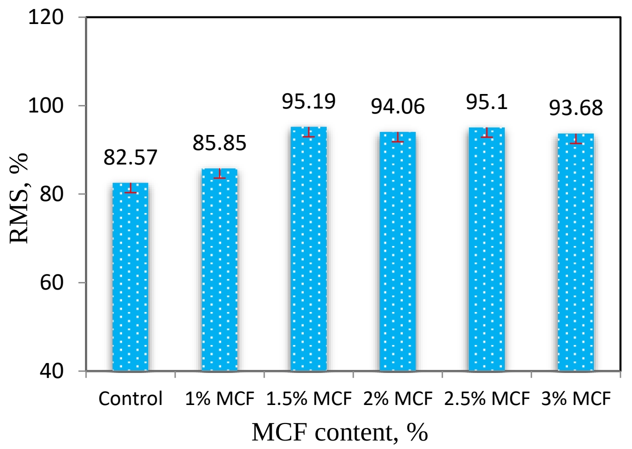


Fig. 11. RMS test result

4.3. Indirect tensile strength and moisture damage resistance test results

In the study, the *ITS* test was applied to conditioned and unconditioned MCF added and control samples, and their resistance to coating deterioration caused by water was determined. *ITS* and *TSR* values are given in Fig. 12 and Fig. 13, respectively.

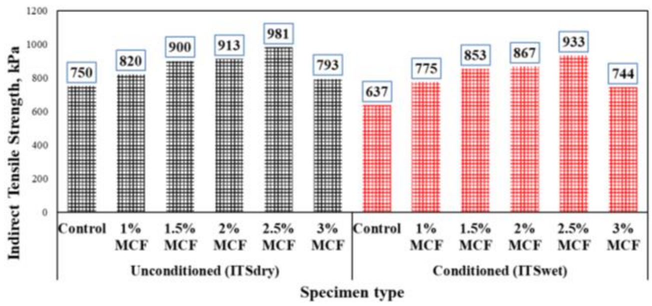


Fig. 12. *ITS* values of the control and MCF asphalt mixtures

When Fig. 12 is examined, there were changes in *ITS* values of asphalt mixture samples conditioned with MCF additive increase (ITS_{wet}) compared to the control sample. These changes are 21.7 %, 33.9 %, 36.1 %, 46.5 % and 16.8 % increases, respectively, compared to the carbon fiber-free control mix prepared with limestone. The changes in the *ITS* values of the unconditioned (ITS_{dry}) mixture samples are 9.3 %, 20 %, 21.7 %, 30.8 % and 5.7 % increase, respectively, compared to the control sample. It is seen that the ITS_{wet} and ITS_{dry} values of the mixture samples increased in general with the MCF additive.

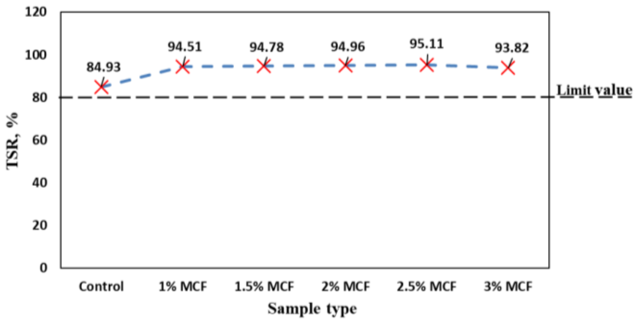


Fig. 13. Tensile strength ratio results

Therefore, it is understood that hot mixes with MCF added asphalt increases the resistance of the coating against tensile stresses caused by traffic loads.

When Fig. 13 is examined, changes occurred in TSR values with the increase in MCF contribution. These changes are 11.3 %, 11.6 %, 11.8 %, 12.0 % and 10.5 % increases, respectively, compared to the control mixture. According to these results, the highest TSR value was observed in mixtures with 2.5 % MCF additives. Therefore, it can be said that the most resistant mixtures against deterioration caused by water are the mixtures with 2.5 % MCF additives. In addition, the fact that the TSR values of the mixtures with the MCF additive are above 80 % indicates that the MCF additive has an improving effect on the resistance of the HMA coatings to water-induced deterioration.

5. CONCLUSIONS

In the study, the effects of MCF on the mechanical behavior and moisture damage resistance of HMA were investigated and the results obtained are summarized below.

1. According to MS test results, MS of HMA with MCF additive increased by 8.5 % and the highest stability value was obtained from mixtures with 1.5 % MCF additive.
2. OBR were calculated for each series and it was observed that the values obtained were within the limits of economic use and remained within the limit values determined for the wear layer of the HTS.
3. According to the MQ results, the highest MQ value was obtained from the mixture with 2.5 % MCF additive, and therefore, the resistance of the MCF additive coating against shear stresses was improved.
4. According to the RMS results, it was observed that the resistance of the hot mixtures against the effects of humidity increased significantly with the addition of MCF, and the highest resistance was obtained from the mixtures with 1.5 % MCF addition.
5. According to the TSR results, it was observed that the highest TSR value was obtained from the mixture with 2.5 % MCF addition, and the addition of MCF significantly improved the moisture resistance of the road pavements by increasing the adhesion and cohesion ability of the HMA.
6. According to the test results, the highest density value was obtained in the 1.5 % MCF added bituminous hot mix samples. Therefore, it is expected that the impermeability property of the 1.5 % series samples will be better than the other MCF added samples.
7. When the flow results are examined, it is seen that in addition to there being a decrease in all series with MCF addition compared to the control sample, it is also within the limit values specified in the HTS. For this reason, it is thought that all MCF-doped series will exhibit a resistant behavior against plastic deformation formation.

As a result, it is possible to state that the use of MCF as an additive in HMA has an improving effect on increasing the moisture resistance and mechanical properties (stability) of flexible coatings.

Acknowledgments

This study is derived from Ayşe Cansel DURMAZ's master's thesis. Authors wish to thank the Scientific Research Projects (BAP) Coordination Department of Isparta University of Applied Sciences (Project Number:2022-YL1-0165) for financial support.

REFERENCES

1. **Ahmedzade, P., Sengoz, B.** Evaluation of Steel Slag Coarse Aggregate in Hot Mix Asphalt Concrete *Journal of Hazardous Materials* 165 (1–3) 2009: pp. 300–305. https://doi.org/10.1016/j.jhazmat.2008.09.105
2. **Sargın, Ş., Saltan, M., Morova, N., Serin, S., Terzi, S.** Evaluation of Rice Husk Ash as Filler in Hot Mix Asphalt Concrete *Construction and Building Materials* 48 2013: pp. 390–397. https://doi.org/10.1016/j.conbuildmat.2013.06.029
3. **Morova, N.** Investigation of Usability of Basalt Fibers in Hot Mix Asphalt Concrete *Construction and Building Materials* 47 2013: pp. 175–180. https://doi.org/10.1016/j.conbuildmat.2013.04.048
4. **Mawat, H.Q., Ismael, M.Q.** Assessment of Moisture Susceptibility for Asphalt Mixtures Modified by Carbon Fibers *Civil Engineering Journal* 6 (2) 2020: pp. 304–317. http://dx.doi.org/10.28991/cej-2020-03091472
5. **Günay, T., Ahmedzade, P., Hassanpour-Kasanagh, S., Fainleib, A.M., Starostenko, O.** Effect of Maleic Anhydride Grafted and Gamma-irradiated Waste Polypropylene on Rheological Properties of Asphalt Binder *International Journal of Pavement Engineering* 23 (13) 2022: pp. 4819–4830. https://doi.org/10.1080/10298436.2022.2046742
6. **Oruç, Ş., Yılmaz, B., Sancak, K.** Characterization and Rheological Behavior of Asphalt Binder Modified by a Novel Cyclic Borate Ester Additive *Construction and Building Materials* 348 2022: pp. 128673. https://doi.org/10.1016/j.conbuildmat.2022.128673
7. **Geçkil, T., İnce, C.B., Tanyıldızı, M.M.** Physical, Rheological and Microstructural Properties of Waste LDPE and TEOA Modified Bitumens *Journal of the Chinese Institute of Engineers* 45 (6) 2022: pp. 477–487. https://doi.org/10.1080/02533839.2022.2078416
8. **Wang, Y., Li, A., Zhang, S., Guo, B., Niu, D.** A Review on New Methods of Recycling Waste Carbon Fiber and its Application in Construction and Industry *Construction and Building Materials* 367 2023: pp. 130301. https://doi.org/10.1016/j.conbuildmat.2023.130301
9. **Geckil, T., Ahmedzade, P.** Effects of Carbon Fibre on Performance Properties of Asphalt Mixtures *Baltic Journal*

of Road & Bridge Engineering (RTU Publishing House) 15 (2) 2020: pp. 49 – 65.
https://doi.org/10.7250/bjrbe.2020-15.47

10. **Shanbara, H.K.** Effect of Carbon Fiber on The Performance of Reinforced Asphalt Concrete Mixture *Muthanna Journal of Engineering and Technology (MJET)* 1 (1) 2011: pp. 40 – 52.
https://doi.org/10.52113/3/eng/mjet/2011-01-01/40-52
11. **Notani, M.A., Arabzadeh, A., Ceylan, H., Kim, S., Gopalakrishnan, K.** Effect of Carbon-fiber Properties on Volumetrics and Ohmic Heating of Electrically Conductive Asphalt Concrete *Journal of Materials in Civil Engineering* 31 (9) 2019: pp. 04019200.
https://doi.org/10.1061/(ASCE)MT.1943-5533.0002868
12. **Zarei, M., Akbarinia, F., Rahmani, Z., Zahedi, M., Zarei, A.** Economical and Technical Study on The Effect of Carbon Fiber with High Strength on Hot Mix Asphalt (HMA) *Electronic Journal of Structural Engineering* 20 2020: pp. 6 – 12.
https://doi.org/10.56748/ejse.20240
13. **Zhang, M.R., Fang, C.Q., Zhou, S.S., Cheng, Y.L., Hu, J.B.** Modification of Asphalt by Dispersing Waste Polyethylene and Carbon Fibers in it *New Carbon Materials* 31 (4) 2016: pp. 424 – 430.
https://doi.org/10.1016/S1872-5805(16)60022-7
14. **Zhang, K., Lim, J., Nassiri, S., Englund, K., Li, H.** Reuse of Carbon Fiber Composite Materials in Porous Hot Mix Asphalt to Enhance Strength and Durability *Case Studies in Construction Materials* 11 2019: pp. e00260.
https://doi.org/10.1016/j.cscm.2019.e00260
15. **Upadhya, A., Thakur, M.S., Sihag, P.** Predicting Marshall Stability of Carbon Fiber-reinforced Asphalt Concrete Using Machine Learning Techniques *International Journal of Pavement Research and Technology* 2022: pp. 1 – 21.
https://doi.org/10.1007/s42947-022-00223-5
16. **Jahromi, S.G., Khodaii, A.** Carbon Fiber Reinforced Asphalt Concrete *Arabian Journal for Science & Engineering (Springer Science & Business Media BV)* 33 2008: pp. 355 – 364.
17. **Yang, Z., Zhang, Y., Shi, X.** Impact of Nanoclay and Carbon Microfiber in Combating the Deterioration of Asphalt Concrete by Non-chloride Deicers *Construction and Building Materials* 160 2018: pp. 514 – 525.
https://doi.org/10.1016/j.conbuildmat.2017.11.059
18. **Abtahi, S.M., Sheikhzadeh, M., Hejazi, S.M.** Fiber-reinforced Asphalt-concrete–A Review *Construction and Building Materials* 24 (6) 2010: pp. 871 – 877.
https://doi.org/10.1016/j.conbuildmat.2009.11.009
19. **Cleven, M.A.** Investigation of the Properties of Carbon Fiber Modified Asphalt Mixtures. M.Sc. Thesis, Michigan Technological University, 2000.
20. **General Directorate of Highways. State Highways Technical Specifications (HTS);** General Directorate of Highways: Ankara, Turkey, 2013.
21. **Terzi, S., Karaşahin, M., Gökova, S., Tahta, M., Morova, N., Uzun, I.** Asphalt Concrete Stability Estimation from Non-destructive Test Methods with Artificial Neural Networks *Neural Computing and Applications* 23 2013: pp. 989 – 997.
https://doi.org/10.1007/s00521-012-1023-1
22. **Hınıslıoğlu, S., Ağar, E.** Use of Waste High Density Polyethylene as Bitumen Modifier in Asphalt Concrete Mix *Materials Letters* 58 (3 – 4) 2004: pp. 267 – 271.
https://doi.org/10.1016/S0167-577X(03)00458-0
23. **Aksoy, A., Iskender, E., Kahraman, H.T.** Application of the Intuitive k-NN Estimator for Prediction of the Marshall Test (ASTM D1559) results for asphalt mixtures *Construction and Building Materials* 34 2012: pp. 561 – 569.
24. **Ogundipe, O.M.** Marshall Stability and Flow of Lime-modified Asphalt Concrete *Transportation Research Procedia* 14 2016: pp. 685 – 693.
https://doi.org/10.1016/j.trpro.2016.05.333
25. **Tapkın, S., Çevik, A., Uşar, Ü.** Prediction of Marshall Test Results for Polypropylene Modified Dense Bituminous Mixtures Using Neural Networks *Expert Systems with Applications* 37 (6) 2010: pp. 4660 – 4670.
https://doi.org/10.1016/j.eswa.2009.12.042
26. **Zoorob, S.E., Suparma, L.B.** Laboratory Design and Investigation of the Properties of Continuously Graded Asphaltic Concrete Containing Recycled Plastics Aggregate Replacement (Plastiphalt) *Cement and Concrete Composites* 22 (4) 2000: pp. 233 – 242.
https://doi.org/10.1016/S0958-9465(00)00026-3
27. **Geçkil, T., Seloğlu, M., İnce, C.B.** The Effect of RET Additive on Water Damage Resistance of Hot Mix Asphalt *Fırat University Journal of Engineering Science* 33 (2) 2021: pp. 537 – 546.
https://doi.org/10.35234/fumbd.880528
28. **Gürer, C., Selman, G.Ş.** Investigation of Properties of Asphalt Concrete Containing Boron Waste as Mineral Filler *Materials Science (Medžiagotyra)* 22 (1) 2016: pp. 118 – 125.
https://doi.org/10.5755/j01.ms.22.1.12596
29. **Akbulut, H., Gürer, C., Çetin, S., Elmacı, A.** Investigation of Using Granite Sludge as Filler in Bituminous Hot Mixtures *Construction and Building Materials* 36 2012: pp. 430 – 436.
https://doi.org/10.1016/j.conbuildmat.2012.04.069
30. **Chadbourn, B.A., Skok, E.L, Newcomb, D.E., Crow, B.L., Spindle, S.** The Effect of Voids in Mineral Aggregate (VMA) on Hot-mix Asphalt Pavements, Minnesota Department of Transportation, Final Report, MN/RC – 2000-13; 1999.
https://hdl.handle.net/11299/198800