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The effect of filler additives on moisture damage in stone mastic asphalt (SMA) mixtures

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Research Paper

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The effect of filler additives on moisture damage in stone mastic asphalt (SMA) mixtures

SMA mixtures improve the permanent deformation resistance of hot-mixed asphalt mixtures. The effects of filler additives on moisture damage of SMA mixtures are investigated in this study. The class C and class F fly ashes and hydrated lime are used as filler additives. These are replaced with filler material at 0.5%, 1.0%, 2.0%, and 4% of the total weight of the mixture. Dry and wet (slurry) methods are used in mixing the filler additives. Class C fly ash significantly improved resistance to moisture damage. However, the effect of using liquid antistripping agent with filler additives is insignificant.

Key words:
stone mastic asphalt (SMA), moisture damage, stripping, fly ash, hydrated lime

Prethodno priopćenje

Altan Çetin

Učinak aditiva punilu na otpornost djelovanja vode u mješavinama splitmastiksasfalta (SMA)

SMA mješavine poboljšavaju trajnu otpornost na deformacije vruće miješanih asfaltnih mješavina. U ovom istraživanju ispituju se učinci aditiva za punila na oštećenje SMA mješavina od djelovanja vode. Kao aditivi za punila koriste se leteći pepeo C i F razreda i hidratizirano vapno. Oni se zamjenjuju materijalima za punjenje (punilima) - 0,5 %, 1,0 %, 2,0 % i 4 % ukupne težine mješavine. U miješanju aditiva za punila primjenjuju se suhe i vlažne (slurry) metode. Leteći pepeo razreda C značajno poboljšava otpornost oštećenja zbog djelovanja vode. Međutim, učinak tekućeg sredstva protiv ljuštenja pomoću aditiva za punilo je beznačajan.

Ključne riječi:
splitmastiksasfalt (SMA), oštećenje zbog djelovanja vode, ljuštenje, leteći pepeo, hidratizirano vapno

1. Introduction

Stripping resulting from weakening of the adhesive bond between aggregate and bitumen due to moisture damage can be most often seen on bituminous pavements. Moisture also weakens cohesive bonding in bitumen. Moisture damage decreases strength of asphalt mixtures causing deterioration such as rutting and cracking on asphalt pavement [1, 2]. Besides climate and traffic effects, asphalt mixture properties also have an important effect on moisture damage of asphalt mixtures. Additive materials can be used to improve adhesion between bitumen and aggregate and to reduce moisture damage of asphalt mixtures. Many chemical liquid antistripping additive materials used for this purpose belong to the family of amines or amidoamines [3, 4]. Additives are developing and so is the testing against stripping due to water damage. Amines-based liquid antistripping agents (LAA) improve rutting resistance and stripping of asphalt mixtures [5, 6].

Some appropriate materials can also be used to decrease hydrophilic properties of aggregates by coating. Mineral powder filler (passing through the 0.063 mm sieve size) improves some negative properties at the contact between aggregate and bitumen [7]. Filler materials fill voids in asphalt mixtures and thus an impermeable structure is created. They affect high and low temperature performance of asphalt mastic [8]. Portland cement used as filler material increases resistance of asphalt mixtures to water absorption [9]. Fly ash used as mineral filler improves water strength of hot-mixed asphalt mixtures [10]. Lime is widely used in this respect. Hydrated lime can be used in the proportion of 1-2 % of the total aggregate weight as filler material in asphalt mixtures [11-14]. While hydrated lime can be mixed with aggregate either dry or wet, It can also be mixed as a slurry. Hydrated lime is widely and effectively used by mixing it with wet aggregate or in slurry form [15]. It has been proven that hydrated lime changes rheological properties of asphalt mixtures significantly. Many experimental results show that addition of hydrated lime to asphalt mixtures improves the moisture damage strength when subjected to the wet-dry process [16, 17]. Many researchers have indicated that hydrated lime also improves moisture strength and adhesion between aggregate and bitumen [18-20].

The use of fly ash as an alternative filler additive has recently aroused a great interest in the area of asphalt pavements. This is due to the fact that fly ash is more economical and workable than hydrated lime. Fly ash produced in thermal power plants is difficult to dispose of, and its disposal in regular disposal areas is quite expensive. The use of fly ash in asphalt mixtures is beneficial to environment while also reducing the quantity of waste. When fly ash is used instead of mineral filler, it improves rutting and moisture damage properties. Fly ash having free lime and hydrophobic nature decreases potential stripping of asphalt mixtures. Asphalt pavement mixtures similar to SMA have coarse gradation and are hence able to carry intensive and heavy traffic loads. Therefore, fly ash used as mineral filler is needed to make the mixture hard and to reduce bitumen draindown [21].

Some previous studies show that the addition of fly ash improves performance of hot-mixed asphalt mixtures. Adding 3-6 % of fly ash to an asphalt mixture gives results that are comparable to those of other antistripping agents used for curbing moisture damage [22]. It has been reported that fly ash can also be used as a hardener and void filler [23, 24]. Ali et al. [25] indicated that fly ash added to asphalt mixtures in the proportion of 2 % of the total weight of aggregate improves not only stiffness properties but also the strength and stripping resistance of mixtures. Huang et al. [26] added 1.0 % of class F fly ash to asphalt mixtures. They obtained resilient modulus results similar to those of control specimens. However, the resilient modulus values of fly ash mixed samples are lower than those of lime mixed samples. According to indirect tensile test results, the tensile strength of fly ash added samples is by 15 % higher than that of control specimens. However, the tensile strength of lime added samples is by 25 % higher than that of control specimens.

SMA is a gap-graded bituminous hot mixture that is quite popular around the world. SMA was first developed in Germany in the 1960s and has been widely used since 1990s due to its high potential resistance to permanent deformation or rutting [27]. However, the research on SMA behaviour with regard to stripping and moisture damage is still quite limited. SMA has not only the gap graded structure but also coarser materials. Therefore, it needs stabilization to prevent bitumen drainage. This can be done by adding modifiers, such as fibres or polymers, to the mixture [28].

The thickness of bitumen film is an important parameter for reducing stripping of asphalt pavements. The film thickness increment in mixtures has a positive effect with regard to the stripping phenomenon. Stone mastic asphalt mixtures developed to improve rutting resistance due to the high bitumen ratio are becoming increasingly important in terms of moisture sensitivity. The adhesion between aggregate and bitumen Is considered significant because of the high coarse aggregate ratio in SMA mixtures. Filler additives are needed due to the decreasing quantity of fine materials in SMA mixtures. At this point, filler additives used in SMA mixtures are considered functional in terms of moisture damage. In effect, it has been revealed that they have some positive effects against moisture damage, thus extending service life of asphalt pavements. Nowadays, development of asphalt pavement types shows that filler type materials have to be evaluated with regard to moisture damage. In order to decrease moisture damage, fly ash obtained from thermal power plants can be used as an effective filler additive. In addition, the use of fly ash is economical for Turkey and the world at large.

The effects of filler additives against moisture damage of gap-graded hot-mixed asphalt mixtures are investigated in this study. Class C and class F fly ash are considered with regard to their lime content and pozzolanic properties as an alternative to the use of hydrated lime against water damage. The effects of fly ash (class C), which contains high amount of quick lime, are compared to those of other filler additives. The effects of the quantity of filler additives and mixing methods (dry and wet) are also investigated. The effect of commercial antistripping agent in relation to moisture sensitivity is equally studied. Samples are prepared according to Turkish Highway Technical Specifications and compacted by means of a gyratory compactor. The Nicholson stripping test and the AASHTO T283 [29] method are used to determine moisture susceptibility. The indirect tensile strength test is carried out to determine the bitumen film thickness.

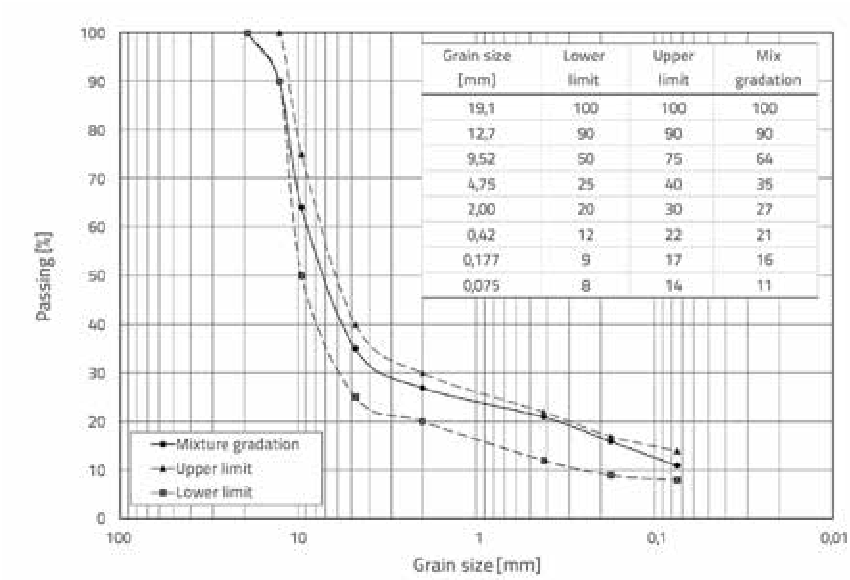

Figure 1. Aggregate gradation and specification limits for SMA mixture

2. Experimental studies

2.1. Materials

One type of aggregate and bitumen was used to design SMA mixtures. Cellulosic fibre was used to stabilize bitumen in the mixtures. Class C and F fly ashes and hydrated lime were used as filler additive. Some properties of crushed limestone aggregate are given in Table 1. Specific gravity and water absorption values of aggregate are given in Table 2. The grain size distribution of aggregate, including upper and lower limit specifications for SMA Type-1, is given in Figure 1. B 50/70 bitumen class was used at the production stages of all specimens since it is frequently chosen in many hot mix bituminous binder applications due to climatic conditions in Turkey. Some properties of bituminous binder are given in Table 3.

Class C and F fly ash and hydrated lime were used as filler additive in this study. Hydrated lime which contains 90 % of Ca(OH)2 was used as an antistripping agent of asphalt mixtures. Class C and F fly ashes were obtained from Soma thermal power plant and Catalagzı thermal power plant,

Table 1. Physical properties of crushed limestone aggregate

Characteristics	Specifications	Values	Specification limits*
Los Angeles abrasione [%]	TS EN 1097-2	18	< 25
Sodium sulphate soundness [%]	TS EN 1367-1	0.85	< 14
Crushing value [%]	TS EN 933-5	100	< 25
Flakiness index [%]	TS EN 933-3	7.8	100
Polished stone value	EN 1097-8	53.1	> 50
Stripping resistance [%]	EN 12697-11	45-50	> 50
*Turkish Highway Technical Specification - SMA Mixture			

Table 2. Specific gravity and water absorption values of aggregate fractions

Aggregate fractions	Standards	Apparent specific gravity	Bulk specific gravity	Water absorption [%]
Coarse aggregate	TS EN 1097-6	2.863	2.795	0.39
Fine aggregate	TS EN 1097-6	2.881	2.796	1.54
Filler	TS EN 1097-7	2.786	—	—

Table 3. Physical characteristics of bituminous binder (B 50/70)

Properties	Standarts	Results	Limits
Penetration at 25 °C, 0.1 mm	TS EN 1426	65	50-70
Softening point, °C	TS EN 1427	49.2	46-54
Flash point, °C	TS EN 12593	304	> 230
Specific gravity	TS EN 15326	1.037	1.00 to 1.05
Penetration index	EN 12591-Annex A	-0.682	-1.5 to +0.7

Table 4. Physical characteristics of additional filler materials

Properties	Fly ash (Class C)	Fly ash (Class F)	Hydrated lime
Specific gravity [g/cm^3]	2.41	2.00	2.24
Percent retained [%] (90 μm)	33.7	21.4	4.89
Percent retained [%] (45 μm)	52.6	38.7	15.4

Table 5. Chemical composition of additional filler materials

Oxide [%]	Fly ash (Class C)	Fly ash (Class F)	ASTM C 618	
			Class F	Class C
SiO_2	41.26	58.48		
Al_2O_3	19.50	25.34		
Fe_2O_3	4.25	5.77		
$SiO_2+Al_2O_3+Fe_2O_3$	65.01	89.59	> 70.00 %	> 50.00 %
CaO	26.80	1.48	< 10.00 %	> 10.00 %
MgO	1.82	2.22		
SO_3	1.10	0.12	< 5.00	<5.00
K_2O	1.15	4.09		
Na_2O	0.32	0.59		
Loss on Ignition	3.05	1.01	< 5.00	< 6.00
Cl-	0.009	0.027		

respectively. Some physical properties of additives used in this study are given in Table 4. Chemical composition of Class C and F fly ashes is given in Table 5. Class C fly ash is classified according to ASTM C-618 as the high lime content fly ash. The content of SiO2+Al2O3+Fe2O3 is over 50 % (65.01 %) and CaO content is over 10 % (26.50 %). Class F fly ash is classified as the low lime content fly ash. The content of SiO2+Al2O3+Fe2O3 is above 70 % (89.59 %) and CaO content is less than 10 % (1.48 %).

Liquid chemical antistripping agents are widely using to decrease moisture damage in asphalt mixtures. Liquid antistripping agents are used to increase cohesive strength between bitumen and aggregate. The commercial Liquid Antistripping Agent (LAA) used in this study belongs to the amido-amines family and is yellow in colour. Its specific gravity is 0.96 g/cm^3 and its flash point is 160°C. Suggested values given by the manufacturer are between 0.1 % and 0.4 %. The chosen value is 0.3 % for use as bitumen modifier. Bitumen was first heated to 150°C and then additive was added. The mixture was finally mixed for 20 minutes using a high shear mixer at a speed of 600 rpm.

2.2. Preparation of specimens

Samples were prepared according to Turkish Highway Technical Specifications. SMA samples were prepared using a gyratory compactor (Figure 2) according to the superpave mixing procedure proposed by NAPA using 100 gyrations, 600 kPa pressure, and 4.0 % of targeted air gap value. The percentage of 0.6 % cellulosic fibre in the total aggregate weight, embedded into bitumen to prevent bitumen draindown from the mixture, was mixed with dry aggregate to obtain a homogenous mixture. Control samples were prepared at bitumen ratios of 5 %, 5.5 %, 6.0 %, 6.5 % and 7 % targeting the 4.0 % void ratio. The optimum bitumen ratio was determined as 6.5 %. The volumetric specific gravity of compacted samples and theoretical maximum density of loose asphalt samples were determined according to AASHTO T166 [30] and AASHTO T209 [31], respectively. Mixture design parameters, such as air voids in compacted mixture (VA), voids in mineral aggregate (VMA) and voids filled with asphalt (VFA), were determined according to test results.

Figure 2. Gyratory compactor and compacted specimen

Two methods, wet and dry, are generally used for the modification of asphalt mixtures. In the dry method, additives were added by weight of aggregate at percentages of 0.5 %, 1.0 %, 2.0 % and 4.0 % with replacement of stone powder filler in the mixture. In the wet method, the slurry form of additives was mixed with aggregate. First, slurry was formed by mixing water by weight of one third of class C and F fly ash and hydrated lime, and then coarse aggregate was added. Samples prepared in this manner were dried in oven at 160 °C for 24 hours and the liquid antistripping agent, with the same percentages and methods, dry and wet, was used. Therefore, samples were prepared at an optimum bitumen ratio of 6.5 % for additives (class C and F fly ash, hydrated lime, and antistripping agent). In the preparation of additive mixed samples, 1200 g of aggregate were first mixed with cellulosic fibre for at least two hours and then heated at 170°C. Bitumen was heated up to 145°C and then mixed with aggregate for about 2.0 minutes at an optimum bitumen content. At least three samples were tested for each additive.

2.3. Test methods

2.3.1. Nicholson stripping test

Stripping means that bitumen is separated from aggregate due to the effects of both water and traffic load. In Turkey, deterioration of asphalt pavements after winter season generally occurs due to an insufficient stripping resistance of aggregates. In this study, the effects of additive filler types, ratios, and mixing methods on stripping strength of asphalt binders were investigated with and without LAA. The effects of dry and wet form of fly ash (class C and class F) and hydrated lime, added at 0.5 %, 1.0 %, 2.0 % and 4.0 % of aggregate weight, on stripping strength of aggregate were determined. A total of 25 samples were tested. The Nicholson stripping test was performed according to ASTM D 1664 [32]. In this test, 600 g of aggregate, measuring 10-6.3 mm in size, were sieved at a 63 mm sieve. After sieving, aggregates retained on 6.3 mm sieve were washed and then dried in oven at 110±5 °C. Bitumen was also dried at 150±5 °C. 5 % of bitumen by weight of aggregate was added and then mixed homogenously (Figure 3a). The mixture was put in the Petri dish. The water was added on top of the mixture (about 3 cm) and the mixture was dried in oven at 60 °C (Figure 3b). Then the water in the Petri cap was

Figure 3. Stages of Nicholson stripping test: a)mixing bitumen-aggregate; b) conditioning the sample; c) observing the sample

poured and the mixture was observed by eye (Figure 3c). 60 % of aggregate left was not stripped, according to the Turkish Highway Technical Specification [33].

2.3.2. Indirect tensile strength test

The strength of asphalt mixtures depends on tensile strength of bitumen film. The indirect tensile strength test is widely used to determine behaviour of bitumen binding and bitumen matrix under load. This test was performed according to ASTM D 6931 using the Marshall stability test with the tensile apparatus at the 50mm/minute deformation rate and at 25°C. The cylindrical sample was placed between the curved loading plates and subjected to load (Figure 4). The tensile strength (σt) was calculated using the maximum breaking load (P), sample height (h), and sample diameter (d).

$$\sigma_t = \frac{2 \cdot P}{\pi \cdot h \cdot d} \tag{1}$$

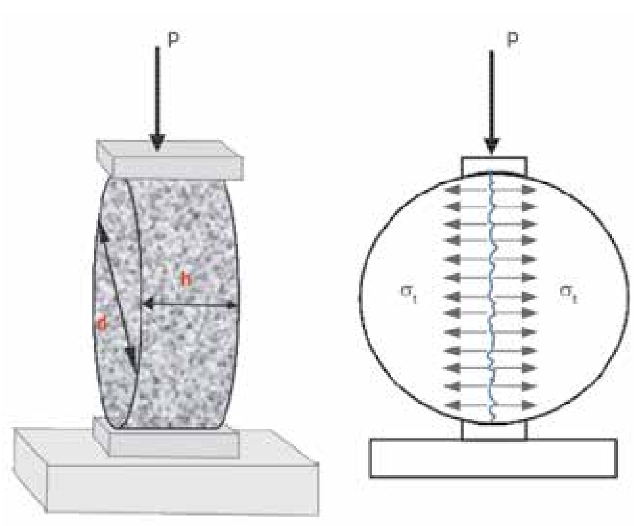

Figure 4. Indirect tensile strength test load conditions

2.3.3. Resistance to moisture damage

When water penetrates the asphalt mixture, it causes damage to the bounds between the aggregates and the asphalt binder, therefore accelerating deterioration of pavement [34]. The indirect tensile test ranks among the methods that can effectively be used to determine the effect of water on adhesion between aggregate and bitumen, and the strength of bitumen film. The moisture susceptibility test was performed according to the procedure described in AASHTO T-283. The modified Lottman test is widely used to determine water damage in asphalt pavement. In this method, the indirect tensile strength of two groups of compacted samples is determined. Conditional samples were saturated by applying vacuum for about 5 minutes (Figure 5a) and were then wrapped tightly in a plastic film layer. Then each wrapped sample was placed in a plastic bag containing 10 ml of water. Subsequently, the samples were kept inside a freezing-thawing machine for 16 hours at -18°C (Figure 5b) and for 24 hours at 60°C in a water bath (Figure 5c). Finally, the samples were subjected to an indirect tensile test after curing for 2.0 hours at 25°C in a water bath. The original strength (TSR) was calculated using the numerical index of strength ($s_{c)}$ and strength after freezing-thawing (s_{uc}).

$$TSR = \frac{\sigma_c}{\sigma_{uc}} \tag{2}$$

3. Results

3.1. Mixture design and analysis

Mixture design parameters of the control and additive mixed samples are given in Table 6. When the volumetric properties of control and additive mixed samples were examined, voids increased with an increase in filler amounts both in the mixture (VA) and between the aggregates (VMA). However, voids filled by asphalt (VFA) and unit weights decreased with an increase in filler amounts. This is due to the smaller grain size of fly ash

Figure 5. Conditioning stages of the moisture susceptibility test: a) vacuuming; b) freeze-thawing; c) heating in water bath

Table 6. SMA mixtures design and volumetric properties of SMA mixtures with additional filler

	Content of added filler [%]	OAC [%]	VA [%]	VMA [%]	VFA [%]	Density
Control mixture	0.0	6.5	4.01	16.30	75.4	2.509
Specification[a]	-	≥ 5.8	3-4	≥ 16.0	-	-
Fly ash (class C)	0.5	6.5	3.98	16.23	75.6	2.511
	1.0	6.5	4.02	16.27	75.1	2.508
	2.0	6.5	4.17	16.40	74.6	2.505
	4.0	6.5	4.32	16.53	73.7	2.498
Fly ash (class F)	0.5	6.5	3.96	16.20	75.2	2.510
	1.0	6.5	4.07	16.31	74.8	2.507
	2.0	6.5	4.37	16.57	73.6	2.497
	4.0	6.5	4.65	16.52	73.7	2.991
Hydrated lime	0.5	6.5	4.10	16.34	74.9	2.508
	1.0	6.5	4.17	16.40	74.6	2.503
	2.0	6.5	4.46	16.48	74.2	2.496
	4.0	6.5	4.99	17.10	70.9	2.483

[a]Technical specifications for the construction of highway [33].

compared to that of stone powder, and is also dependent on applying optimum bitumen content (OAC) and compaction energy. While there was not much difference between the design values of filler added mixtures, void values of 2 % and 4 % additives were above the limit value of 4 %. The additives were substituted by stone powder with different percentages and mixed with optimum bitumen of 6.5 % determined by using control specimens. Optimum bitumen ratio shows a little change due to the changes in unit weight and grain size distribution of additives used in this study. Depending on this case, void values in the mixture and between the aggregates changed by adding additive types and by increasing additive amount, as expected.

3.2. Nicholson stripping test

This test was conducted according to ASTM D 1664. The effects of additive type, amount and mixing methods on stripping strength of asphalt mixtures were determined. Pictures of mixtures prepared by mixing hydrated lime class using dry method are given in Figure 6. The best result was obtained using hydrated lime class as an additive at Nicholson stripping test. The best stripping value was obtained by adding 1.0 %-2.0 % of hydrated lime class, as shown in Figure 6. Pictures of mixtures prepared by class C fly ash additive using wet method are given in Figure 7. The best stripping value was obtained by adding 0.5 % of class C fly ash, as shown in Figure 7. Dry method gives better stripping strength results than wet method for class C fly ash additive mixtures. The addition of LAA as an additive to bitumen relatively improves stripping properties of mixtures. This improvement can not be seen in indirect tensile test values. Stripping results for other additives are given in Table 7. The addition of LAA to asphalt mixtures noticeably improves properties of samples prepared by adding both class C and class F fly ashes. The wet method is partially successful compared to lime added samples prepared by dry method. However, Using LAA with lime does not improve properties of samples. In the wet method, samples mixed with and without LAA can not be improved compared to control

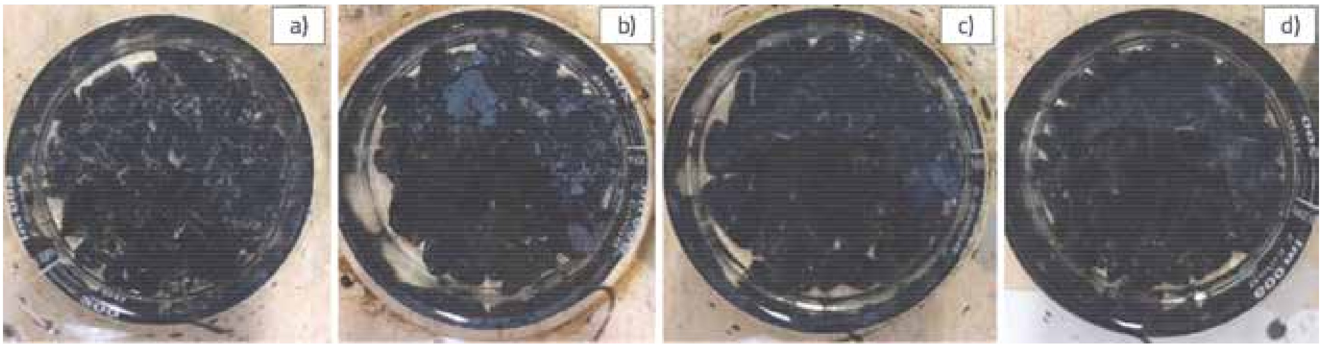

Figure 6. Nicholson stripping test of hydrated lime class without LAA for dry method: a) 0.5 %; b) 1.0 %; c) 2.0 %; d) 4.0 %

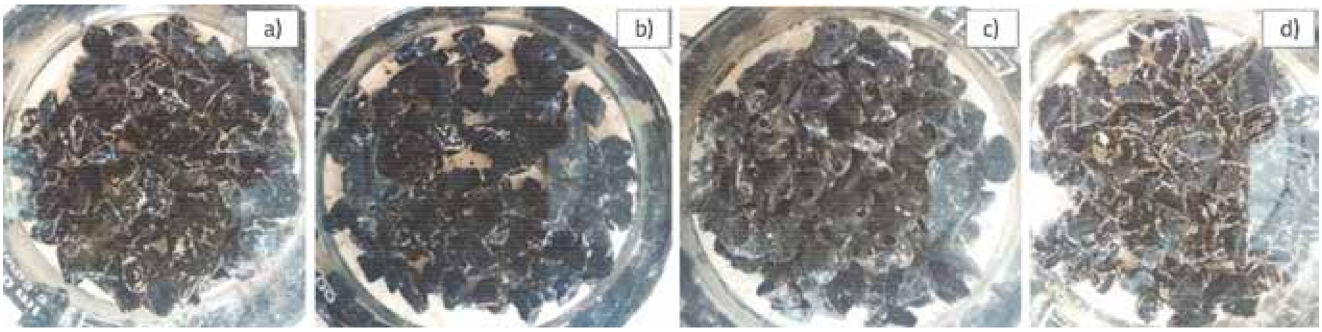

Figure 7. Nicholson stripping test of class C fly ash without LAA for wet method: a) 0.5 %; b) 1.0 %; c) 2.0 %; d) 4.0 %

Table 7. Nicholson stripping test results

Type of additive in mixtures	Content of added filler [%]	Dry method		Wet method	
		Without LAA	With LAA	Without LAA	With LAA
Control mixture	0.0	50-55	65-70	50-55	80-85
Fly ash (class C)	0.5	60-65	75-80	50-55	75-80
	1.0	85-90	90-95	75-80	85-90
	2.0	80-85	90-95	70-80	80-85
	4.0	75-80	85-90	60-65	75-80
Fly ash (class F)	0.5	65-70	75-80	60-65	70-75
	1.0	75-80	85-90	75-80	85-90
	2.0	85-90	95-100	80-85	90-95
	4.0	80-85	85-90	75-80	85-90
Hydrated lime	0.5	80-85	85-90	85-90	90-95
	1.0	90-95	90-95	95-100	95-100
	2.0	95-100	95-100	90-95	90-95
	4.0	85-90	90-95	90-95	85-90

samples. It can be observed that visual stripping areas can not be decreased on mixtures prepared using wet method with class C and class F fly ash. In the slurry method, not enough bonding formed between the fly ash and aggregate due to clumping. However, improvement can be seen on samples prepared by both types of fly ash using antistripping agent. The slurry method is partly more effective than dry method in the case of hydrated lime added mixtures. It can be observed that the use of antistripping agent with lime does not improve the stripping strength of mixtures.

3.3. Indirect tensile strength

The indirect tensile test is especially used to study the effect of bitumen film on strength properties of asphalt mixtures. Additive properties are an important parameter for bitumen film thickness. The dry method is an effective method for preparing mixtures with filler additives. The effects of filler types, filler amounts, and mixing methods on indirect tensile strength of mixtures are investigated in this section. The strength of samples prepared using LAA with fly ash and lime is also determined.

It can be seen that the strength of samples prepared by adding class C fly ash decreased compared to control specimens at all percentages using the dry method. The strength of samples prepared by adding LAA with 4 % class C fly ash increased by 15 % compared to that of control specimens (Figure 8a). When experimental results were evaluated, the strength of class C fly ash added samples prepared using dry method decreased compared to control specimens. The strength of samples prepared using LAA with 4 % class C fly ash increased by 15 % compared to control specimens. The addition of LAA to the mixtures increased in itself the strength of samples (Fig 8a). In general, the strength of samples prepared by adding class F fly ash slightly decreased compared to that of control specimens. However, 4 % added class F fly ash prepared mixtures increased the strength of samples by about 37 %. Strength values of samples prepared with LAA were more or less quite close to each other (Figure 8a). However, the strength of samples prepared using hydrated lime increased with an increase in

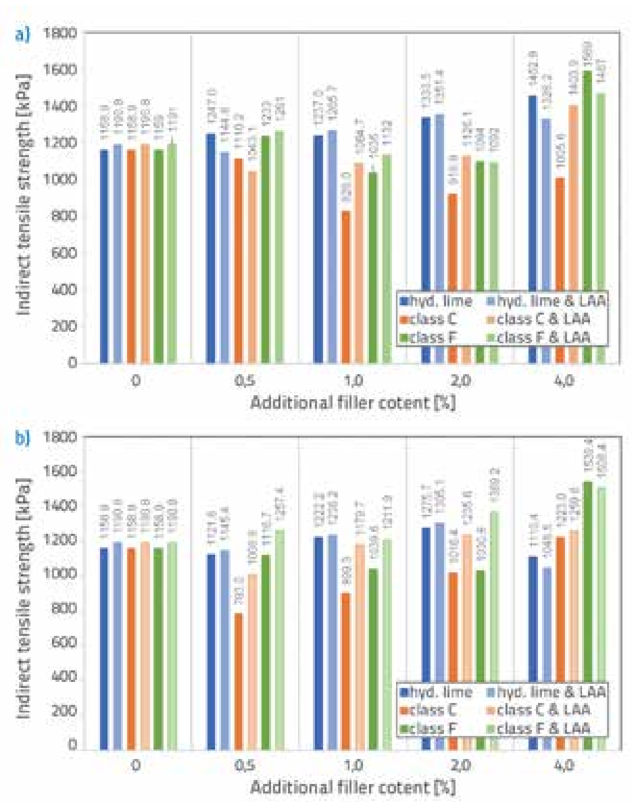

Figure 8. Indirect tensile test results: a) dry method; b) wet method

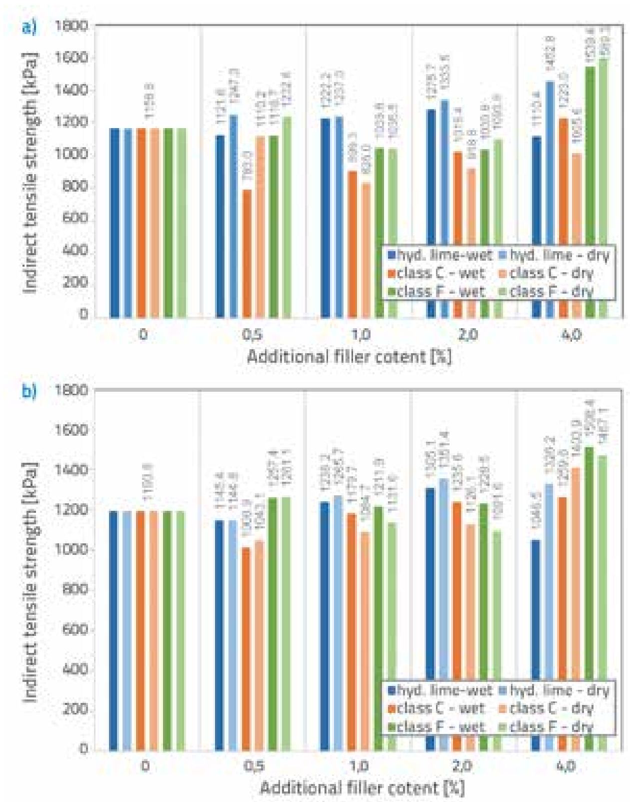

Figure 9. Indirect tensile test results of additional filler (a) without LAA (b) with LAA

additive amounts. 4 % added hydrated lime prepared mixtures increased the strength of samples by about 25 %. Adding LAA to mixtures did not significantly increase the strength of mixtures (Figure 8a). The strength of hydrated lime added samples regularly increased and the best strength results were obtained using lime added samples. However, the strength of class F fly ash (4 %) prepared mixture revealed an important jump (Figure 9a). The strength of samples prepared with class C fly ash gave the lowest value among them and was lower compared to control samples. The addition of LAA to samples prepared with class C fly ash improved the indirect tensile strength of mixtures significantly (Figure 9b).

Indirect tensile test results for samples prepared using the wet method are given in Figure 8b and Figure 9. Strength values of class C added samples (with all percentages) were lower compared to control specimens. However, the addition of 4 % fly ash (class C) increased the strength of samples. The addition of LAA to the mixtures generally improved the strength of fly ash (class C) added samples. However, the improvement was very low with the addition of 4 % fly ash (class C). The addition of LAA to the mixtures did not bring considerable improvement as compared to control specimens (Figure 8b). The strength of samples prepared with all percentages of fly ash (class F), except 4 %, using the wet method without LAA, was generally lower compared to control samples. The addition of 4 % fly ash (class F) increased the strength by 33 %. The addition of all percentages of fly ash (class F), except 4 %, using the wet method with LAA, generally improved the strength properties of mixtures (Figure 8b). In the wet method, the addition of class F and class C fly ashes generally gave lower values compared to control samples. Indirect tensile strength values of class C fly ash added samples with LAA were improved significantly. The addition of hydrated lime increased the strength of samples. However, a sudden decrease in strength was observed at samples prepared by adding 4 % of lime. This shows that the optimum value for lime is around 1.0-2.0 %. A great influence of adding LAA to the mixtures was not observed (Figure 8b).

The best results were obtained by adding all percentages of lime (except 4 %) to mixtures with LAA. The best result was obtained by adding 4 % of fly ash (class F) having 33 % of increment compared to control specimens. However, the strength of samples prepared with low percentages of fly ash (class F) was lower compared to control specimens. The strength of 4 % of fly ash (class C) mixed samples was higher by 5.5 % compared to control specimens. The strength of fly ash (class C) added mixtures had the lowest value among the additives and showed decreasing trend compared to control specimens. However, the strength dropped considerably by adding 4 % of lime to the mixtures (Figure 9a). The indirect tensile strength of fly ash added samples (class C) prepared with LAA using the wet method improved considerably. However, strength values of all added materials with all percentages, except 4 %, were more or

less close to each other (Figure 10b). The addition of class F fly ash to mixture gave a good result and it was obvious in the case of 4 % added fly ash (Figure 9b). However, the strength of 4 % lime added mixtures decreased considerably when they were prepared using the wet method (Figure 9b).
The strength of fly ash (class C) added mixtures without LAA was higher than that of mixtures prepared by using the dry method. The strength increment of samples prepared by using the wet method regularly increased after adding 1 % of class C fly ash. The strength of 4 % added samples prepared using the wet method was by 18 % higher than that of the dry method (Figure 11a). The samples prepared using the wet method with LAA gave better result than that of the dry method, except for the 4 % added samples (Figure 11b).
The highest strength results were obtained at samples prepared with class F fly ash using the wet method with LAA compared to dry method with LAA (Figure 11). However, strength results of samples without LAA prepared using wet and dry methods were quite close to each other. While the strength of lime added samples prepared using the dry method without LAA was slightly higher, this difference was eliminated in the case of LAA added specimens. The strength of samples prepared using the wet method by adding 4 % of hydrated lime was considerably lower compared to that of the dry method (Figure 11). The wet method did not improve stripping properties of asphalt specimens prepared by adding fly ash. The slurry form of fly ash did not provide enough adhesion between the particles. Therefore, agglomerated particles occurred in the mixture and these particles could not be homogenously spread into bitumen and thus the influence of fly ash was reduced.

3.4. Resistance to moisture damage

The modified Lottman test was conducted to determine sensitivity to moisture of asphalt mixtures. Indirect tensile strength values were proportioned to determine resistance of conditioned and unconditioned specimens to water damage according to AASHTO T-283. The numerical index was also calculated. Indirect tensile strength values of additives mixed samples prepared using dry method are given in figures 10a and 11. Indirect tensile strength values for 1.0 %, 2.0 % and 4 % fly ash (class C) added samples prepared without LAA were better compared to control specimens. Contrary to expectations, indirect tensile strength values of samples with LAA were lower compared to strength values of 1.0 % and 2.0 % fly ash added samples. However, 4 % fly ash added samples gave the indirect tensile strength value that exceeded the limit value of 80 % (Figure 10a). Indirect tensile strength values of fly ash (class F) added samples without LAA were by 3-4 % higher than those of samples with LAA. Indirect tensile strength values of additives mixed samples and control specimens were close to each other. However, strength values of 4 % fly ash added samples showed very low values and dropped under the limit value of 80 % (Figure 10a). Indirect tensile strength values of lime added samples decreased regularly. This cannot be seen as an improvement compared to control specimens. Moisture sensitivity values of 2.0 % and 4 % lime added samples remained under the limit values. The effect of LAA on the improvement of moisture sensitivity of samples could not be observed (Figure 10a). Indirect tensile strength values of additives mixed samples prepared using the wet method are given in figures 10b and 11. Samples prepared by adding class C fly ash without LAA exhibited better results compared to other additives. Indirect tensile test values of 0.5 %, 1.0 % and 2 % fly ash (class C) added samples prepared without LAA were better compared to control specimens. 0.5 % and 1.0 % fly ash (class C) added specimens prepared with LAA showed little improvement. Indirect tensile strength values of 4 % fly ash (class C) added specimens prepared with and without LAA remained under the limit value of 80 % (Figure 10b). Indirect tensile strength values of fly ash (class F) added samples decreased with an increase in the percent of additives (Figure 10b). Indirect tensile strength values of 4 % fly ash (class F) added samples prepared without LAA are little higher than those with LAA. Indirect tensile strength values of lime added sample regularly decreased with an increase in the percent of additives. Indirect tensile values of lime added samples prepared with LAA were lower than those without LAA. Indirect tensile strength values of lime added samples prepared with and without LAA remained under those of control specimens. Moisture sensitivity values of 2.0 % and 4.0 % lime added samples remained under the limit value of 80 % (Figure 10b).

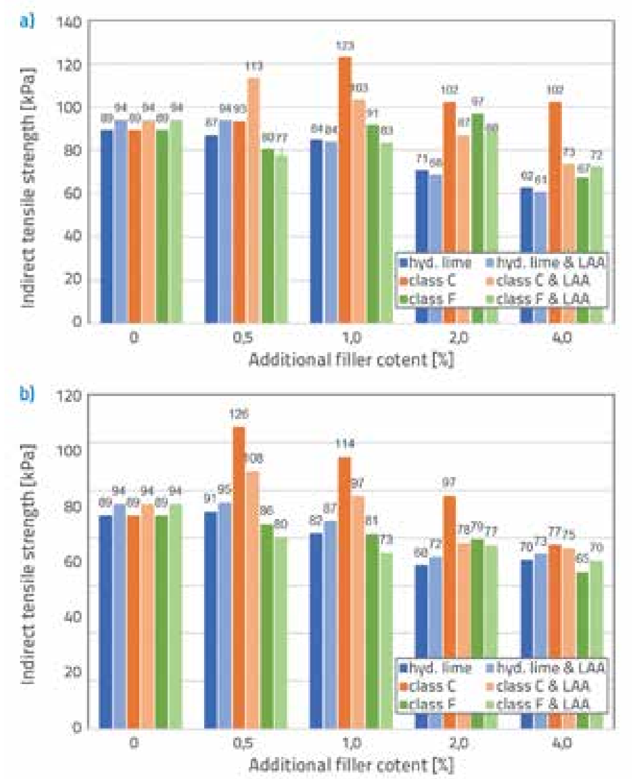

Figure 10. Indirect tensile ratio: a) dry method; b) wet method

Comparing the additives in terms of moisture sensitivity, indirect tensile strength values of fly ash (class C) added samples without LAA, except 4.0 %, exceeded 100 % and thus showed important improvement compared to control specimens. The best result was obtained at 1.0 % fly ash (class C) added sample. While the indirect tensile strength values of fly ash (class F) added samples showed little improvement, indirect tensile strength values of lime added samples decreased and had the lowest values (Figure 11a). While the indirect tensile strength values of fly ash (class C) added samples with LAA decreased, strength values of other additives added samples exhibited values similar to those of samples without LAA (Figure 11b).

When the effects of filler materials on moisture sensitivity of samples prepared using the wet method were investigated, it was established that indirect tensile strength values of fly ash (class C) added samples without LAA were better than those of samples prepared using the dry method, except for 0.5 % class C fly ash added samples. Class C fly ash added samples (except 4.0 %) showed an important improvement. The best results were obtained at 0.5 % C type of fly ash added samples prepared using the wet method and at 1.0 % class C fly ash added samples prepared using the dry method. Samples prepared using the dry method with LAA exhibited better results than those of the wet method. It can be seen that both methods give more or less similar results (Figure 11).

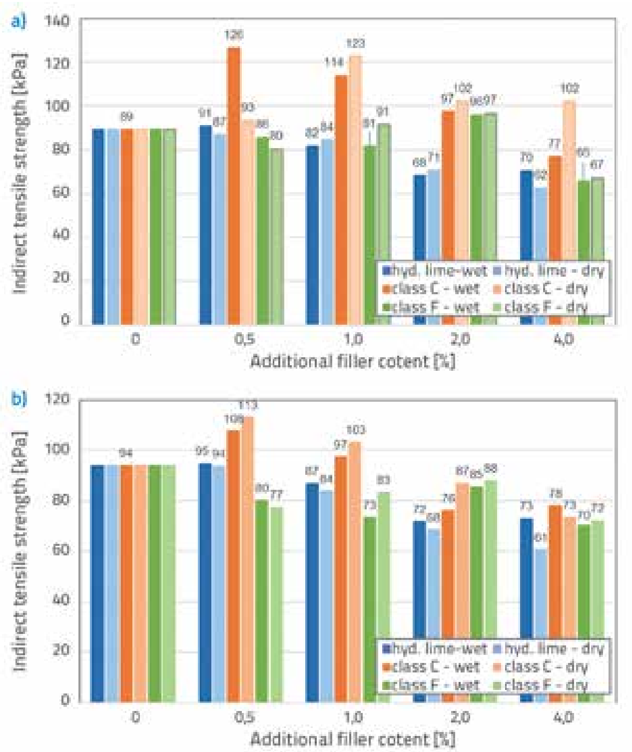

Figure 11. Indirect tensile ratio of class C fly ash: a) without LAA; b) with LAA

Indirect tensile strength values of samples improved by adding 2.0 % class F fly ash prepared samples without LAA. Indirect tensile strength values of samples prepared using dry and wet methods with and without LAA were close to each other (Figure 11a).

Indirect tensile strength values of samples decreased with an increase in the percent of lime. This phenomenon was the same for both methods. Samples prepared with LAA using the wet method exhibited better results than those without LAA (Figure 11a). In general, the effects of mixing methods in the cases of class F fly ash and hydrated lime added samples are not noticeable. The effects with and without LAA on moisture sensitivity of samples are also not noticeable.

4. Conclusion

The effects of additives, such as class C and class F fly ashes and hydrated lime, on the strength and moisture sensitivity of asphalt specimens prepared in laboratory are investigated. Some results and recommendations are given below:

- Addition of hydrated lime is more efficient compared to other additives as indicated by the Nicholson stripping resistance of asphalt specimens prepared using the dry method. However, considering other additives, stripping test results do not coincide with moisture susceptibility test results.
- According to indirect tensile test results for dry methods, the addition of lime to the asphalt mixtures prepared without LAA increases the strength with an increase in the percentage of additives. In this case, the diameter of lime particles is smaller than that of other additives. Therefore, an increase in the surface area forms fine film particles and thus indirect tensile strength values increase.
- There is only a small difference in indirect tensile test results after adding low percentages of class F fly ash to asphalt mixtures. However, the addition of 4.0 % class F fly ash greatly improves strength properties of asphalt mixtures. The addition of class C fly ash decreases the strength of samples compared to other additives. The strength of class C fly ash added samples is also lower than that of control samples. However, the addition of LAA to the mixtures prepared by adding class C fly ash improves strength properties of mixtures.
- The results show that an optimum value for lime is around 1.0-2.0 %. The addition of 4.0 % lime to the asphalt mixture during the wet method is quite a lot, and so the particles are agglomerated and adhesion cannot occur and, therefore, the strength decreases.
- Nicolson stripping resistance is relatively improved by adding a commercial liquid antistripping agent. However, moisture susceptibility obtained by indirect tensile strength values does not improve noticeably.

- While the indirect tensile strength values of unconditioned samples show low performance and relative improvement, indirect tensile ratios are above 100 %. As an additive, class C fly ash can improve moisture susceptibility of SMA mixtures.
- In general, the effects of mixing methods for class F fly ash and hydrated lime are not at a noticeable level in the moisture susceptibility test.
- The slurry (wet) method does not show an expected performance. Practical methods can be investigated to find additives that will effectively cover aggregate surface.
- It is certainly necessary to investigate the effects on the silicate composition of aggregate that is generally used in SMA.

REFERENCES

[1] Caro, S., Masad, E., Airey, G., Bhasin, A., Little, D.: Probabilistic analysis of fracture in asphalt mixtures caused by moisture damage, Transp. Res. Rec., J. of Transp. Res. Bord, 2057 (2008), pp. 28-36, https://doi.org/ 10.3141/2057-04

[2] Khodaii, A., Haghshenas, H.F., Kazemi Tehrani, H., Khedmati, M.: Application of response surface methodology to evaluate stone matrix asphalt stripping potential, KSCE J. of Civil Eng., 17 (2013) 1, pp. 117-121, https://doi.org/ 10.1007/s12205-013-1698-6

[3] Arabani, M., Hamedi, G.H.: Using the surface free energy method to evaluate the effects of liquid antistrip additives on moisture sensitivity in hot mix asphalt, Inter. J. of Pave. Eng., 15 (2014) 1, pp. 66-78, https://doi.org/ 10.1080/10298436.2013.778410

[4] Lu, Q., Harvey, J.T.: Investigations for conditions for moisture damage in asphalt concrete and appropriate laboratory test methods, University of California Pavement Research Center, Research Report: UCPRC-RR-2005-15, 2005

[5] Chen, X., Huang, B.: Evaluation of moisture damage in hot mix asphalt using simple performance and superpave indirect tensile tests, Construction and Building Material, 22 (2008) 9, pp. 1950-1962, https://doi.org/ 10.1016/j.conbuildmat.2007.07.014

[6] Park, D.W., Seo, W.J., Kim, J., Vo, H.V.: Evaluation of moisture susceptibility of asphalt mixture using liquid anti-stripping agents, Construction and Building Material, 144 (2017), pp. 399–405, https://doi.org/ 10.1016/j.conbuildmat.2017.03.214

[7] Pasandín, A.R., Pérez, I.: The influence of the mineral filler on the adhesion between aggregates and bitumen, Inter. J. of Adh. & Adhesives, 58 (2015), pp. 53–58, https://doi.org/ 10.1016/j.ijadhadh.2015.01.005

[8] Zhou, S.B., Liu, S., Xiang, Y.: Effects of filler Svojstva on the performance of asphalt mastic: A statistical analysis of the laboratory testing results, Inter. J. of Civil Eng., 16 (2018), pp.1175–1183, https://doi.org/ 10.1007/s40999-017-0272-x

[9] AbuEl-Maat,y B.A.E.: Laboratory evaluation of resistance to moisture damage in asphalt mixtures, Ain Shams Eng. J., 4 (2013), pp. 351–363, https://doi.org/ 10.1016/j.asej.2012.10.009

[10] Epps, J., Berger, E., Anagnos, J.N.: Treatments. In: Pr oCeedings of the national seminar on moisture sensitivity of asphalt pavements. Transportation Research Board, 2003

[11] Airey, G.D., Collop, A.C., Zoorob, S.E., Elliot R.C.: The influence of aggregate, filler and bitumen on asphalt mixture moisture damage, Constr. Build. Mater., 22 (2008) 9, pp. 2015–2024, https://doi.org/10.1016/j.conbuildmat.2007.07.009

[12] Jahromi, S.G.: Estimation of resistance to moisture destruction in asphalt mixtures, Constr. Build. Mater., 23 (2009), pp. 2324–2331, https://doi.org/ 10.1016/j.conbuildmat.2008.11.007.

[13] Kim, Y.R., Pinto, I., Park, S.W.: Experimental evaluation of anti-stripping additives in bituminous mixtures through multiple scale laboratory test results, Constr. Build. Mater., 29 (2012), pp. 383–393, https://doi.org/ 10.1016/j.conbuildmat.2011.10.012

[14] Nejad, F.M., Hamedi, G.H., Azarhoosh, A.: The use of surface free energy method to evaluate the mechanism of the effect of hydrate lime on moisture damage of hot mix asphalt, J. Mater. Civil Eng., 25 (2012) 8, pp. 1119-1126, https://doi.org/ 10.1061/(ASCE)MT.1943-5533.0000650

[15] National Lime Ass oCiation: How to add hydrated lime to asphalt, an overview of current methods. National Lime Ass oCiation, 2003.

[16] Fwa, T.F., Ong, B.K.: Effect of moisture in aggregates on performance of asphalt, Trans. Res. Rec., 1454 (1994), pp. 28–35.

[17] McCann, M., Sebaaly, P.E.: Evaluation of moisture sensitivity and performance of lime in hot-mix asphalt, Transp. Res. Rec., 1832 (2003), pp. 9–16, https://doi.org/ 10.3141/1832-02

[18] Gorkem, C., Sengoz, B.: Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime, Constr. and Build. Mater., 23 (2009) 6, pp. 2227-2236.

[19] Little, D.N., Epps, J.A.: The benefits of hydrated lime in HMA, National Lime Ass oCiation, 2001.

[20] Esarwi, M.A., Hainin, M.R., Chik, A.A.: Stripping resistance of Malaysian hot mix asphalt mixture using hydrated lime as filler, EASTS Inter. Symp. on Sustainable Transp. Incorp. Malaysian Universities Transport Res. Forum Conference (MUTRFC08). Universiti Teknologi Malaysia. 12-13 August, 2008.

[21] American Coal Ash Ass oCiation: Fly ash facts for highway engineers, Washington D.C., Federal Highway Administration, 2003.

[22] Rosner, J.C., Chehovits, J.G., Morris, G.R.: Fly ash as a mineral filler and antistrip agent for asphalt concrete, Challenge of change – 6th international ash utilization symposium, In: Pr oC US Dept of Energy, Morgantown, West Virginia,1982.

[23] Henning, N.E.: Evaluation of lignite fly ash as a mineral filler in asphaltic concrete. Report No. (2)-73, Twin City Testing and Engineering Laboratory, St. Paul, Minneapolis, 1974.

[24] Dougan, C.: Past and current use of recycling materials by the Connecticut Department of Transportation, Report No. 343-26-91-1, Connecticut DOT, Wethersfield, Connecticut, 1991.

[25] Ali, N., Chan, J.S., Simms, S., Bushman, R., Bergan, A.T.: Mechanistic evaluation of fly ash asphalt concrete mixtures, J. Mater. Civil Eng., 8 (1996) 1, pp. 19–25, https://doi.org/ 10.1061/(ASCE)0899-1561(1996)8:1(19)

[26] Huang, B., Shu, X., Dong, Q., Shen, J.: Laboratory evaluation of moisture susceptibility of hot-mix asphalt containing cementitious fillers, J. of Mater. in Civil Eng., (2010), pp. 667-673, https://doi.org/ 10.1061/(ASCE)MT.1943-5533.0000064

[27] Moghadas Nejad, F., Aflaki, E., Mohammadi, M.A.: Fatigue behavior of SMA and HMA mixtures. J of Constr. and Build. Mater., 24 (2010) 7, pp. 1158-1165, https://doi.org/ 10.1016/j.conbuildmat.2009.12.025

[28] Serfass, J.P., Samanous, J.: Fiber-modified asphalt concrete Svojstva, application and behavior. J. Ass oC. Asph. Pav.Tech. AAPT, 65 (1996), pp. 193-230.

[29] AASHTO T283. Standard method of test for resistance of compacted asphalt mixtures to moisture-induced damage, American Ass oCiation of State Highway and Transportation Officials, Washington, DC, USA, 2014.

[30] AASHTO T166. Standard method of test for bulk specific gravity (Gmb) of compacted hot mix asphalt (HMA) using saturated surface-dry specimens, American Ass oCiation of State Highway and Transportation Officials, Washington, DC, USA, 2016.

[31] AASHTO T 209 (2012) Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt (HMA)", American Ass oCiation of State Highway and Transportation Officials, Washington, DC, USA.

[32] ASTM D1664-80. Test method for coating and stripping of bitumen-aggregate mixtures, Annual Book of ASTM Norme, 1985.

[33] Turkish State Highways Technical Specifikacije. General Directorate of Highways, Ankara, Turkey, 2013.

[34] Shen, D.H., Wu, C.M., Du, J.C.: Performance evaluation of porous asphalt with granulated synthetic lightweight aggregate. Constr and Buil Mater., 22 (2008) 5, pp. 902-910.