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The Effect of Hydrated Lime Mixing Forms and Ratios on Performance in Asphalt Pavements

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ABSTRACT

In this study; the water damage problem and indirect tensile strengths (ITS) were investigated for different hydrated lime (HL) additive ratios and adding methods. In this regard, identical briquettes modified with hydrated lime have been produced. HL was used both in the bituminous binder (wet method) and as part of the filler aggregate. The hydrated lime was added in two different ways to form the defined equivalent ratios. By producing nine identical briquettes in each option, the values of water damage and ITS in both unconditioned and modified mixtures were compared, and the level of significance differences between the identical briquettes and mixtures was questioned. Increasing the HL content increases the standard deviation between identical samples in terms of ITS. The workability of the mixture is adversely affected by the increase in the hydrated lime ratio. When HL is mixed into the asphalt cement (AC), the standard deviations of ITS values among identical samples remain lower due to the increase in mixing rates. Increasing the ratio of adding HL to the asphalt cement reduces the ITS ratios compared to the option of adding filler to aggregate. If HL is added to the mixture in low HL content, the water damage ratios show, on average, higher water damage resistance (15% higher) than the HL being added to the AC. However, if the HL content is increased to medium and high levels, mixing HL to AC creates higher water damage resistance than adding it as filler.

Keywords: Asphalt pavements, hydrated lime, HL mixing forms, mechanical tests.

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1. INTRODUCTION

During the past 40 years, researchers from all over the world have focused their attention on the effects of hydrated lime as an active filler in the asphalt mixtures, finding that hydrated lime (HL) can actually provide many other benefits to asphalt mixtures in addition to the reduction of moisture sensitivity and to the mitigation of stripping [1].

In the United States, the use of lime as a filler in asphalt pavements is a common practice for more than hundred years. In Europe, hydrated lime is commonly used as a filler in porous asphalt pavements to decrease water damage susceptibility of mixtures. In Netherlands, for example, 90% of the highways are paved with open-graded friction course asphalt mixtures that contain hydrated lime from 1% to 2% by weight of dry aggregates [2].

The presence of HL in the filler (20% of the total filler weight), increases deformability and tensile resistance of both mastics and asphalt mixtures and decreases the creep compliance when both unmodified and modified binders are used [3]. Since lime is an effective asphalt modifier for improving the moisture resistance of asphalt pavements, it is often used as a mineral filler in asphalt concrete mixtures. Addition of lime can also improve pavement performance and durability. Hydrated lime added to asphalt can increase penetration and on the other hand can lower the viscosity of asphalt cements [4-6].

Hydrated lime is known to be an effective moisture damage additive, and it can also reduce the chemical ageing of the AC and stiffen the mastic. However, the optimum content and fineness of hydrated lime used in asphalt have been rarely studied [7].

Different laboratory testing methods and field studies have shown that HL is equal to or better than chemical anti-stripping agents and additives such as cement. However, the differences between the effects of the additives was not equally demonstrated by the different test methods. For example, the difference between additives is not remarkable when the retained Marshall stability approach is used. However, multiple freeze-thaw methods, e.g. the repeated Lottman and Texas freeze-thaw method are more differentiated test methods in addition to the Hamburg rutting tests. The use of HL in asphalt mixtures revealed long-term improvement in the mechanical properties of asphalt mixtures such as stiffness, resistance to cracking, rutting and aging [8-10].

It has been found that about 4-6% of the asphalt absorbed on the surface of the HL particles cannot be recovered and the addition of HL can significantly reduce the formation of anhydride, ketone and most carboxylic acids, thereby slowing the aging process of asphalt. It is stated that HL collects calcium ions on the aggregate surface, making the aggregate and asphalt bond closer. Using HL reduces the difference between the surface free energies of asphalt-aggregate and water-aggregate, indicating that more energy is required for stripping to occur and the rate of moisture damage is reduced. HL was used instead of mineral powder, and the test results showed that the retaining Marshall Stability (MS0) and Indirect Tensile Strength Ratio (ITSR) of the mixed material after adding HL could fully meet the specification requirement [11].

For more than four decades, hydrated lime has been a well-known material for improving the resistance against moisture and frost damage of asphaltic mixtures. The decrease of asphalt quality, as a result of the oil crisis in 1970s, made the mixtures prone to moisture and frost damage, and the modification of asphaltic mixtures by HL improved the performance of the mixtures. HL is composed of calcium hydroxide [Ca(OH)2] which is produced from quicklime by slaking it with water using a hydrator as a specific equipment.

HL was added to the mixtures by two different methods. The method of adding lime as filler, a method widely used by many institutions, has been applied. Second, HL is blended with asphalt cement. The second method is used by few researchers and even less in practice [12]. State agencies in North America estimate that by using HL at the usual range of 1–2%, the durability of asphalt mixtures in highways increases by 25–50% [13]. For lime modified mixes, ITSR and dynamic modulus |E*|, good resistance to moisture damage with the data has been established [14].

In this study; modified Lottman water damage model and indirect tensile strength test were used as an important indicator of load-spreading capacity as a widely accepted test method in evaluating water damage performance. The aim of the research is to determine how the application of hydrated lime affects the water damage and indirect tensile strength performance approaches. For this purpose, hydrated lime mixing ratios were chosen as an option and also hydrated lime was mixed with mixtures of these amounts in two different methods. Three different mixing ratios in the form of low-medium-high usage rates for hydrated lime were used as two different alternatives, both by mixing hydrated lime into filler aggregate and directly mixing into the bituminous binder. However, experimental study results are examined by using nine identical samples in each option due to the sensitivity of the study and the interpretation of the subject at the point of change of identical samples.

The use of HL in asphalt pavements showed that the performance properties of asphalt mixes such as rigidity, cracking resistance, rutting and aging were improved [8-10]. HL was used instead of mineral filler powder. According to the experimental results, it showed that the retaining Marshall Stability and Indirect Tensile Strength Ratio (ITSR) with the HL modification could fully meet the specification requirements [15]. By using HL for modification purposes normally in the range of 1-2%, it is evaluated that the durability of asphalt mixes on roads is increased by 25–50% [13]. The HL-containing samples have greater resistance to deformation at nanoscale in the mastic and matrix phases. The resistance is more pronounced in the mastic phase. There is also strong evidence suggesting that HL has the most potent effect on the mastic phase, with significant increase in elastic modulus and hardness [16]. HL is typically used as an additive to enhance the anti-stripping resistance of asphalt mixtures. As a result, HL has received the greatest share of academic attention, and its other long-term effects such as the resulting resistance against fatigue cracks have been relatively neglected. Effects of different quantities of HL (by weight of aggregate) on the fatigue properties of asphalt mixtures was investigated by four-point bending fatigue testing of unaged and aged specimens. Laboratory long-term aging procedure was carried out in accordance with AASHTO PP2 (120 h of treatment at 85 °C). Fatigue tests were conducted in strain-controlled mode with a sinusoidal load applied with frequency of 10 Hz (without rest) at 20 °C. Fatigue life was evaluated with the stiffness reduction and dissipated energy methods. Test results showed that fatigue life of asphalt mixtures is sensitive to their HL content. Addition of 1%, 1.5% and 2% of HL to mix design was found to improve the fatigue life of unaged asphalt specimens. For the aged specimens, adding of 1% and 1.5% HL increased the fatigue life by 25% and 50%, respectively, but use of 2% HL led to 40% reduction. For all asphalt mixtures, the best improvement in the fatigue life was achieved by mixes containing 1.5 of HL [17]. The addition of HL enhances the mechanical properties and durability of asphalt mixture in terms of the resilient modulus, rutting resistance, moisture susceptibility under freeze-thaw conditions, and fatigue life. HL can be used not only for anti-strip aims in the mixtures for wearing course but also in the mixtures for other structural courses to produce an integration of the improvements in mechanical and durability behaviour of pavement structures. The improvement of the mechanical properties works in a relatively wide range of weather temperatures. A high HL content does not mean a definite improvement of the durability of mixtures, because extra HL reduces the effective amount of asphalt cement, the active binder. In general, an optimum maximum of 2.5% HL content by total weight of aggregate to replace the same weight of conventional mineral filler is suggested for all practices in terms of both mechanical behaviour and durability improvement [18].

The aim of this research is to evaluate the performance of hydrated lime for low-medium-high usage rate options, depending on the method of adding it to asphalt mixtures. The use of HL as a filler aggregate in AC at different rates and its direct relationship with the AC chemistry, as well as the interaction performance between the aggregate granule and asphalt, by adding the filler to the aggregate, are important variables. It was aimed to question the hydrated lime in terms of mixing practice by considering the field plant conditions. Indirect tensile strength tests and water damage assessment methods were chosen as performance tests. Depending on the addition ratio of hydrated lime; it is considered important to investigate the homogeneity of dispersion in the mixture, the degree of dispersion, the degree of effectiveness, and its ability to fulfil its expected function. In this respect, it is planned to increase the sensitivity of the study by working on nine identical samples with the same options for the determined multiple additive options. The water damage and indirect tensile strengths of the mixtures with and without additives in the selected options are examined in the context of the benefit mechanisms of HL.

2. MATERIALS AND METHOD

In this study, asphalt cement as bituminous binder and basalt rock aggregates were used. Specific properties of bituminous binder and general physical properties of aggregates were given in Table 1 and Table 2, respectively.

Table 1 - Properties of used asphalt cement

Test	Test Method	Value
Specific gravity (25°C)	ASTM D-70	1.014
Softening point (°C)	TS EN 1427	48.4
Flash point (Cleveland)	TS EN ISO 2592	324
Penetration (25°C)	TS EN 1426	53
Retaining penetration (%)	TS EN 12607-1	72
Ductility (25°C)	ASTM D-113	100+

Dense graded aggregate combination was used in accordance with the Turkish Highways Technical Specification. Aggregate gradation used and specification limits were given in Table 3.

Table 2 - Engineering properties of basalt rock aggregates

Properties	Test Method	Value
Specific gravity (coarse agg.)	TS EN 1097-6	2.696
Specific gravity (fine agg.)	TS EN 1097-6	2.676
Specific gravity (filler)	TS EN 1097-7	2.628
Los Angeles abrasion (%)	ASTM C-131	22
Flakiness (%)	BS 812 (Part 105)	12.3
Stripping resistance (no additive) (%)	ASTM D-1664	65-70
Water absorption (%)	ASTM C-127	0.40
Soundness in $MgSO_4$ (%)	ASTM C-88	2.0

Table 3 - Aggregate gradation and specification limits

Sieve size (mm)	Specification limits (%) [19]		Aggregate gradation (%)	Aggregate fractions
	Lower limit	Upper limit		
19.0	100	100	100.0	Coarse aggregate, 52%
12.5	88	100	90.7	
9.5	72	90	80.0	
4.75	42	52	48.0	Fine aggregate, 42.5%
2.00	25	35	30.5	
0.425	10	20	14.9	
0.18	7	14	9.3	
0.075	3	8	5.5	Filler, 5.5%

In the study, the effect of adding hydrated lime (HL) additive to asphalt mixtures was investigated in terms of water damage with different additive ratios. HL can be added to the asphalt cement (AC) or aggregate mixture. Dry method; It is generally preferred because it is simpler and more economical. In the dry method, HL is added to the dry aggregate mixture (mostly filler material) at the rate of total aggregate weight. In the wet method, HL is added to the moistened aggregate mixture. In the third method, known as the slurry method, a mortar is formed by adding water to the HL and this mortar is mixed with the aggregate mixture. In the wet method and the slurry method, the moisture in the mixture is dried. Afterwards, the asphalt mixture is prepared by adding AC.

In this study, two participation methods were used for HL. In the first method, HL was added to AC with a high shear mixer. The modification process was applied at 160ºC temperature and at 5000 rpm mixing speed for 30 minutes. In this method, 10%, 20% and 30% of HL by weight of AC is used. These rates are expressed as HL10, HL20 and HL30 in the article, respectively. Modification parameters were decided in the light of previous experience and similar studies in the literature [20]. In the second method, HL was added to the dry aggregate mixture at the rates of 0.5%, 1% and 1.5%. These options were expressed as HL0.5, HL1.0 and HL1.5 respectively. The total amount of HL used for a Marshall briquette in both methods is shown in Table 4.

Table 4 - Amount of hydrated lime per briquette (gr)

Lime adding method	L10	L20	L30	L0.5	L1.0	L1.5
Amount of HL for a briquette	5.46	10.93	16.38	5.75	11.50	17.25

The important point here is the hydrated lime. It was used in three different rates of additions, which can be described as low, medium and high. In case of hydrated lime as part of filler or in AC; in the context of the selected ratios, (L10-L0.5), (L20-L1.0) and (L30-L1.5) mixtures are compared as equivalent mixtures.

Dense graded asphalt concrete design was done according to the Marshall design method. Optimum AC content was determined using base AC. The optimum AC content was taken as the percentage of AC corresponding to 4% air voids and determined as 4.75%. Optimum AC content determined by base AC was used for modified AC options. There are similar studies in the literature in which the content of base asphalt cement is used for modified mixtures or AC [21-22]. Many briquettes were produced and the mixtures were evaluated according to the Modified Lottman (AASHTO T283) method in terms of water damage resistance. Nine conditioned and three unconditioned briquettes were used for each type of mixture.

3. TEST RESULTS AND DISCUSSIONS

3.1. Indirect Tensile Strength (ITS) Test

Control and modified mixtures were evaluated by indirect tensile strength test. The test results were given in Table 5, Figure 1 and 2 for conditioned and unconditioned mixtures.

In performance analysis processes of asphalt mixtures, the sensitivity of producing identical samples is extremely important. Even when identical samples are produced under the same conditions such as the same compaction energy, the same mixture temperature, the same gradation, performance differences between identical samples may be occur. For this reason, it is important to determine the change interval between identical briquettes. The strength differences between identical samples produced for conventional mixtures may be higher than the strength differences between conventional and modified ones for some additive types and mixture designs. Here, when mixing parameters are used the same, aggregate individual properties and angularity can come to the fore. For these reasons, the production of many identical briquettes has been planned as the main subject of the study. Although gradation works were carried out in a controlled manner, differences may occur between identical samples due to the angularity parameters and various variables (such as the dispersion of the additive in the mixture, and the individual mineral characteristics of the aggregate) in the selected aggregates. In various studies, it has been observed that the performance criteria emerging between the additive and control options may be greater than the performance difference between the samples with or without additives. Therefore, it is important that the samples produced in this context are excessive and they should be evaluated with these aspects among themselves. Especially, the issue becomes more important when filler additives, such as hydrated lime, can make the mixture more rigid, as in this study.

Table 5 - Indirect tensile strength test results

Unconditioned mixtures							
Mixture	L10	L20	L30	L0.5	L1.0	L1.5	Control
Sample 1	1049.67	1111.83	1120.85	1560.97	1230.13	1162.96	828.14
Sample 2	1068.72	1081.75	1156.94	1456.71	1329.38	1089.77	841.32
Sample 3	1041.65	1154.94	1186.02	1548.94	1365.47	1138.90	881.12
Conditioned mixtures							
Mixture	L10	L20	L30	L0.5	L1.0	L1.5	
Sample 1	1018.59	1031.63	1046.66	1309.33	1182.01	1259.20	
Sample 2	1033.63	948.41	919.34	1242.16	1289.28	1083.76	
Sample 3	977.49	1030.62	1099.80	1270.23	1231.13	1075.74	
Sample 4	1017.59	1085.76	1004.56	1276.25	1229.13	1107.82	
Sample 5	985.51	1071.73	1064.71	1225.12	1226.12	1134.89	
Sample 6	1051.68	1032.63	1061.70	1318.35	1276.25	1131.88	
Sample 7	977.49	994.53	1054.68	1283.27	1233.14	1118.85	
Sample 8	1017.59	1053.68	978.49	1197.05	1301.31	1086.77	
Sample 9	1047.67	1055.69	1032.63	1341.41	1154.94	1185.02	

Experimental research was carried out on briquettes produced according to Marshall Design. Nine identical samples were prepared at each addition rate. Standard deviations between identical samples were examined. Mixtures without additives are considered as control mixtures. Many identical Marshall briquettes were produced for different additive ratios and different additive options. The performance variation between the briquettes with and without additives was questioned, and the mixtures with and without additives were compared in terms of average values. This comparison is considered important in terms of questioning the consistency of the results of the experiments and interpreting the additive performance correctly. The preparation of a large number of identical samples in terms of the selected mixture design parameters was aimed at this point. After all, two different types of lime adding; in each addition process, three different addition rates and nine identical samples were studied at each addition rate. In case HL is used both in AC and as filler, the degree of homogeneous mixture is considered important due to the increase in the additive ratio. With the increase in HL ratio, the issue of mixing especially in AC becomes more difficult. It is considered that the hydrated lime additive that is sufficient for the chemical modification of the asphalt cement reacts, but more of it remains in its present form in the mixture. Therefore, mixing time is considered important and special attention should be paid to uniform mixing time.

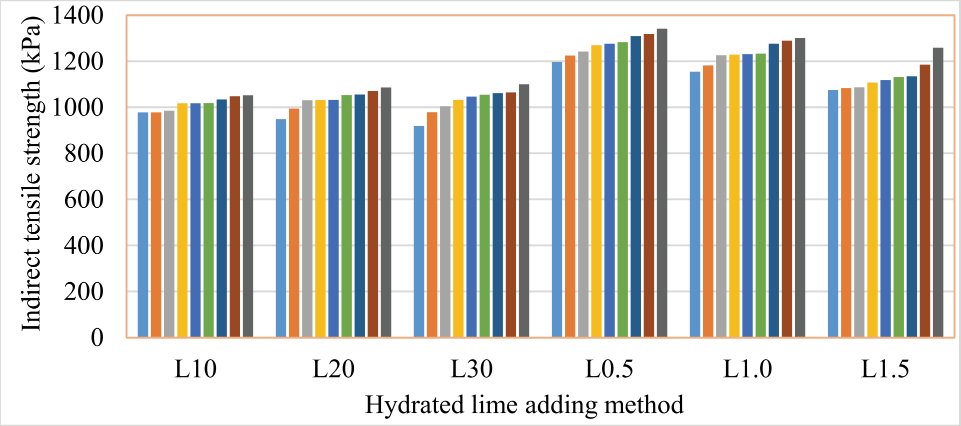

Figure 1 - Relationship between HL adding method and tensile strength for conditioned mixtures

The results obtained from the indirect tensile strength tests performed on conditioned briquettes are shown in Figure 1. ITS values of nine samples were given for each mixing ratio and type. As clearly seen from the figure, if hydrated lime is used as filler (L0.5-L1.0-L1.5), it shows higher indirect tensile strength compared to lime incorporation in the AC (L10-L20-L30).

In the method where hydrated lime is added to the asphalt cement (it is described as the wet method), the indirect tensile strength values offer similar values. This trend is valid for all three selected additive rates. Similar strength values are obtained for the selected incremental additive ratio values. In case lime is added to AC, the indirect tensile strength values seem independent of the lime ratio.

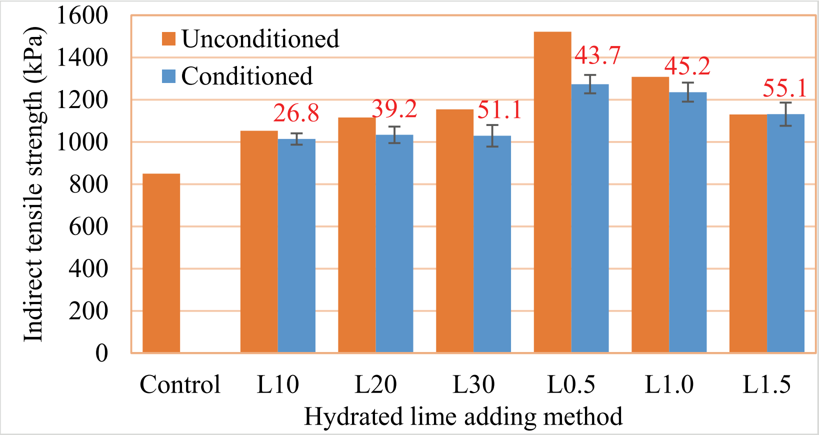

Figure 2 - Average strength of HL modified conditioned and unconditioned mixtures

The ITS values of the unconditioned and water damage conditioned briquettes are presented in Figure 2. Water damage reduces the ITS of identical samples for all mix options. HL when mixed to the filler in the low usage rate option (L0.5), it gives higher ITS values in the unconditioned and conditioned conditions. Questioning the mix performance in the conditioned situation is important to determine the water damaged performance in the field. Modified Lottman test results of conditioned briquettes have similar values when HL is added to AC (L10-L20-L30). When HL is added to the filler, the ITS values decrease with the increase of the HL content. ITS tests were carried out by keeping the same briquettes in a 25°C temperature cabinet. When ITS conditioned values are interpreted in medium temperature condition; it is recommended to add HL to the filler material at a low rate. In cases where HL may need to be used at a high rate for design; it is considered more appropriate to include fillers as part of the aggregate.

Depending on the HL adding method and the rate of HL for unconditioned samples, the standard deviation values of the tensile strengths were shown in Figure 2. With the increase of HL content, the standard deviation between identical samples increases. Asphalt mixtures are produced under the same conditions in terms of production technique. Although they are known as heterogeneous mixtures, they are produced under the same conditions as homogeneous mixtures to obtain the desired performance levels in terms of production logic. Due to the wide variety of material properties, they are seen as heterogeneous mixtures. This heterogeneity approach is in question in terms of changes in aggregate angularity values, distribution of additives in the mixture, individual properties of aggregates and especially rock mineralogy. Current studies on the application of mixtures more homogeneously both in plant conditions and in laying conditions come to the fore. Increasing standard deviation with increasing HL content reveals that due to the lime usage rate, much more attention should be paid to mixing, field laying and compaction conditions in terms of quality control because the raveling problems which may also develop in a limited amount, can trigger different damage conditions that can affect the entire pavement together.

The interpretation that the homogeneity of the mixtures was negatively affected was expressed based on the following point. While preparing identical briquettes, all mixing parameters were selected the same. Although the gradation is controlled, depending on the effect of the angularity of the aggregate and the placement of the aggregates in the mixture mortar, identical samples may reveal different results in performance approaches. For example; in questioning the performance of an additive, the difference between identical samples for the same mixtures can sometimes be greater than the average difference between conventional and modified mixtures. Various efforts are also being made to homogenize the holistic performance levels that the mixture will give, that is, to create similar mixing conditions (in the mortar structure) at the point of quality control processes. Trying to reflect the angularity issue, preferring the same mineralogical rocks, and other compatibilizing additives is considered as a situation where it is desired to give similar results at every point of the mixtures. Here, the increase in the standard deviation between samples is interpreted as differentiating the mixing conditions. The workability of the mixture is adversely affected by the increase in the hydrated lime ratio.

ITS values were performed on nine identical samples. Standard deviation between the strength values of these identical samples; for low and medium usage rates, it is smaller if the hydrated lime is mixed with AC. If the hydrated lime is mixed into AC at a low rate, the standard deviation between identical samples decreases, that is, the opportunity to produce a more homogeneous mixture. When the hydrated lime additive is used at high rates, the standard deviation value between samples exceeds 50kPa. This change (50 kPa) is valid for both addition types of hydrated lime. This result shows that asphalt mix mixing conditions are getting difficult.

The ITS values of nine samples in each option were examined. If HL is added to the fillers, higher ITS values are obtained for both unconditioned and conditioned samples. L0.5-L1.0-L1.5 mixtures, which express the incorporation of HL into the filler aggregate, and the L10-L20-L30 mixtures, which express the addition of AC (wet method) (one-to-one mixtures in terms of mixing ratio) were compared for nine samples. The range of variation of sample results was examined. These differences show that the load distribution capacity of the mixture changes. ITS values obtained for equivalent mixtures with different additive ratios were compared in terms of determining the highest and lowest variation range. Table 6-9 presents the highest and lowest limits.

The most important conclusions that can be drawn from the interpretation of the Table 9 are; in terms of indirect tensile strengths, it is more appropriate to use hydrated lime at low rates and as filler material. If hydrated lime is intended to be used at high rates as part of design analysis processes, it may be advisable to use lime in filler. Use as a high percentage of filler may be an alternative to use with a low rate of AC. However, this benchmark appears as an important issue for future research that requires research as a long-term performance problem. The method of adding to filler, according to the method of adding AC, is between 13% and 37% in the low rate of use of hydrated lime; it shows higher indirect tensile strength between 6%- 37% in medium usage rate and (- 2)% - 37% in high usage ratio. Low-medium rate in filler and low-rate use options in AC can be specified as a more accurate choice in terms of quality control. In cases where hydrated lime is compulsory or preferred for mixing into the AC in terms of central plant conditions, it is more reasonable to use it in AC in order to achieve the level of added value to filler.

Table 6 - Tensile strength ratios according to hydrated lime addition method (L10)

	L10									
	L0.5/L10	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L0.5	S. 1	1.225	1.225	1.215	1.176	1.176	1.175	1.158	1.143	1.138
	S. 2	1.253	1.253	1.243	1.204	1.204	1.203	1.185	1.169	1.165
	S. 3	1.271	1.271	1.260	1.221	1.221	1.219	1.202	1.186	1.181
	S. 4	1.299	1.299	1.289	1.248	1.248	1.247	1.229	1.212	1.208
	S. 5	1.306	1.306	1.295	1.254	1.254	1.253	1.235	1.218	1.214
	S. 6	1.313	1.313	1.302	1.261	1.261	1.260	1.242	1.225	1.220
	S. 7	1.339	1.339	1.329	1.287	1.287	1.285	1.267	1.250	1.245
	S. 8	1.349	1.349	1.338	1.296	1.296	1.294	1.275	1.258	1.254
	S. 9	1.372	1.372	1.361	1.318	1.318	1.317	1.298	1.280	1.276
	L10									
	L1.0/L10	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L1.0	S. 1	1.182	1.182	1.172	1.135	1.135	1.134	1.117	1.102	1.098
	S. 2	1.209	1.209	1.199	1.162	1.162	1.160	1.144	1.128	1.124
	S. 3	1.254	1.254	1.244	1.205	1.205	1.204	1.186	1.170	1.166
	S. 4	1.257	1.257	1.247	1.208	1.208	1.207	1.189	1.173	1.169
	S. 5	1.259	1.259	1.249	1.210	1.210	1.209	1.191	1.175	1.171
	S. 6	1.262	1.262	1.251	1.212	1.212	1.211	1.193	1.177	1.173
	S. 7	1.306	1.306	1.295	1.254	1.254	1.253	1.235	1.218	1.214
	S. 8	1.319	1.319	1.308	1.267	1.267	1.266	1.247	1.231	1.226
	S. 9	1.331	1.331	1.320	1.279	1.279	1.278	1.259	1.242	1.237
	L10									
	L1.5/L10	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L1.5	S. 1	1.101	1.101	1.092	1.057	1.057	1.056	1.041	1.027	1.023
	S. 2	1.109	1.109	1.100	1.065	1.065	1.064	1.048	1.034	1.031
	S. 3	1.112	1.112	1.103	1.068	1.068	1.067	1.051	1.037	1.033
	S. 4	1.133	1.133	1.124	1.089	1.089	1.088	1.072	1.057	1.053
	S. 5	1.145	1.145	1.135	1.100	1.100	1.098	1.082	1.068	1.064
	S. 6	1.158	1.158	1.149	1.112	1.112	1.111	1.095	1.080	1.076
	S. 7	1.161	1.161	1.152	1.115	1.115	1.114	1.098	1.083	1.079
	S. 8	1.212	1.212	1.202	1.165	1.165	1.163	1.146	1.131	1.127
	S. 9	1.288	1.288	1.278	1.237	1.237	1.236	1.218	1.202	1.197

Table 7 - Strength ratios according to hydrated lime addition method (L20)

	L20									
	L0.5/L20	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L0.5	S. 1	1.262	1.204	1.161	1.160	1.159	1.136	1.134	1.117	1.102
	S. 2	1.292	1.232	1.189	1.188	1.186	1.163	1.160	1.143	1.128
	S. 3	1.310	1.249	1.205	1.204	1.203	1.179	1.177	1.159	1.144
	S. 4	1.339	1.277	1.232	1.231	1.230	1.206	1.203	1.185	1.170
	S. 5	1.346	1.283	1.238	1.237	1.236	1.211	1.209	1.191	1.175
	S. 6	1.353	1.290	1.245	1.244	1.243	1.218	1.216	1.197	1.182
	S. 7	1.381	1.317	1.270	1.269	1.268	1.243	1.240	1.222	1.206
	S. 8	1.390	1.326	1.279	1.278	1.277	1.251	1.249	1.230	1.214
	S. 9	1.414	1.349	1.302	1.300	1.299	1.273	1.271	1.252	1.235
	L20									
	L1.0/L20	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L1.0	S. 1	1.218	1.161	1.121	1.120	1.118	1.096	1.094	1.078	1.064
	S. 2	1.246	1.189	1.147	1.146	1.145	1.122	1.120	1.103	1.089
	S. 3	1.293	1.233	1.190	1.189	1.187	1.164	1.161	1.144	1.129
	S. 4	1.296	1.236	1.193	1.191	1.190	1.167	1.164	1.147	1.132
	S. 5	1.298	1.238	1.195	1.193	1.192	1.168	1.166	1.149	1.134
	S. 6	1.300	1.240	1.196	1.195	1.194	1.170	1.168	1.151	1.136
	S. 7	1.346	1.283	1.238	1.237	1.236	1.211	1.209	1.191	1.175
	S. 8	1.359	1.296	1.251	1.250	1.249	1.224	1.221	1.203	1.187
	S. 9	1.372	1.308	1.263	1.261	1.260	1.235	1.233	1.214	1.199
	L20									
	L1.5/L20	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L1.5	S. 1	1.134	1.082	1.044	1.043	1.042	1.021	1.019	1.004	0.991
	S. 2	1.143	1.090	1.052	1.051	1.050	1.029	1.027	1.011	0.998
	S. 3	1.146	1.093	1.054	1.053	1.052	1.031	1.029	1.014	1.001
	S. 4	1.168	1.114	1.075	1.074	1.073	1.051	1.049	1.034	1.020
	S. 5	1.180	1.125	1.086	1.085	1.083	1.062	1.060	1.044	1.030
	S. 6	1.193	1.138	1.098	1.097	1.096	1.074	1.072	1.056	1.042
	S. 7	1.197	1.141	1.101	1.100	1.099	1.077	1.075	1.059	1.045
	S. 8	1.249	1.192	1.150	1.149	1.148	1.125	1.123	1.106	1.091
	S. 9	1.328	1.266	1.222	1.221	1.219	1.195	1.193	1.175	1.160

Table 8 - Strength ratios according to hydrated lime addition method (L30)

	L30									
	L0.5/L30	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L0.5	S. 1	1.302	1.223	1.192	1.159	1.144	1.135	1.127	1.124	1.088
	S. 2	1.333	1.252	1.220	1.186	1.170	1.162	1.154	1.151	1.114
	S. 3	1.351	1.269	1.237	1.203	1.187	1.178	1.170	1.167	1.129
	S. 4	1.382	1.298	1.264	1.230	1.214	1.204	1.196	1.193	1.155
	S. 5	1.388	1.304	1.270	1.236	1.219	1.210	1.202	1.199	1.160
	S. 6	1.396	1.311	1.277	1.243	1.226	1.217	1.209	1.205	1.167
	S. 7	1.424	1.338	1.303	1.268	1.251	1.241	1.233	1.230	1.191
	S. 8	1.434	1.347	1.312	1.277	1.260	1.250	1.242	1.238	1.199
	S. 9	1.459	1.371	1.335	1.299	1.282	1.272	1.263	1.260	1.220
	L30									
	L1.0/L30	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L1.0	S. 1	1.256	1.180	1.150	1.118	1.103	1.095	1.088	1.085	1.050
	S. 2	1.286	1.208	1.177	1.145	1.129	1.121	1.113	1.110	1.075
	S. 3	1.334	1.253	1.221	1.187	1.171	1.163	1.155	1.152	1.115
	S. 4	1.337	1.256	1.224	1.190	1.174	1.165	1.158	1.154	1.118
	S. 5	1.339	1.258	1.226	1.192	1.176	1.167	1.160	1.156	1.119
	S. 6	1.341	1.260	1.228	1.194	1.178	1.169	1.161	1.158	1.121
	S. 7	1.388	1.304	1.270	1.236	1.219	1.210	1.202	1.199	1.160
	S. 8	1.402	1.318	1.283	1.249	1.232	1.222	1.214	1.211	1.172
	S. 9	1.415	1.330	1.295	1.260	1.243	1.234	1.226	1.222	1.183
	L30									
	L1.5/L30	S. 1	S. 2	S. 3	S. 4	S. 5	S. 6	S. 7	S. 8	S. 9
L1.5	S. 1	1.170	1.099	1.071	1.042	1.028	1.020	1.013	1.010	0.978
	S. 2	1.179	1.108	1.079	1.050	1.035	1.028	1.021	1.018	0.985
	S. 3	1.182	1.111	1.082	1.052	1.038	1.030	1.024	1.021	0.988
	S. 4	1.205	1.132	1.103	1.073	1.058	1.050	1.043	1.040	1.007
	S. 5	1.217	1.143	1.114	1.083	1.069	1.061	1.054	1.051	1.017
	S. 6	1.231	1.157	1.127	1.096	1.081	1.073	1.066	1.063	1.029
	S. 7	1.234	1.160	1.130	1.099	1.084	1.076	1.069	1.066	1.032
	S. 8	1.289	1.211	1.180	1.148	1.132	1.124	1.116	1.113	1.077
	S. 9	1.370	1.287	1.253	1.219	1.203	1.194	1.186	1.183	1.145

Table 9 - Min. & max. strength increase rates according to hydrated lime addition method

	Min. strength increase ratio	Max. strength increase ratio	Difference
L0.5/L10	1.138	1.372	0.234
L0.5/L20	1.102	1.414	0.312
L0.5/L30	1.088	1.459	0.371
L1.0/L10	1.098	1.331	0.233
L1.0/L20	1.064	1.372	0.308
L1.0/L30	1.050	1.415	0.365
L1.5/L10	1.023	1.288	0.265
L1.5/L20	0.991	1.328	0.337
L1.5/L30	0.978	1.370	0.392

3.2. Moisture Damage Evaluation

The tensile strength ratios of the modified mixtures were calculated by proportioning the conditioned tensile strength to the unconditioned. The ratios calculated using the average tensile strengths were given in Figure 3.

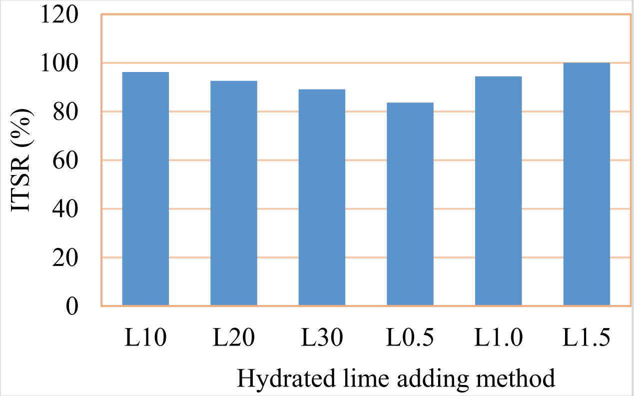

Figure 3 - ITSR – lime adding method interaction (conditioned/unconditioned)

When acceptable limit that the mixture shows sufficient resistance against water damage was taken as 80%; it can be stated that all mixtures show sufficient resistance to stripping (Figure 3). At the point of interpretation of stripping damage, if the hydrated lime is added to the AC, the resistance to water damage partially decreases with the increase in the rate of use. In terms of water damage performance, it is considered a more correct approach to add hydrated lime to AC at lower rate. But; in case the hydrated lime is added to the filler aggregate, the water damage resistance increases with the increase in usage rate. In terms of water damage resistance, it is more accurate to use hydrated lime with low AC, medium and high filler.

When used at low rates in AC, the capacity of binding and wetting the aggregate is increased, and when used with filler, it is understood that the aggregate harmonizes the surface energy and creates better binding.

In terms of average stripping resistance; with low hydrated lime content, if lime is added to the mixture (as filler), it shows higher water damage resistance (12% more) than adding the AC. However, if the hydrated lime content is increased to medium and high levels, mixing lime to AC creates lower water damage resistance than adding it as filler. It is known that hydrated lime shows its effect in the presence of water. The reactions occur with the entry of water into the mortar and reach the stability to function under the damage systems that occur over time. With the applied Lottman water damage modeling, ITSR values of all mixtures (conditional/unconditional) are given. In case the hydrated lime is added directly to the bituminous binder, according to the fillers' aggregation system, 1% higher water damage resistance at moderate rate and 11% higher water damage resistance is obtained in the upper usage rate.

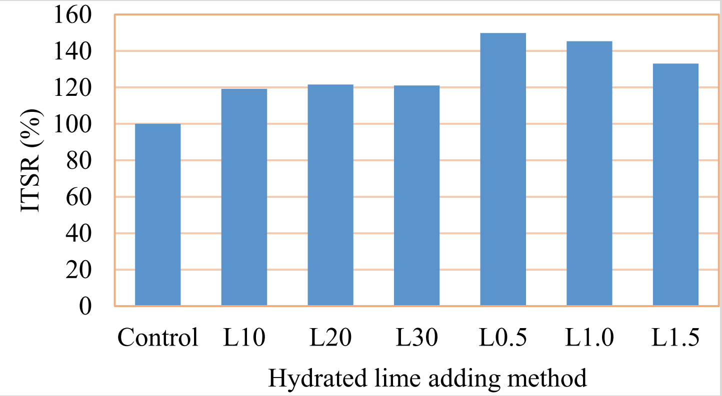

Figure 4 - Average ITSR values for all mixtures (conditioned/control-conditioned)

At the point of active and passive adhesion, the indirect tensile strength of conditioned averages of each mixture type were divided by the average of unconditioned strength values of the same mixture and stripping damage ratios were obtained. Figure 4 shows these conditioned/unconditioned ratio values. It is understood that the selected Modified Lottman water damage conditioning model creates an observable damage in all mixtures.

An evaluation was made by proportioning the conditioned strength averages of each modified mixture to the average control-unconditioned strength values of the no additive mixtures. All modified mixtures show 20% to 40% higher water damage resistance than base mixtures, as seen in Figure 5. However, if the hydrated lime is mixed with filler, there are higher water damage resistance values compared to AC, which means that there is approximately 20% more resistance.

In Figure 5, there are basic ratios expressing the interpretation of stripping damage: The hydrated lime increases the resistance of water damage in all cases, creates similar water damage resistance for all usage rates when added to the AC, and its low rate is considered sufficient, higher water damage resistances are obtained in case of addition to filler. It can be emphasized that the water damage resistance decreases as the addition rate to filer increases, and it is more logical to use it in low AC in terms of water damage resistance.

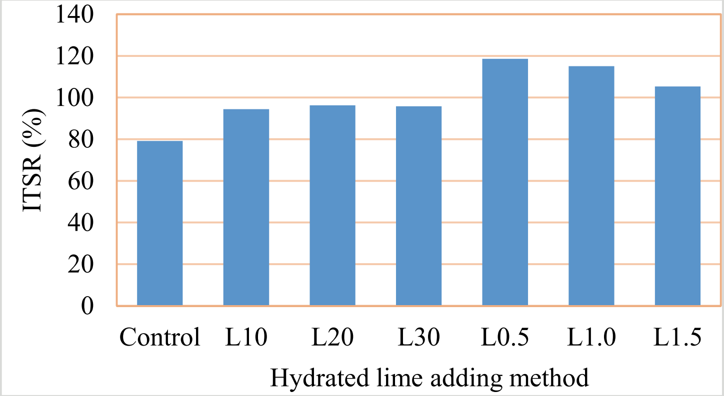

Figure 5 - Average ITSR values for asphalt mixtures (conditioned/control-unconditioned)

In low lime content, if lime is added to the mixture (filler), water damage ratios show, on average, higher water damage resistance (15% more) than lime being added to the AC. However, if the lime content is increased to medium and high levels, mixing lime to AC creates higher water damage resistance than adding it as filler. Participation in AC creates a 6% water resistance in medium use and 12% in high use. In terms of interpretation of water damage, in this study, the Modified Lottman test was used and the average of 27 values was used in each mixture; if the hydrated lime is used at a low rate, it is seen that higher values are obtained in terms of both water damage and indirect tensile strength. It is considered more reasonable to add hydrated lime to filler at a low rate under these conditions.

Asphalt mixtures modified with HL using wet method showed better performance properties as compared to mixtures modified with HL using dry or slurry method ones. This could be attributed to the best coverage of aggregate surfaces with HL in the case of wet method. Overall description aids that the wet method is better than dry or slurry methods in spite of the little effect on Marshall and water susceptibility test results when comparing all the test result and seems to provide better performance for pavement courses. Application of HL decreased the Marshall Stability values of asphalt mixtures by a little effect but increased Indirect Tensile strength by more than 10%. Wet method gave the highest ITS values with respect to method of HL application in increasing fatigue properties of asphalt. ITS ratios show that the samples have resistance against water susceptibility. Therefore, the addition of HL in all three methods improve the water susceptibility properties [21].

HL has been added to asphalt pavements for many years. HL rehabilitates asphalt pavement mixes in many ways and improves performance. It has been observed that the use of HL in asphalt mixtures is beneficial. There is still confusion as to the appropriate method for obtaining the criteria of the optimum modification of HL. Methods are discussed. HL modification is done in different ways. Mixture modifications can be made by adding dry HL to dry or wet aggregates or by adding lime mortar to dry aggregates. The mechanical and fatigue properties of asphalt mixes were evaluated using different application methods. Mechanical and simulative tests, namely ITS test, elastic modulus test and controlled stress fatigue test were applied. The overall results showed that regardless of the method of adding HL to the mixtures, the mechanical and fatigue properties were generally improved by adding HL. Mechanical test results were sensitive to the method of adding HL to mixtures, unlike fatigue tests. Mixtures modified with HL added in the form of mortar showed the best results compared to mixtures modified with HL using the dry and wet methods [23].

The performance of hot mix asphalts modified with rubber with HL additive was investigated. HL was added in three different ways: dry-wet method and mortar method. The performance of the defined mixtures was examined according to ITS, modulus of elasticity, fracture resistance, fatigue life and creep compliance. Fracture strength and fatigue life were determined using the semi-circular bending test and split tension-controlled stress fatigue test, respectively. A power law model was used to characterize the creep compliance behaviour of the studied asphalt mixtures. The crumb rubber content of 15% by weight of the bituminous binder and the HL content of 3% by weight of the total mixture were included for all samples tested. The test temperature was kept constant as 35°C. HL treatment increased ITS, hardness, fatigue strength, fracture resistance and permanent deformation properties of rubber modified HMA blends. The mixtures contain HL added using the wet method, meeting the highest ITS, modulus of elasticity, fracture resistance and lowest creep compatibility. The fatigue life of the mixtures tested showed less dependence on the HL application method [24].

One of the common anti-stripping additives, HL, is considered to improve the properties of asphalt mixture in resisting water damage. The HL application process can be introduced to asphalt mixture by either adding dry HL to wet aggregates or adding HL slurry to dry aggregates. This study goals to evaluate the laboratory performance-based properties of asphalt mixtures using two different HL application processes as well as to compare between HL-modified and polymer modified asphalt mixture. Results showed that the performance of HL modified asphalt mixture in moisture damage and rutting resistance is related to the HL application processes. Adding HL to asphalt binder is an effective and economical method to improve performance of asphalt mixture in moisture damage and rutting resistance [25].

HL has traditional been preferred in asphalt mixtures primarily for increasing the water damage resistance of bituminous mixtures. Most available literature is about studies realized on mixes in which HL was added as filler material. It was explored that the effect of different proportions of HL added by two different methods (wet and dry methods) on the rutting performance of bituminous mixes. The rutting characteristics of unmodified and HL modified binders were evaluated in terms of superpave binder rutting parameter ($G*/\sin\delta$) and non-recoverable creep compliance. Mix rutting performance was measured in terms of $E*$, $E*/\sin\varphi$, flow number and accumulated strain measured in dynamic creep test. Rutting performance of mixes improved significantly by HL modification. Wet method of addition of HL has significantly higher beneficial effect than the dry method. Flow number determined at 60°C showed the beneficial effect of HL more distinctly compared with the dynamic creep test conducted at 40°C. The beneficial effect of HL addition in reducing rutting was realized more at higher mix temperatures [26].

The use of both HL addition methods exhibited a good resistance against the moisture damage, an increase in ITSR is achieved by 4.2%, 5.3%, 5.9% 10.9%, 12% and 9.0% for dry

HL replacement method and 3.4%, 6%, 18.8%, 20.8% and 19.8% for wet HL replacement method corresponding to 1.0, 1.5, 2.0 and 3.0 HL contents, respectively. The wet addition method was more effective than the dry method in improving the resistance to moisture induced damage of asphalt concrete pavement modified with HL. The permanent deformation parameters, slope and intercept, was significantly affected using dry and wet HL addition methods employing different percentages of HL and this effects are more pronounced at high testing temperatures. The HL modified mixed with 2.5 percent in dry method and wet method result in a decrease in permanent deformation slope at higher temperature of 40°C and 60°C as compared to control mixture with no HL [27].

Depending on the methods of adding hydrated lime to asphalt mixtures and different addition rates in different adding methods; in the point of evaluating of proportional water damage based on indirect tensile strength test and Lottman water damage conditioning, the discrimination of the selected methodologies was found to be superior.

The effectiveness of hydrated lime additive, which is a performance enhancer in asphalt pavements, is directly related to the degree of performance, the method of adding the mixes and the ratio of addition. Hydrated lime reveals different performance levels according to the method of addition.

In terms of average water damage rates; When lime is added to the mixture at low lime content, it shows higher water damage resistance (15% more) than AC. However, if the lime content is increased to medium and high levels, mixing lime into AC creates higher water damage resistance than adding lime as filler. Inclusion in AC, according to filler joining aggregate; it creates 6% higher water damage resistance in medium use and 12% higher in high use. It is considered more logical to add hydrated lime to the filler at a low rate under these conditions. It appears that the Lottman water damage conditioning model chosen causes observable damage to all mixtures. Hydrated lime increases the resistance to water damage in all cases, creates similar water damage resistance for all usage rates in case of AC addition, and its low rate is sufficient, higher water damage resistance is obtained in the case of adding to filler, water damage resistance decreases with the increase of the added ratio to filler, water damage, it can be emphasized that it is more logical to use it in low AC in terms of resistance.

Depending on the methods of joining hydrated lime into asphalt mixtures and different additive rates in different addition methods; The discrimination of the selected methodologies was found to be superior at the point of interpretation of proportional water damage based on the indirect tensile strength test and Lottman water damage conditioning. The efficiency of the hydrated lime additive used, which is a performance enhancer in asphalt pavements, is directly related to the degree of performance, the method of addition to the mixtures and the rate of addition. Hydrated lime reveals different performance levels according to the addition method.

4. CONCLUSIONS

With this research, it is possible to reach the following conclusions.

The use of HL as a part of the AC gives higher ITS values. HL increases ITS values. If HL is used as part of the fillers, ITS values decrease for HL ratios increasing from low to high. It is considered appropriate to use HL as a part of filler at a low rate.

The increase in the standard deviation in terms of performance between identical samples with the increase of the HL rate requires attention to the quality control process in terms of field conditions. HL should be used at a low rate in AC.

Although low use of AC seems to be equivalent to high use in fillers, the issue should be examined in terms of long-term performance, for example, fatigue strength.

Increasing use of HL in AC reduces water damage resistance. Increasing use with filler increases water damage resistance. It is recommended to use with AC at a low rate and with filler for medium-high rates. Using with AC at a low rate creates a more homogeneous mixture.

Modified Lottman water damage conditioning reduces ITS values and gives distinctive results.

Symbols

AC : Asphalt cement

HL : Hydrated lime

HMA : Hot mix asphalt

ITS : Indirect tensile strength

ITSR : Indirect tensile strength ratio

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