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Effect of Mastic Properties on Moisture Damage and Adhesive Failure Mechanism in Asphalt Mixtures

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ABSTRACT

Moisture damage reduces the mechanical properties of asphalt mixture *via* two main mechanisms (cohesion and adhesion failures). Accordingly, attempts were made in this research to investigate the effect of different mastic properties on parameters affecting adhesive failure mechanism. Two types of aggregate (limestone and granite) and four types of filler (stone powder, Portland cement, calcium carbonate and hydrated lime) were evaluated, in addition to AC 60/70 and 85/100 as asphalt binders. Results obtained in this research show that stone powder and Portland cement fillers increase acid components of binder, but calcium carbonate and hydrated lime fillers show a different behavior (reducing acid components in binder 60/70 and increasing acid property in binder 85/100). In addition, the use of binder causes a reduction in non-polar component. Results obtained by statistical analysis show that changing mastic type changes free energy of adhesion, but stripping parameter will not change significantly.

KEYWORDS: HMA, Moisture damage, Mastic properties, Surface free energy, Stripping, Adhesion.

INTRODUCTION

The pavement structure can bear loads to some extent. However, exceeding the limit leads to permanent deteriorations of the pavement, such as potholes, surface deformation, longitudinal cracking, fatigue cracking, edge defects, patching and rutting. To solve these problems, new techniques and material types for the road pavement structure need to be established (Ibrahim et al., 2016). Asphalt binder is very important as a binder material in asphalt concrete. Highway professionals are looking for modifiers to decrease rutting, fatigue and other distresses of asphalt mixtures (Ghuzlan and Al-Assi, 2016; Liu and Wu, 2017).

One of the most common damages in asphalt mixtures is due to destructive effects of moisture on the cohesion of asphalt binder and adhesion of asphalt binder-aggregate called moisture damage (Zhang et al., 2017). In this regard, the analysis of adhesion failure mechanism has more sensitivity. Because in addition to all three constitutive phases of asphalt mix (bitumen, aggregate and filler) having influence on its occurrence, secondary factors, such as moisture entrance into the asphalt mix, also affect this mechanism (Pasandín and Pérez, 2015). A number of studies have been conducted to investigate the effect of fillers on the adhesive and cohesion failure mechanisms. Roberts et al. (1996)

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found that using mineral fillers in HMA enhances asphalt mixture performance, because fillers fill the voids in the aggregate skeleton to create a denser mixture, improving the cohesion of asphalt binder and the stability of the mixture. In addition, results obtained by other researchers show that cementitious fillers cause a reduction in moisture sensitivity of asphalt mixtures (Nejad et al., 2012; Hesami et al., 2013; Hamedi et al., 2015; Hamedi et al., 2016). The importance of fillers in moisture sensitivity has caused debates related to thermodynamic theory to be entered into this area of science parallel to these research studies.

Cheng (2002) investigated surface free energy (SFE) concepts and their application in asphalt mixtures. He observed that thermodynamic changes in SFE of adhesion and cohesion lead to the loss of strength of the interface of aggregate and binder. After conducted research studies which were mostly toward validation *via* thermodynamic method, next studies entered into a new phase with an approach of the effect of properties of materials in asphalt mixture on moisture sensitivity. Regarding this issue, in a research study, Fe_2O_3, Al_2O_3 and TiO_2 have been used on the nano-scale; it was observed that these materials have positive effects on thermodynamic parameters and have caused an improvement in the resistance against moisture (Azarhoosh et al., 2016). Alvarez et al. (2012) used SFE to show the effect of adding mineral fillers (sand, basalt and lime stone) on the binder. In this research, it was observed that changes in energy parameters vary in aggregate-mastic system and depend on different combinations of binder, aggregate and filler, which finally lead to changes of resistance against fracture and moisture damage in mastic-aggregate system.

Research Objectives

Despite the mentioned importance of the impact of materials on the adhesion failure mechanism, previous research did not pay much attention to the influence of mastic types on the effective factors in the occurrence of adhesion failure. The most important desirable goals of this research include:

- Investigating the effect of mastic properties on thermodynamic parameters affecting mastic-aggregate adhesion (active adhesion state);
- Investigating the effect of mastic properties on thermodynamic parameters of stripping in asphalt mixtures (passive adhesion state);
- Determining the amount of dependency between mastic properties and parameters affecting adhesive failure.

Research Methodology

It is noteworthy that for each aggregate blend and asphalt binder, at least three separate samples were produced to determine the reproducibility of the results.

Materials

Two types of aggregate, including lime (basic) and granite (acidic) aggregates, are used in this study with different sensitivities to moisture damage. Asphalt binders of 60/70 and 85/100 penetration grade from the Isfahan mineral oil refinery were used. Four different fillers were used in this research, including stone powder, calcium carbonate, hydrated lime and Portland cement.

Tests

Wilhelmy Plate Test

In order to measure the SFE energy components of binder or mastic, WP test can be used. In this method, a glass plate coated with binder and hanging from an accurate balance is soaked into a specific liquid with a constant and slow speed and then is withdrawn, so that the contact angle between liquid and glass plate is formed.

Universal Sorption Device Test

USD method is one of the common methods used to obtain the SFE of porous and irregular materials using dynamic absorption technique. In this method, the given sample and probe molecules are investigated as the constant and mobile phases, respectively.

RESULTS

Effect of Mastic on Parameters Related to Adhesion

Considering previous research conducted on this issue, it was found that the type of mineral constituting the aggregate has a significant effect on the amount of water absorption (Liu et al., 2018). In addition, it has been approved that any change in acid and base components can influence adhesion (Khodaii et al., 2013). Accordingly, attempts have been made to address stripping potential by evaluating the strength rate of asphalt mixtures in the presence of water and investigating the effect of mastic properties on polar (acid-base) and non-polar (Lifshitz-van der Waals) components.

Acid-Base Component

According to the results shown in Figure 1, it is observed that this parameter has the maximum value in the mastic containing stone powder filler and using this filler causes an increase in binder 60/70 and binder 85/100 by 46 % and 33% compared to the basic state, respectively, indicating the greater affectability of binder 60/70. In addition, it is observed that using calcium carbonate and hydrated lime fillers causes a slight reduction in binder 60/70 and a slight increase in binder 85/100 (compared to the basic state), but using Portland cement filler only causes an increase in this parameter in binder 60/70.

Fillers used in this research, except stone powder, all have basic properties, because their pH is higher compared to the neutral state (the acidity level of the neutral state is equal to 7).

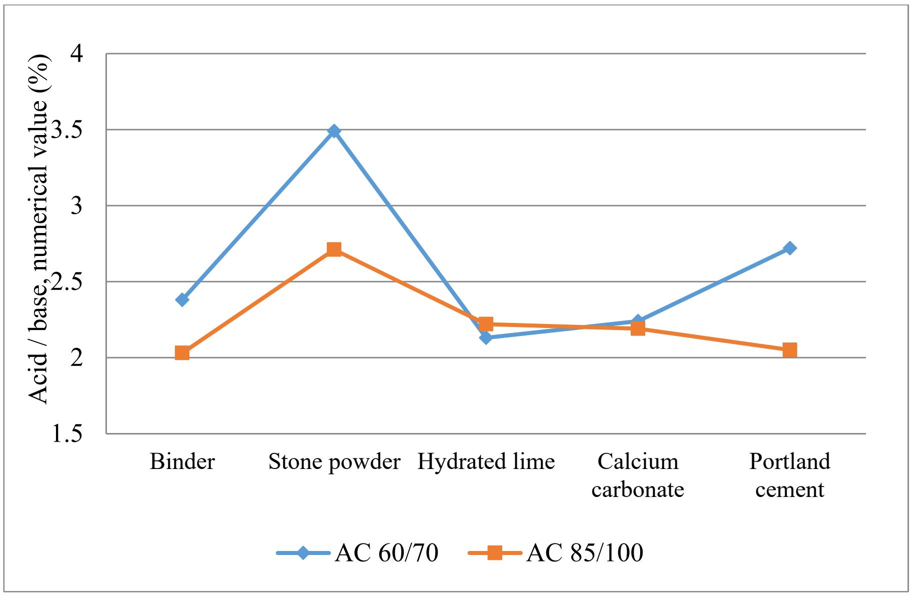

Figure (1): Numerical value of acid/base in different types of mastic and binder

Non-polar Component

As the link formed between the aggregate and binder is mainly due to non-polar dispersion forces, it can be concluded that an increase in the amount of non-polar component of SFE can improve the adhesion between aggregate and binder. Accordingly, based on the data presented in Figure 2, it is concluded that mastics containing calcium carbonate and hydrated lime whose non-polar component is lower than those of other mastics will have less adhesive force. In addition, it is observed that fillers have reduced this component in general and hydrated lime and calcium carbonate have the most reduction in binders 60/70 and 85/100 by 46% and 34%, respectively. The pH values of fillers used in this research, especially hydrated lime and calcium carbonate, are significantly higher than that of base asphalt binder, which has relatively acidic properties. This factor causes more polar bonds to be formed. On the contrary, the bond of base bitumen, which is a relatively non-polar material, is of covalent type, which leads to a relatively large non-polar component.

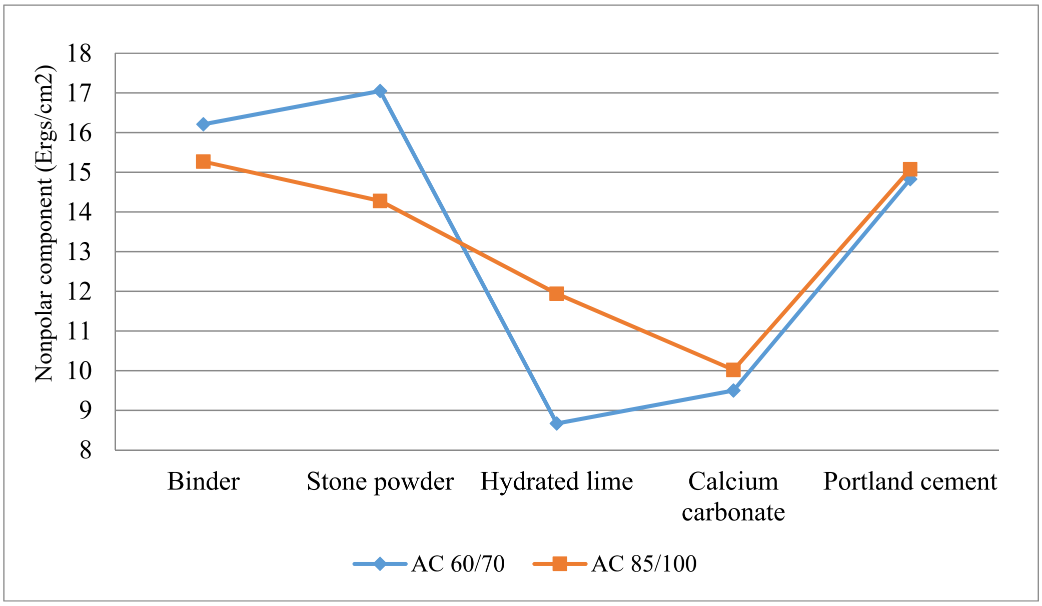

Figure (2): Non-polar component in different types of mastic and binder

Free Energy of Adhesion

The important point related to adhesion issue in asphalt mixtures is that in addition to molecular attractive force, other factors such as mechanical locks and fasteners have a significant effect on this parameter. But, according to the analysis conducted in the form of comparison between groups containing the same corresponding aggregates, the effect of this factor on the result is not so significant. In other words, as the aggregates used in different groups are similar to each other, factors affecting adhesion (porosity, degree of roughness of aggregate surface, … etc.) have not been taken into account in comparative investigations. It should be noted that direct investigation of free energy of adhesion parameter has not been considered and presenting this parameter is only to achieve accurate results in statistical investigations.

Considering that the main objective of this research is to investigate the role of different common mastics on parameters affecting adhesive failure mechanism in the two active and passive states, these cases are investigated using statistical analysis as follows:

1. Is the change in the free energy of adhesion related to the type of filler? Are changes that occur in free energy of adhesion by adding various types of filler insignificant?
2. To which type of mastic are the highest and the lowest differences in the free energy of adhesion related?

One-way analysis of variance (ANOVA) is a suitable solution to investigate the above mentioned objectives, because in this analysis, the means of quantitative features are compared in three or more than three groups. In ANOVA, if the null hypothesis is rejected, at least two means will have a significant difference. In addition, tests should be carried out between all pairs of means to determine which of them are significantly different from each other. In the current research, Tukey's test was used to determine this difference.

Before performing ANOVA, it is necessary to assure homogeneity of groups.

Considering the obtained sig. value in the ANOVA output which is equal to 0.007 and is smaller than 0.05, the null hypothesis indicating the mean equality of free energy of adhesion is rejected. Therefore, it can be concluded that the mean values of adhesion free energy in groups 1, 2, 3 and 4 are not equal. However, it cannot be definitively determined which groups have different means. For this purpose, Tukey's HSD test was used. Results are shown in Table 1.

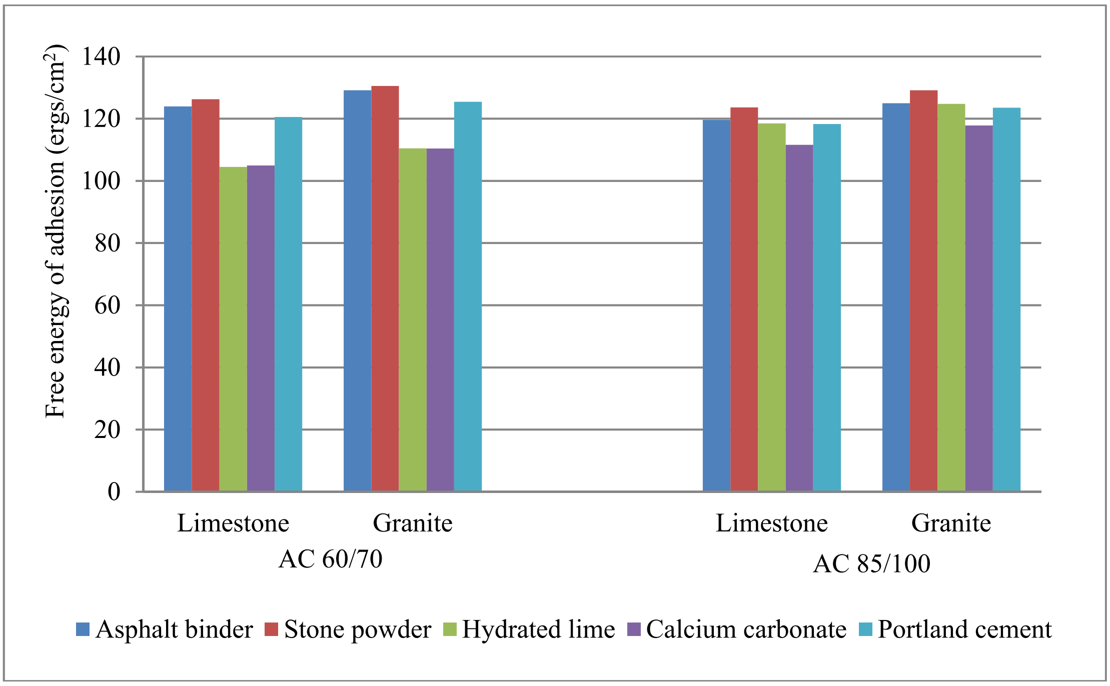

Figure (3): Mastic-aggregate free energy of adhesion

Table 1. ANOVA output about free energy of adhesion

Method: ANOVA	Sum of squares	df	Mean square	F	Sig.
Between groups	638.937	3	212.979	6.719	0.007
Within groups	380.373	12	31.698		
Total	1019.310	15			

As mentioned, Tukey's test was used to more exactly investigate and compare corresponding groups shown in Figure 3. Results are presented in Table 2. In this table, the mean values are compared to each other and the sig. value or the level of significance for each of them is presented in each row. For example, row 1 of this table shows the comparison of the two means of groups 1 and 2. The sig. value is obtained to be 0.032. As this value is smaller than 0.05, there is a significant difference between these two means. Similarly, other results are interpreted. Therefore, it can be concluded that the highest difference in the mean values of adhesion free energy is between groups 1 and 3 with a significance level of 0.007, referring to mastics containing stone powder and calcium carbonate fillers, while the lowest difference in the mean values of adhesion free energy is between groups 2 and 3 with a significance level of 0.835.

Table 2. Multiple comparisons between the four groups

Method: Tukey HSD						
(I) Reduction	(J) Reduction	Mean difference (I-J)	Std. error	Sig.	95% Confidence interval	
					Lower bound	Upper bound
1	2	12.85750	3.98106	0.032	1.0381	24.6769
	3	16.20000	3.98106	0.007	4.3806	28.0194
	4	5.45500	3.98106	0.540	-6.3644	17.2744
2	1	-12.85750	3.98106	0.032	-24.6769	-1.0381
	3	3.34250	3.98106	0.835	-8.4769	15.1619
	4	-7.40250	3.98106	0.295	-19.2219	4.4169
3	1	-16.20000	3.98106	0.007	-28.0194	-4.3806
	2	-3.34250	3.98106	0.835	-15.1619	8.4769
	4	-10.74500	3.98106	0.079	-22.5644	1.0744
4	1	-5.45500	3.98106	0.540	-17.2744	6.3644
	2	7.40250	3.98106	0.295	-4.4169	19.2219
	3	10.74500	3.98106	0.079	-1.0744	22.5644

Effect of Mastic on the Potential of Stripping

Considering the data presented in Figure 4, it is obvious that mastic containing stone powder filler has the most critical conditions compared to other mastics. However, in compounds containing binder 60/70, other mastics have caused an improvement in stripping potential and in compounds containing 85/100 binder, mastics with calcium carbonate and Portland cement fillers have created positive changes in the process of stripping. It should be noted that in the case of 60/70 binder, mastics containing hydrated lime and carbonate calcium fillers have exhibited the best performance with a reduction of 13% in the stripping potential.

In this part, considering the importance of the stripping potential adhesion free energy in the process of moisture damage, the difference amount of this parameter occurred due to the use of various fillers in the investigation. Accordingly, as mentioned in the investigation of free energy of adhesion, the homogeneity of groups should be first investigated. Considering the obtained sig. value which is equal to 0.0895 and greater than 0.05, it can be concluded that the variance over samples is homogeneous.

Considering the obtained sig. value in the ANOVA output which is equal to 0.085, the null hypothesis indicating the mean equality of stripping potential is rejected at $\alpha = 0.01$. Therefore, it can be concluded that the mean values of stripping potential in groups 1, 2, 3 and 4 are not equal at $\alpha = 0.01$. However, it cannot be definitively determined which groups have different mean values. For this purpose, Tukey's HSD test was used. Results are presented in Table 3.

Similar to the previous state, in order to more accurately investigate and correspondingly compare groups mentioned in Figure 4, Tukey's test was used. Results are presented in Table 4. As it can be observed, there is a significant difference between groups 1 and 3 at the level of $\alpha = 0.01$ and the mean values of stripping parameter show no significant differences between other groups.

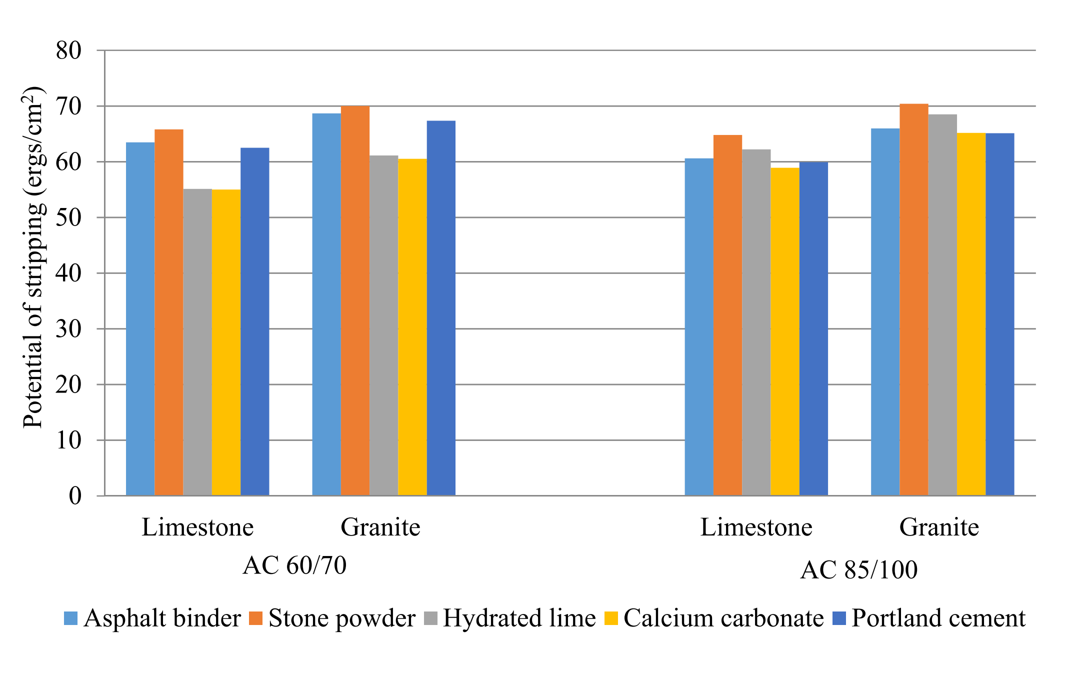

Figure (4): Potential of stripping

Table 3. ANOVA output about potential of stripping

Method: ANOVA	Sum of squares	df	Mean square	F	Sig.
Between groups	137.672	3	45.891	2.807	0.085
Within groups	196.188	12	16.349		
Total	333.859	15			

Table 4. Multiple comparisons between the four groups

Method: Tukey HSD						
(I) Reduction	(J)Reduction	Mean difference (I-J)	Std. error	Sig.	95% Confidence interval	
					Lower bound	Upper bound
1	2	6.12500	2.85910	0.195	-2.3634	14.6134
	3	7.87500	2.85910	0.072	-0.6134	16.3634
	4	4.12500	2.85910	0.499	-4.3634	12.6134
2	1	-6.12500	2.85910	0.195	-14.6134	2.3634
	3	1.75000	2.85910	0.926	-6.7384	10.2384
	4	-2.00000	2.85910	0.895	-10.4884	6.4884
3	1	-7.87500	2.85910	0.072	-16.3634	0.6134
	2	-1.75000	2.85910	0.926	-10.2384	6.7384
	4	-3.75000	2.85910	0.573	-12.2384	4.7384
4	1	-4.12500	2.85910	0.499	-12.6134	4.3634
	2	2.00000	2.85910	0.895	-6.4884	10.4884
	3	3.75000	2.85910	0.573	-4.7384	12.2384

CONCLUSIONS

As the properties of filler in asphalt mixture can play an important role in moisture sensitivity, attempts were made in this research to investigate the role of different types of mastic in the potential of durability and resistance against adverse effects of moisture.

The most important results obtained by this research include:

- Mastics containing carbonate calcium and hydrated lime have a weak acid property and this has negative effects on adhesion. It should be noted that the increase amount of this parameter due to adding stone powder filler is about 46% and 33% in 60/70 and 85/100 binders, respectively.
- With 46% and 34%, hydrated lime and calcium carbonate have the maximum reduction in non-polar component of 60/70 and 85/100 binders, respectively.
- The highest difference in the free energy of adhesion is between mastics containing stone powder and calcium carbonate filler with a significance level of 0.007 and the lowest difference is between mastics containing hydrated lime and calcium carbonate with a significance level of 0.835.
- Mastic containing stone powder filler has the most critical conditions of stripping parameter compared to other mastics, whereas in compounds containing binder 60/70, other mastics have caused an improvement in stripping potential. In compounds containing 85/100 binder, mastics with calcium carbonate and Portland cement fillers have caused positive changes in the process of stripping.
- In the case of 60/70 binder, mastics containing hydrated lime and calcium carbonate fillers have shown the best possible situation for the potential of stripping.
- In contrary to adhesion free energy, different mastic types have no significant effect on the stripping parameter.

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