Investigation of the effect of using preheated aggregate and modified binder on chip seal adhesion properties

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ABSTRACT

Chip seal constructed on a compacted granular base are widely used in Turkey, South Africa, Australia, New Zealand, England, etc. Especially, a significant portion of 40183 km of Turkey's 67333 km road network consists of chip seal roads. Chip seals are also used for deterioration preventive maintenance purposes for bituminous hot mix asphalt. The performance of the chip seal can be affected by numerous factors before and after construction. The adhesion performance of the aggregate in the chip seal is significantly affected by the traffic volume of the road, its location, climate, the nominal size of the applied aggregates and the construction method, etc. In this study, three types of aggregates and two types of bitumens were used. Also, bitumen samples were modified with Poly Phosphoric Acid (PPA) at three different percent (at 0.5%, 1.0 and 1.5% by weight) so totally eight type bitumen samples were used. The effect of using heated aggregates at four different temperatures (80 ^oC, 90 ^oC, 100 ^oC, 120 ^oC) on the adhesion performance of chip seal was investigated by Vialit adhesion and Nicholson stripping tests. Besides, a benefit/cost (B/C) analysis of the improvement of adhesion due to heating the aggregates and modifying the bitumen with PPA in the chip seal application was performed. It was understood that the heating of the aggregates and the PPA additive played a healing role on the adhesion. It was concluded that the use of preheated aggregates provides a higher B/C value than the use of PPA additives. The most important reason for this is that the unit cost of the PPA additive is higher than the aggregate heating cost

and the adhesion performance is as good as the PPA added bitumen.

Keywords: Adhesion; Bitumen; Chip seal; Preheated aggregate; Vialit adhesion test.

1. INTRODUCTION

Chip seals are a cost-effective, sustainable, flexible pavement type that has been widely used since 1920 on low volume roads, preventative maintenance of hot mix asphalt (HMA) pavements, on compacted and prime sealed granular base (Kutay *et al.*, 2016; Alvarez *et al.*, 2018; *Gheni et al.*, 2018; Jalali and Vargas-Nordcbeck, 2021).

The most important parameter affecting the performance of chip seal is adhesion, also called bond between aggregate and binder (Gransberg and James, 2005; Gürer, 2012; Alvarez *et al.*, 2018; You *et al.*, 2019). Numerous factors could directly or indirectly affected aggregate-binder adhesion. These factors; insufficient binder, very low surface temperature, sudden reduce in temperature after spreading, precipitation after spreading, the inadequacy of construction techniques, aggregate angularity, using dusty, moist, and poor-quality aggregates, the interaction between aggregate binder and etc. (Gransberg and James, 2005; Gürer 2012; Guirguis *et al.*, 2017; You *et al.*, 2019, Chang *et al.*, 2021). Aggregate types classified as hydrophobic (acidic aggregates) and hydrophilic (basic aggregates) also greatly influence adhesion properties.

Water can penetrate between the asphalt film and the aggregate, weakening the adhesion between the binder and the aggregate and thus causing the pavement to deteriorate (Gransberg and James, 2005; You *et al.*, 2019). Seeing that water affects the service life of the chip seal, the researchers examined the water leak process that can cause damage. They found that water penetration into the aggregate macropores in the chip seal adversely affects the adhesion. In this case, they noted, the aggregates must be heated to remove water from the aggregate surface as completely (You *et al.*, 2019).

Since water infiltration cannot be prevented on the chip seal, researchers were performed studies to increase the adhesion performance of the pavement with different methods by changing the binders or aggregate (Louw *et al.*, 2004; Gürer *et al.*, 2012; Liu *et al.*, 2018; Rahmany, 2019; You *et al.*, 2019).

Louw *et al.*, (2004) performed a series of detailed experimental studies on binder samples at various temperatures to assess the low-temperature performance of binders and the suitability of the Vialit test. According to the results of the Vialit adhesion test, which they conducted on the samples they prepared at 5^{o}C and 50^{o}C using bitumen with 80/100 penetration and 3% Styrene Butadiene Rubber (SBR) modified bitumen, it was concluded that the adhesion properties are positively affected from high temperatures. In addition, it was observed an improvement in adhesion properties according to the results of their tests on pre-coated aggregates. Liu *et al.*, (2018) investigated the factors affecting the adhesion of aggregates to the surface according to the finite element model. Buss *et al.*, (2018) to establish straightforward field measurements that provide an indication to chip seal performance. Eight chip seal roadways was studied to evaluate pavement performance using laboratory, field testing, and also performance monitoring. It was reported that chip seals constructed with good quality materials enhance the surface texture properties and reduce the appearance of distresses over the two-year monitoring period for most sections. Alvarez *et al.* (2018) applied conventional tests such as plate stripping and boiling water to assess the adhesion quality of chip seals. It was concluded that energy parameters and adhesion quality can be optimized in terms of chip seal design and field performance improvement. You *et al.* (2019) investigated the effect of the bitumen-aggregate combination and freeze thaw cycle on the durability of chip-seal. The Vialit test was performed to investigate the adhesion of bitumen-emulsion and aggregate at low-temperatures. The poor asphalt-aggregate combination in chip-seal application and the increased freeze-thaw cycles are the main factors for premature stripping of many chip-sealed road pavements. Yao *et al.,* (2019) performed an experimental study about diluted epoxy asphalt binders and their potential application in chip seal. It was concluded that diluted epoxy asphalt showed improved low-temperature performance compared to undiluted epoxy asphalt and better high-temperature performance compared to pure SBS-modified asphalt and reported that 1:1 dilution ratio to be most suitable from the aspects of performance, cost, and practical use. Kumbargeri *et al.,* (2021) performed a comprehensive laboratory evaluation of hot-applied and emulsion-based chip seals at different binder, emulsion, and aggregate application rates. It was reported that can help road agencies to proceed confidently when switching between hot-applied binder and emulsion materials.

The primary aim of this study is to improve the adhesion properties between aggregate and binder in chip seal by preheating the aggregates and using PPA modified bitumen and also to understand which method is more effective. With improved adhesion, extending the chip seal production season and ensuring higher performance from chip seal is another aim of this study. Increasing the adhesion performance of chip seals will also contribute to the reduction of maintenance and repair costs. For this aim, Vialit adhesion tests were carried out by producing 180 samples totally at five different aggregate temperatures using three different types of aggregates and four different types of binders (Two unmodified bitumen and two modified bitumen for B50/70, B160/220) and . Also, Nicholson stripping tests were performed. Besides, a benefit/cost analysis was carried out for heating the aggregates and modifying the bitumen with PPA in the chip seal application. Based on this work's results, the preheated aggregate application was efficient on adhesion. Using preheating aggregate could be expanded the construction season of the chip sealed pavement.

2. EXPERIMENTAL DESIGN

In the study, three different aggregates, cubic-shaped limestone, basalt, and river rock aggregate, were used between 19-12.5 mm sieves and were suitable for the Vialit test.

Limestone origin aggregates were obtained from a quarry in Afyonkarahisar Karacaören region, basalt aggregates were obtained from Kütahya Region, and river rock aggregates from Afyonkarahisar. The physical and mechanical properties of the aggregates are given in Table 1.

Main oxide, trace, and rare elements (ppm: parts per million) analyzes were performed for the aggregate samples. Representative samples of 120 grams each were selected from the aggregate samples, washed, dried, and sieved through a No:200 sieve. The chemical analysis results of the aggregates are shown in Table 2.

Table 1. Physical and mechanical properties of aggregates (Rahmany, 2019).

Aggregate	Specific Gravity and Water Absorption Values			Unit Volume Weight (g/cm^3)		Loss of Los Angeles Abrasion (%)
	Apparent Specific Gravity g/cm^3	Bulk Specific Gravity g/cm^3	Water Absorption (%)	Loose	Compressed	
River Rock	2.62	2.52	1.62	1.36	1.45	31.43
Basalt	2.81	2.65	2.12	1.49	1.58	12.69
Limestone	2.72	2.69	0.39	1.39	1.52	23.55

Table 2. Chemical composition of aggregate samples (Rahmany, 2019).

Aggregate	Mineral Component (%)										
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
River Rock	85,04	6.01	1,71	0,41	1,29	0,91	2,22	0,16	0,17	0,12	0,02
Basalt	50.57	16.11	9.02	4.12	9.76	2.34	2.27	0,94	0.37	0.19	0.02
Limestone	0.407	0.18	0.07	1.59	55.04	0.04	0.03	-	0.01	-	-

Polyphosphoric acid, or PPA, is a liquid mineral polymer. It is just one of many additives used to change and improve the grade of bitumen. Used alone or in combination with polymers, PPA can be an effective and economical tool for chemical modification. Using the right amount of PPA can improve the physical properties of bitumen (Jaroszek, 2012). Also, the use of additives such as polymers, Strene Butadine Strene (SBS) and Styrene Butadiene Rubber (SBR) in the chip seal can improve the adhesion between the aggregate and bitumen (Louw et al. 2004). The properties of the PPA used in this study are shown in Table 3.

Table 3. Properties of the PPA (Rahmany, 2019).

Properties	Value
Appearance (at 25 ºC)	Viscous liquid
Viscosity (cP at 25 ºC)	150
Density (g/cm^3 at 25 ºC)	1.77

B50/70 and B160/220 type bitumens were used as binder. The bitumen samples were taken from the in TÜPRAŞ (Turkish Petroleum Refineries Corporation) İzmir-Aliağa Refinery. A series of bitumen tests were carried out to determine the optimum percentage of PPA by weight (wt). Two type of bitumen samples (B70/70, B160/220) were mixed with PPA at different rates (0, 0.5, 1.0, 1.5 % by wt) at a mixing temperature of 160 ºC and a speed of 1500 rpm (revolutions per minute) for 60 minutes. After mixing, it was held in an oven at 100 ºC for 20 minutes. Penetration, softening and viscosity tests were carried out to determine the optimum additive ratio on the prepared mixtures. The test results of unmodified and modified binders are given in Table 4. Based on lowest penetration and shear sensitivity index (SSI) and highest softening point (SP), rotational viscosity (RV), penetration index (PI), and modification index (MI) values, optimum % PPA for B50/70 and B160/220 binders were determined as 1.0, and 1.1%, respectively. The results of three different bitumen tests and the arithmetic averages of the index values obtained from these the results are calculated and the optimum PPA percentages by wt are given in Table 5. Two different modified bitumen samples were produced using the optimum PPA values.

Table 4. Test results of unmodified and modified binders.

Bitumen Properties	Specification Used	Bitumen Samples							
		B 50/70				B 160/220			
PPA (%) by wt	-	**0.0**	**0.5**	**1.0**	**1.5**	**0.0**	**0.5**	**1.0**	**1.5**
Penetration (0.1mm), (at 25 °C, 100 g, 5 h)	ASTM D5-06e1, 2006	55.2	40.1	37.3	26.3	178.3	100	91	84
SP (°C)	ASTM D36-06, 2006	49.1	53.9	57.4	60.5	37.9	41.2	44.8	48.1
RV (cP) (135°C)	ASTM D4402-06, 2006	250	325.0	437.5	612.5	125.0	175.0	212.5	275.0
PI	-	-1.200	-0.767	-0.179	-0.288	-1.494	-2.079	-1.135	-0.380
MI (135°C)	-	1.00	1.30	1.75	2.45	0.50	0.70	0.85	1.10
SSI (135°C)	-	1.84	1.93	2.03	2.14	1.61	1.72	1.79	1.87

Table 5. Optimum PPA calculations according to the bitumen tests and indexes values

Bitumen Sample / Bitumen Tests	Penetration Test	SP	RV	PI	MI	SSI	Optimum PPA Value (%)
PPA % for B 50/70	0.5	1.4	1.0	1.2	1.5	0.5	**1.0**
PPA % for B 160/220	0.5	1.0	1.5	1.5	1.5	0.5	**1.1**

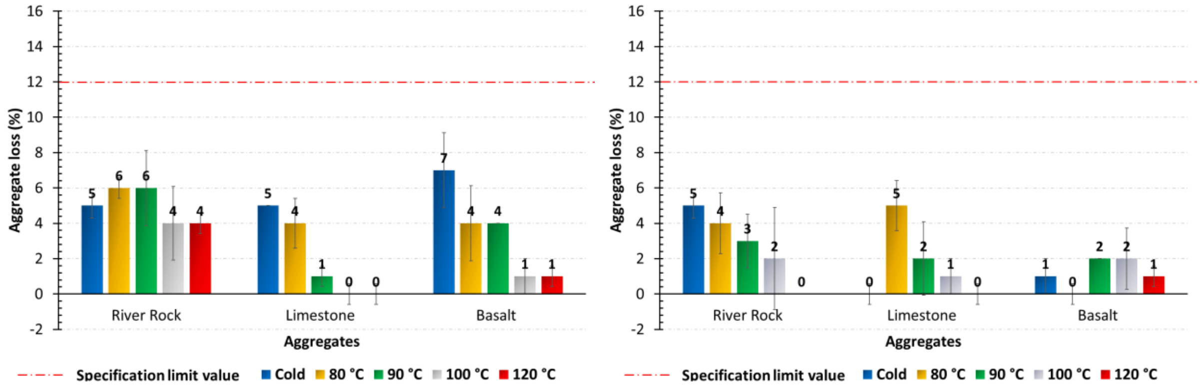
Vialit adhesion test (HTS, 2013) is an experimental method to determine the reduction of adhesion between aggregate-binder in chip seals with the effect of water. This test can also give an idea about stripping in aggregates. Aggregates between 19-12.5 mm sieve were sieved, washed, and dried in an oven at 100 °C for 24 hours. In this way, factors such as dust and moisture that may adversely affect adhesion are eliminated for all samples. One hundred cubic-shaped aggregates were selected from clean and dry samples. A cubic aggregate sample was placed in each cell of the mechanical spreader. The aggregates in the spreader are placed in an oven to reach their rolling temperatures (80, 90, 100, and 120 °C), and the aggregate temperatures were checked with a FLIR® (Forward Looking InfraRed) thermal camera. In addition, the bitumen and steel test plates to be used are heated in an oven at 180 ^{o}C before starting the test. After 40 g bitumen is dropped on the heated plates, it is put in the oven until the bitumen spreads evenly all over the plate. After the bitumen was spread on the test plate is placed under the mechanical spreader, the metal plate under the aggregate cells is pulled rapidly, allowing the aggregates to fall freely on the asphalt layer on the 20×20 cm metal plate. When the rolling temperatures of the samples are reached, the rolling process is performed. Rolling is performed using a rubber-banded roller, three times in two different directions, for six passes. The rolled samples are kept at room temperature until the temperature drops to 35°C and then held in a water bath at 35 °C for 24 hours. The samples are placed properly on the ball drop platform by turning them upside down. The ball is dropped on three times in total, with 10 seconds intervals, from the slightly inclined ball drop part at 50 cm height, integrated on the platform. The amount of aggregate falling over the sample is counted. The number of falling aggregates should be less than 12 (Gransberg and James 2005; HTS, 2013).

Nicholson test is an experimental method to get an idea about the stripping of bitumen on the aggregate surface caused by the effect of water. For the Nicholson test method (HTS, 2013), 30±0.5 g of washed and dried aggregates between 9.5-4.75 mm are used and heated in an oven at 110 ^{o}C for approximately 1 hour. At the same time, 1.5±0.1 g of bitumen is placed in a 100 cm^3 beaker, and then it is kept in an oven at 110 °C with glass baguettes. The heated aggregate is poured into the beaker and mixed with a glass baguette on the heater until all aggregate surfaces are covered with bitumen. The sample is cured for 24 hours in an oven at 60 ^{o}C. Then, the samples in the beaker are quickly and adequately transferred to glass dishes with a diameter of 10 cm. The samples are kept at room temperature for about 10 minutes, are filled with water in glass dishes, and kept in an oven at 60 ^{o}C for 24 hours by closing the lid. After the water in the glass dishes is renewed, observation is made by looking at the unpeeled surface ratio on the upper surface of the mixture under the light. According to the Highways Technical

Specification (HTS), the unstripped aggregate should be at least 50% (HTS, 2013).

3. RESULTS AND DISCUSSION

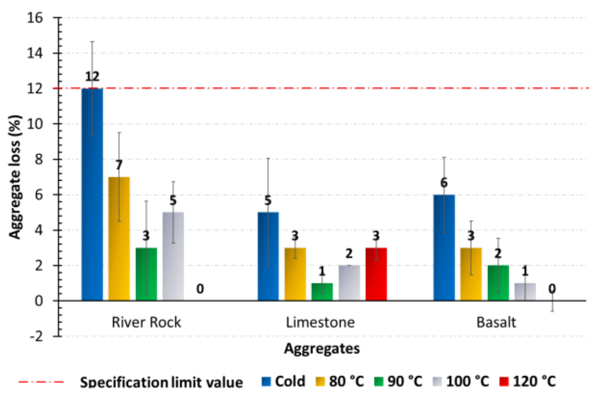
Vialit adhesion test results of five different temperatures, three different aggregates, and two different unmodified bitumen are given in Figure 1. Vialit test results of two different bitumen modified with 1.0% and 1.1% by wt PPA, respectively, for B50/70 and B160/220 binders are shown in Figure 2.



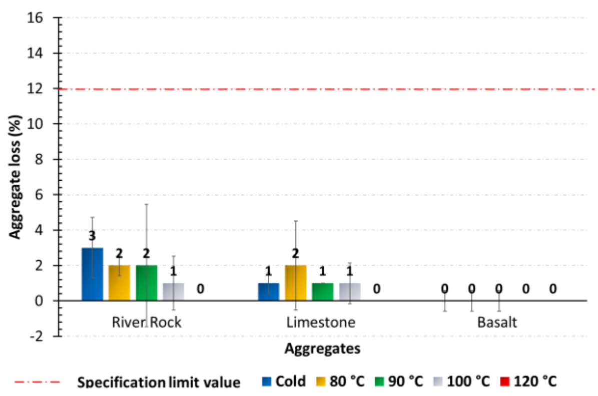
(a) (b)

Figure 1. Vialit adhesion test results (a) unmodified B50/70, (b) unmodified B160/220 binders.

When the unmodified Vialit test results were examined, it was seen that the B160/220 binder was more effective in adhesion than the B50/70 binder. It has been observed that the heating of the aggregates gives more effective results than the B50/70 binder in the experiments using the B160/220 binder. Stability was not obtained in the experiments with B160/220 binder and basalt aggregate. As shown in Table 2, the number of aggregates falling in both binder types is the highest in river rock aggregate with high silica content. Experiment results showed that bituminous binder type, aggregate type, and heating of aggregates were highly effective on adhesion.



(a)

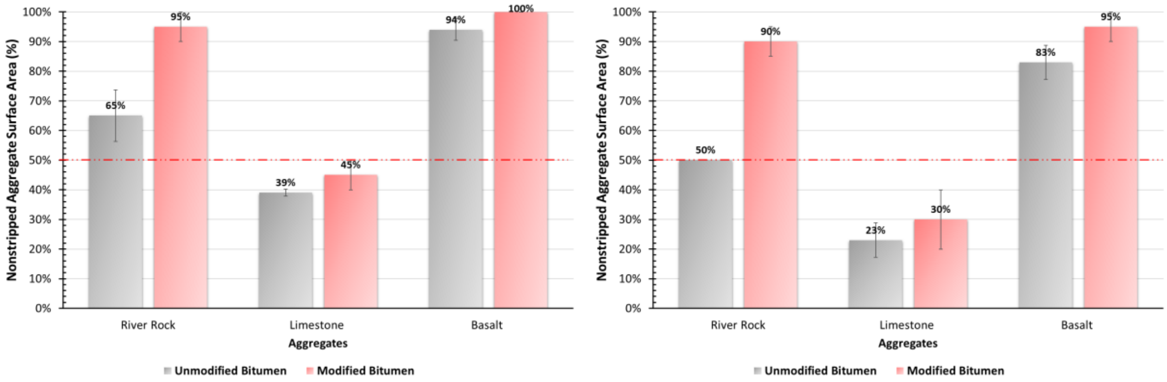


(b)

Figure 2. Vialit adhesion test results; (a) B50/70 binder with 1% PPA, (b) B160/220 binder with 1.1% PPA.

When the modified Vialit test results are examined, it is seen that B160/220 binder provides better performance than B50/70 binder, similar to unmodified bitumen. For B160/220, while the stability was observed in the heating of the river rock aggregate, the heating of limestone and basalt did not give a very effective result. For B50/70, while stability is observed in basalt, there is instability in other aggregate types. It has been observed that the high silica content (Table 2) in the river rock aggregate weakens the adhesion between the aggregate and bitumen in both binder types and increases the number of falling aggregates. Considering the test results, it was seen that the modified bitumen improved the adhesion performance, and the aggregate type and aggregate heating were also the factors affecting the adhesion.

The results obtained by performing three Nicholson stripping tests for two different unmodified and modified bitumen and three different aggregate samples used are given in Figure 3 by taking the arithmetic average.



a) **b)**

Figure 3. Nicholson stripping test results; a) B50/70 binder, b) B160/220 binder.

According to the results obtained, it was observed that the limestone samples exhibited stripping above the specification values for both modified/unmodified bitumen classes. River rock and basalt aggregates provided the specification values. Although river rock and basalt aggregates have high silica content, their stripping percentages are low. It is thought that the high roughness of the river rock and basalt aggregate surfaces is effective in less stripping.

In the chip seal application, the improvement in adhesion due to heating the aggregates and modifying the bitumen with PPA was evaluated in terms of benefit/cost analysis. In the analysis, limestone as aggregate and 1% PPA modified and unmodified B50/70 penetration grade bitumen as bitumen were taken as the basis. E-MAK ® DRY-17-781 (Asphalt Plant Manufacturer) type plant dryer to be used for heating the aggregate has been selected, and its capacity is 155 tons/h (E-MAK). As can be seen in Figure 1(a) and Figure 2(a), an 80% improvement in adhesion performance as a result of heating the limestone to 90 °C was accepted as a benefit. Equation It was used as the heat formula. The specific heat value (c) of the limestone-based aggregate was determined as 0.22 joule/g°C from the literature (Engineering ToolBox, 2003).

$$Q = m.c.\Delta t \tag{1}$$

Where;

Q = Heat received or given (joule), m = Mass of the substance (g), c = Specific heat (joule/g^{o}C), and Δt = Temperature difference (^{o}C).

The values taken as fixed and variable in unit cost calculations are given in Table 6, and since the effect of these values on the cost in both applications is fixed, they are not taken into account in the calculation. The values that differ in the cost of both heated aggregate and PPA added bitumen were accepted as determinants in unit cost calculations.

Table 6. Values taken as constant and variable in calculations.

Constant Values	Cost of heating of bitumen, cost of bitumen, cost of aggregate, Cost of labor, cost of electricity consumption
Variable Values	Cost of heated aggregate, cost of bitumen with PPA additive

The benefit value was determined as 80% improvement in adhesion for both different applications, based on the reduction in the number of falling aggregates in Vialit tests compared to the cold sample (unheated) by heating the aggregates up to 90 °C and using PPA additives (Table 7).

Table 7. Benefit/Cost (B/C) calculation.

Detail	Heating of aggregates until 90 ºC	PPA by wt
Aggregate Heating	✓	-
Use of PPA Additives	-	✓
Benefit (recovery rate of falling aggregates %)	80	80
Heating Cost of Aggregates ($/kg)	0.000363	0
PPA additive cost ($/kg)	0	0.631676
Cost (for 1000 kg of material)	0.363	6,32
Benefit/Cost (B/C)	220.4	12.7

The energy required for heating the aggregates for 1000 kg of material was calculated from equation 1 and then the unit cost was obtained. The unit cost of PPA added bitumen was calculated according to the amount of PPA additive, the optimum use of which was determined as 1% in bitumen. The B/C values were found with the equation (2) detailed below. It was observed that heating the aggregate provides a higher B/C value than the use of PPA additives.

$$\begin{aligned} &Heated\ aggregate = \frac{B}{C} = \frac{80}{0.363} = 220.4\ ; \\ &Bitumen\ with\ 1\%\ PPA = \frac{80}{6.32} = 12.7 \end{aligned} \tag{2}$$

4. CONCLUSIONS

The following conclusion can be drawn as a result of the tests carried out to determine how the heating of the aggregates, the binder used, the PPA additive, and the aggregate type will affect the adhesion behavior:

As seen in the experimental study, both unmodified PPA and PPA modified B160/220 bitumen improved the adhesion performance better than B50/70 bitumen. Aggregate type, binder, aggregate temperature and PPA modifier are very important in terms of adhesion performance between aggregate and bitumen. It will be possible to extend the production season of the chip seal and to obtain higher efficiency from this type of pavement with the improvement in adhesion. Increasing the adhesion performance of chip seals will also contribute to the reduction of maintenance and repair costs. It was understood that the heating of the aggregates and the PPA additive played a healing role on the adhesion. It was concluded that the use of preheated aggregates provides a higher B/C value than the use of PPA additives. The most important reason for this is the high unit cost of the PPA additive material. It is thought that similar results can be obtained with other chemicals used for adhesion improvement. From this point of view, the benefits/costs of using preheated aggregates in chip seal applications are higher in terms of adhesion development.

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