EFFECT OF GRADATION AND AGED BINDER CONTENT OF RECLAIMED ASPHALT PAVEMENT (RAP) ON PROPERTIES OF COLD-RECYCLED ASPHALT MIX

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ABSTRACT

Cold-recycling of asphalt is an effective method enabling agencies to conserve valuable resources during rehabilitation of distressed roads. The objectives of this study are to improve the understanding regarding cold-recycled asphalt performance, investigate the impact of the Recycled Asphalt Pavement (RAP) gradation and RAP binder content on properties of the cold-recycled asphalt at given recycling agent and water content level, and evaluate the effect of recycling agent content and water content levels on the performance of Cold-Recycled asphalt.

Various RAP sources with controlled gradations and five different asphalt content levels were mixed with emulsion at two different dosages and tested for performance properties; including Marshall stability and moisture susceptibility.

The results show that at the early stages of curing the effect of gradation of the RAP is more important than the aged RAP binder content. Moreover, at this stage, increasing emulsion content improves wet stability and moisture susceptibility of the samples regardless of the RAP binder content and gradation of the cold-recycled mix.

Keywords: RAP, Cold Recycled Asphalt, Emulsion, CIR, Cold In-place Recycling, Pavement Preservation

INTRODUCTION

The poor condition of the U.S. pavement is a crucial challenge in front of the nation transportation system. More than a quarter of the nation's major urban roadways, which carry 78 percent of the total annual miles driven in America, are in poor condition (TRIP 2013, Davies and Sorenson 2000). At the same time the overall vehicular traffic increased by 37 percent from 1990 to 2011. Large truck traffic grew at an even faster rate (TRIP 2013). The current highway funding is not sufficient to maintain the current condition of the U.S. highway system (Thomas and Kadrmas 2003, TRIP 2013). The poor condition of the roads cost $80 billion for the nation in addition to vehicle operation costs which makes it significantly important to look for maintenance and preservation methods with lower application cost (TRIP 2013).

Cold recycling of asphalt is one of the cost-effective and sustainable maintenance methods that preserve valuable and scarce natural resources. Cold recycling of asphalt, also known as Cold In-place Recycling (CIR), is not a new pavement rehabilitation strategy. For several years, it has been known as an effective method that enables agencies to rehabilitate the distressed asphalt roads while saving money on materials and energy (Abiodun et al. 2013, Sanchez Caba and Panez Duenas 1996). CIR can be used effectively to remove thermal and reflective cracks, reestablish crowns and improve poor aggregate gradation (Thomas and Kadrmas 2003). A New Mexico study in 1997 showed that using the CIR method can result in approximately $11,000 saving in construction costs per lane-mile (McKeen et al. 1997).

CIR method includes pulverizing the existing asphalt layer to a depth of two to four inches and mixing the reclaimed asphalt pavement (RAP) with emulsion or emulsified recycling agent, water and other additives at ambient temperature. It is optional to add new aggregate to adjust the gradation and improve the quality of final product. Then the produced mix is spread and compacted to create a base course. For lower traffic roads, Cold-Recycled asphalt can be also used as a surface layer (Kandhal 1997, Lee et al. 2014). Each of the components in the Cold-Recycled mix expected to play certain role during the production, placement, and final performance of the road. The emulsion is added to the mix to bind the RAP aggregate together and possibly reactivate the existing asphalt binder in the RAP. The water is added to improve the mixing process and regulate the coating of RAP aggregates. In addition to these components, cementitious materials may be added to the mix to regulate the curing rate of the mix and also, to improve resistance to moisture related damage and stability of the final product (Wen et al. 2011).

To ensure proper performance of the final product, it is important to design a mix that considers different factors that may impact the material performance (Thomas, T. and Kadrmas 2003). These factors include RAP aggregate gradation, RAP binder content, type and amount of new binder and/or recycling agent, and water content. Unfortunately, in spite of wide application of CIR mixes in rehabilitation of asphalt pavements, there is no nationally-accepted standard method to design them; however, there are certain common steps that are followed by different agencies. As any other asphalt mix designs, one of the most important steps in designing CIR is to identify the amount of required new binder (emulsion) to be added to the RAP. The true contribution of the existing aged RAP binder in the final mix and the effectiveness of the emulsion in reactivating the aged asphalt are not fully understood yet (Kandhal 1997, Wen et al. 2011, Chesner et al. 2011).

OBJECTIVE AND METHODOLOGIES

The primary objective of this study was to improve the understanding regarding cold-recycled asphalt performance. Specific objectives included:

- Investigate the impact of the RAP gradation and binder content on characteristics of the Cold-Recycled asphalt.
- Evaluate the effect of recycling agent content on the performance of Cold-Recycled asphalt.

In this work, various RAP sources with controlled gradations and five different asphalt content levels (4.7, 5.1, 5.5, 5.7, and 6.3 percent) were mixed with emulsion at two different dosages (2.5 and 3.5 percent by dry weight of RAP) and tested for performance properties in the laboratory. These properties included dry stability, wet stability (moisture conditioned samples), and moisture susceptibility. The properties are selected based on the California Department of Transportation (Caltrans) specifications (Caltrans LP-8 2005). In addition, the effect of recycling agent content on performance properties of the final mix was investigated.

MATERIAL AND METHOD

Emulsion

A solvent free emulsion which is engineered for cold recycled asphalt applications was used in this study. The properties of the emulsion is presented in Table 1.

Table 1. Properties of Emulsion

	AASHTO Test Method	Test Results
Residue by Distillation, W%	T59	65.2
Oil Distillate, %	T59	Nil
Tests on the Residue		
Penetration, 25 ^{o}C, dmm	T49	122
Viscosity, 60 ^{o}C, Pa.s	T202	1,443

RAP Samples and Gradations

Recycled Asphalt Pavement (RAP) materials from five different locations in southern California were utilized in this research. RAP samples were delivered in the form of cores and were disassembled to smaller size by applying vertical compressive load at ambient temperature. To further reduce their size, they were fed through a jaw crusher and a cone crusher in the laboratory. The crushed RAP material was separated into four bins based on the following sieve sizes:

- Bin 1: passing the 1-inch sieve and retained on the 3/4-inch sieve;
- Bin 2: passing the ¾-inch sieve and retained on the No. 4 sieve;
- Bin 3: passing the No. 4 sieve and retained on the No. 30 sieve; and

- Bin 4: passing the No. 30 sieve and retained on the pan.

The material in each bin was recombined in the laboratory in order to achieve the target medium gradation, required by Caltrans (Caltrans LP-8 2005), shown in Table 2.

Table 2 shows the gradation and asphalt content of each combined RAP sample. The gradation of the combined RAP material is presented in Figure 1. The gradation was determined in accordance with Caltrans test method CT 202. Chemical extraction was performed to determine the percentage of asphalt cement content (% AC) in the RAP, following ASTM D2172 method B. The maximum theoretical specific gravity (G_{mm}) was performed in accordance with (Caltrans CT-309 2010).

Table 2. Gradation and basic properties of RAP samples

Code	CIR-4.7%	CIR-5.1%	CIR-5.5%	CIR-5.7%	CIR-6.3%	Target Gradation
1-inch	100	100	100	100	100	100
3/4-inch	95	95	94	96	95	95 ± 2
1/2-inch	83	80	89	75	80	--
3/8-inch	73	75	83	65	67	--
No. 4	51	50	52	50	50	50 ± 2
No. 8	31	29	38	22	27	--
No. 16	20	16	25	12	15	--
No. 30	11	10	12	8	9	10± 2
No. 50	6	6	7	3	5	--
No. 100	3	3	5	1	3	--
No. 200	0.4	0.6	0.8	0.3	1.1	0.8 ± 0.3
AC%	4.7	5.1	5.5	5.7	6.3	--
G_{mm}	2.432	2.457	2.411	2.392	2.400	--

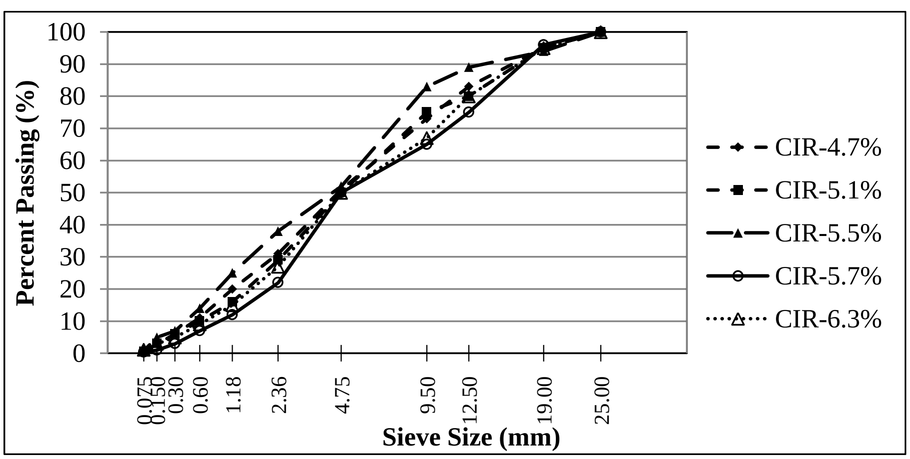

Figure 1. Gradation of RAP samples

Mixing and Compaction

The process of mixing RAP and emulsion was performed in accordance with the Caltrans guideline (Caltrans LP-8 2005). Combined RAP material was dried to constant weight and then mixed with 2.5% of water by the dry weight of RAP (DWR). Then the moist RAP material was mixed with two different emulsion contents (2.5% and 3.5% by DWR). The engineered Emulsion Pass-R was used in this research; emulsion was supplied by Western Emulsions, Idaho. The components were mixed for 60 seconds at the ambient lab temperature (77±4°F).

The prepared samples were immediately compacted for the stability test. A gyratory compactor with 100 mm diameter mold was utilized to compact the specimens at 30 gyrations, per Caltrans guideline (Caltrans LP-8 2005). Six cylindrical specimens were prepared at each emulsion content for each RAP sample.

Curing and Moisture Conditioning

The compacted specimens were placed in a forced draft oven at 140±8°F to cure for 48 hours. Then, the cured specimens cooled down to room temperature for 16 hours. To have statistically meaningful material six samples from each specimen were made. Three of them were cured in dry condition and three of them were moisture conditioned, following the Caltrans guideline, to measure the moisture susceptibility of the samples. Based on this procedure, three compacted/cured specimens were moisture conditioned by applying a vacuum of 13 to 67 KPa absolute pressure for a time period required to vacuum saturate samples to 55 to 75 percent. Moisture conditioned samples were soaked in water bath at 77±2°F for 24 hours, followed by 30 minute soaking at 140±2°F. Dry conditioned samples were put aside after initial 48 hours curing for further testing.

Marshal Stability and Moisture Susceptibility Evaluations

For the stability test, the specimens (dry cured and moisture cured) were immersed in water for 30 minutes at 140±2°F. Then the Marshal Stability test was performed on each specimen in accordance with AASHTO T245 procedures.

The moisture susceptibility of each set of specimens was calculated by dividing the average stability of moisture conditioned specimens (wet stability) with average stability of the dry specimens (dry stability).

RESULTS AND DISCUSSIONS

Effect of RAP Binder Content on Stability and Moisture Susceptibility

Five CIR mixes were prepared using five RAP materials, obtained from different cities in southern California, with different binder contents and different gradations. The Marshal stability of each CIR mix was measured in dry and wet conditions. The stability and moisture susceptibility results for each specimen at 2.5% emulsion content are presented in Table 3. All mixes had achieved more than the Caltrans minimum Marshall stability of 1,250 lb and minimum retained stability of 70%.

To investigate the effect of RAP binder content on stability and moisture susceptibility of the samples, single factor ANOVA analysis was performed on each property for the samples with 2.5% and 3.5% emulsion with 95% reliability. The statistical analysis results for the 2.5% emulsion are presented in Table 4.

The ANOVA analysis, at both emulsion contents, indicates that there is no statistically significant difference among the properties of different CIR samples with various RAP binder content, except for the dry stability. As can be seen in Table 4, the P-values for the wet stability and moisture susceptibility are greater than 0.05 which indicates that at 95% reliability, these samples are behaving similarly even though their RAP binder contents is different.

Table 3. Mechanical Properties of CIR Mixes at 2.5% Emulsion Content

Sample Code		CIR-4.7%	CIR-5.1%	CIR-5.5%	CIR-5.7%	CIR-6.3%
Dry Stability (lb)	**Average @ 2.5% Emulsion**	2,302	2,086	2,517	1,931	2,232
	Average @ 3.5% Emulsion	2,277	1999	--	2,460	2,586
Wet Stability (lb)	**Average @ 2.5% Emulsion**	1,781	1,836	1,813	1,420	2,013
	Average @ 3.5% Emulsion	2,999	1,671	--	2,230	2,118
Moisture Susceptibility (%)	**Average @ 2.5% Emulsion**	78	89	72	74	90
	Average @ 3.5% Emulsion	92	83	--	91	82

The statistical analysis at two different emulsion contents (2.5% and 3.5%) shows that the dry stability for the samples with different RAP binder content and gradation is statistically different. This indicates that the RAP binder content and gradation may have some effect on dry stability of the CIR samples. To further investigate this claim, regression analysis was performed on the dry stability of different CIR mixes as a function of RAP binder content, in Figure 2. Regression analysis results in Figure 2 shows that in spite of the statistically meaningful difference in dry stability of CIRs with different RAP binder content, there is no solid correlation between the RAP binder content and the dry stability of the corresponding sample (low R-square value). This indicates that the RAP binder content doesn't have a significant impact on the stability of the recycled mixes at early curing stages. Therefore, it is reasonable to conclude that the stability differences among the samples are caused by other factors which need to be further investigated.

Table 4. Single Factor ANOVA Analysis

Physical Property	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Dry Stability	**Between Groups**	589,246.9	4	147,311.7	6.03	0.01	3.478
	Within Groups	244,261.8	10	24,426.18			
	Total	833,508.7	14				
Wet Stability	**Between Groups**	564,044	4	141,011	3.33	0.06	3.478
	Within Groups	423,496.9	10	42,349.69			
	Total	987,540.9	14				
Moisture Susceptibility	**Between Groups**	874.6856	4	218.6714	2.03	0.17	3.478
	Within Groups	1,077.844	10	107.7844			
	Total	1,952.529	14				

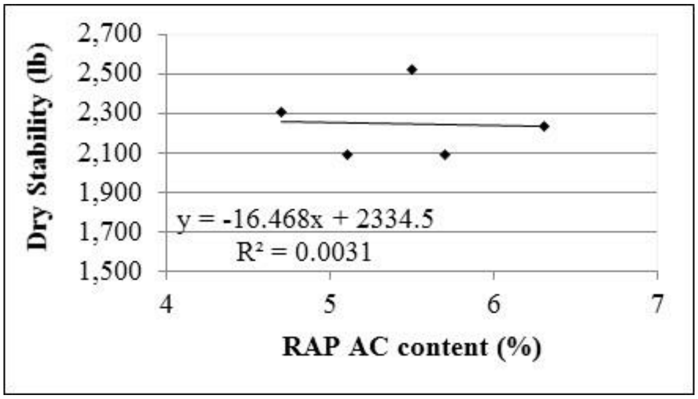

Figure 2. Correlation between dry stability and RAP binder content

Effect of RAP Gradation on Stability and Moisture Susceptibility
The effect of different parameters of the gradation was investigated for possible correlation with dry stability of the CIR samples. Figures 3a and 3b show that as the percentage of material passing sieves No. 8 and 16 increased, respectively, the dry stability increased. It has to be noted that all sample had similar amount of material passing from sieve No. 4 (50 to 52%), as presented in Table 2 and Figure 1. Figure 4 shows that the dry stability increases with the reduction of D_{10} and D_{30}, with high coefficient of determination (R^2). The correlation with D_{60} had lower correlation with the dry stability with R^2 of 0.55. The best correlation was found between the dry stability and each of percent passing sieve No. 8 (2.36 mm) and D_{30} with R^2 of 0.87.

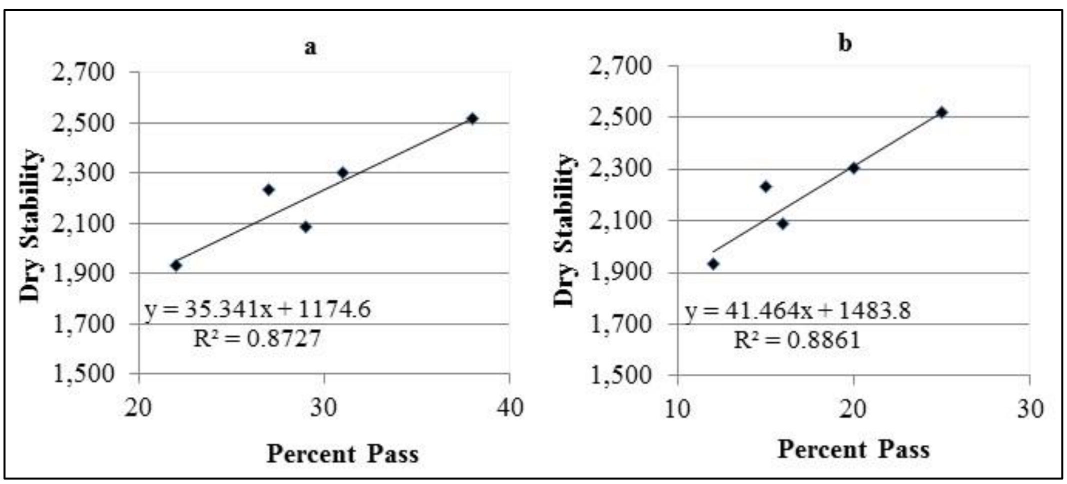

Figure 3. Correlation between dry stability and percent passing a) sieve No. 8 and b) sieve No. 16

The dry stability was also correlated to uniformity coefficient (C_u) and coefficient of curvature (C_c), as presented in Figure 5. It was found that dry stability increased with increasing the C_u, with R^2 of 0.77. The C_u had better correlation with the dry stability than the C_c. The range of values for C_u was more than six, and the range for the C_c values was between 1 and 3, which reflect that all the evaluated materials could be classified as well graded sand with gravel (SW), according to unified soil classification system (ASTM D2487).

All these correlations reflected that the aggregate structure had more impact on the dry stability of the material than the RAP content. It can be concluded that the finer the grading, the higher the dry stability; given that the gradation is well graded. This conclusion is limited to the material in the CIR gradation specification in Caltrans guideline (Caltrans LP-8 2005) and cannot be extrapolated beyond the limits of the gradation used in this study.

$C_u = D_{60}/D_{10}$

$C_c = D_{30}^2 / (D_{10} * D_{60})$

Where:

C_c = coefficient of curvature

C_u = coefficient of uniformity

D_{10}, D_{30} and D_{60} = the particle-size diameters corresponding to 10, 30, and 60 %, respectively, passing on the cumulative particle-size distribution curve.

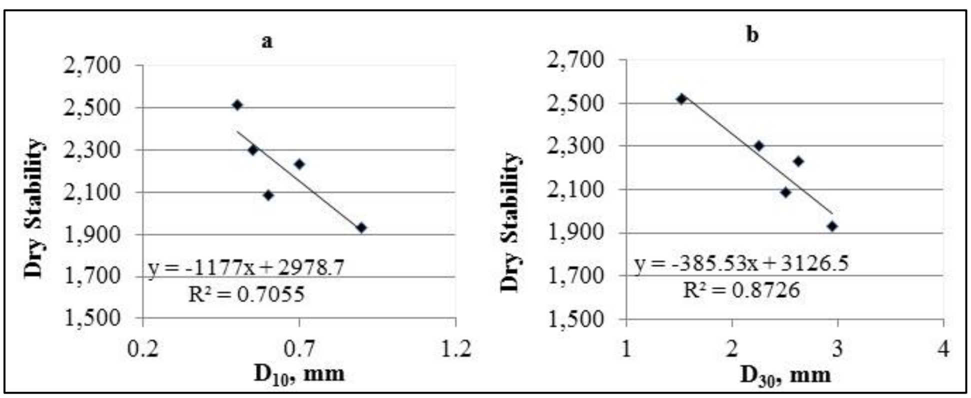

Figure 4. Correlation between dry stability a) D_{10} and b) D_{30}

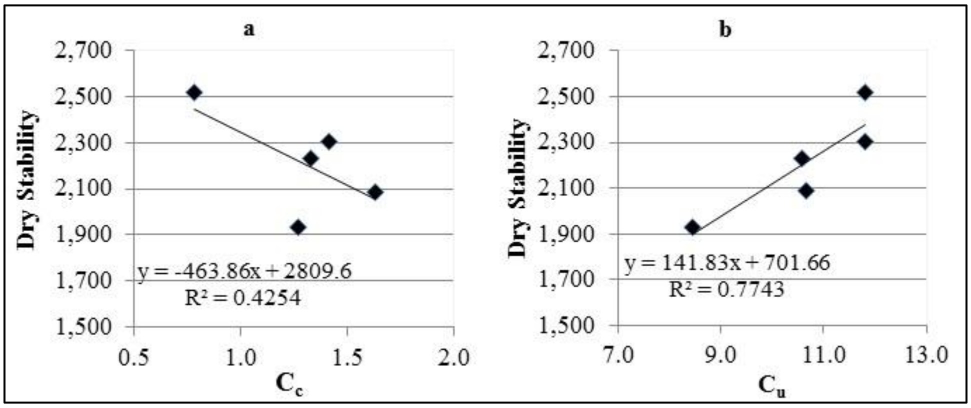

Figure 5. Correlation between dry stability a) coefficient of curvature and b) material uniformity coefficient

Effect of Emulsion Content on Stability and Moisture Susceptibility

The effect of emulsion content on stability and moisture susceptibility of the CIR mixes were investigated using samples with two different emulsion contents (2.5 and 3.5 percent by weight of dry RAP). The results are presented in Figure 6.

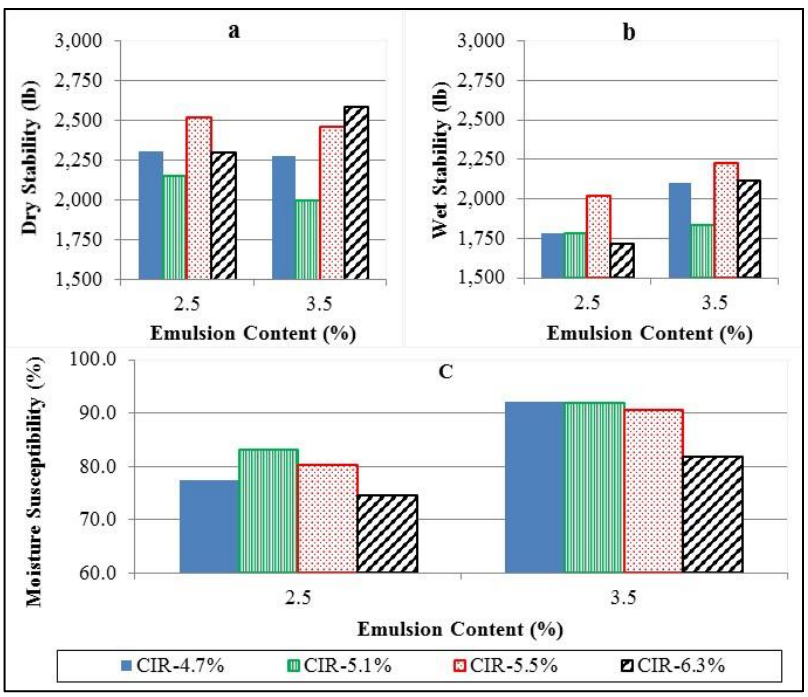

Figure 6. Effect of emulsion content on physical properties of cold-recycled mixes a) dry stability, b) wet stability, and c) moisture susceptibility

As shown in Figure 6a, for the CIR-6.3% sample, increasing emulsion content from 2.5% to 3.5%, increases the dry stability (from approximately 2,300 lb to approximately 2,600 lb) however, for the other RAP samples the stability declines by increasing the emulsion content (i.e. for sample CIR-5.1%, from approximately 2,150 lb to approximately 2,000lb). The reduction in the stability for some of the CIR samples (i.e. CIR-5.1%) may be due to various reasons including RAP sources or RAP aggregate properties which are beyond the scope of the present work. Further investigation is needed to identify the exact difference between CIR-6.3% and other mixes which show decrease in their dry stability as a function of emulsion content increase.

Figures 6b and 6c indicate that increase in emulsion content results in improved wet stability and moisture susceptibility for the samples regardless of the RAP binder content. For example, the results for CIR-5.5% show that the wet stability increased from approximately 2,000 lb to approximately 2,250 lb when emulsion content increased from 2.5 to 3.5% in Figure 6b. The results for the same sample show that moisture susceptibility (ratio of wet to dry stability) is improved by more than 10% with the similar increase in emulsion content (Figure 6c). This can be attributed to better coating of particles at higher emulsion contents.

CONCLUSIONS

Five RAP materials from different projects in southern California with a relatively wide range of asphalt content were selected and utilized to investigate the effect of RAP binder content and aggregate gradation on the performance properties of CIR mixes at early stages of their life. In this regard, ASTM standards, and Caltrans guidelines and test methods were followed. CIR mixes were prepared at two different emulsion contents and their stability before and after moisture conditioning were measured to evaluate their moisture susceptibility. For each sample three replicates were fabricated and tested.

Single factor ANOVA analysis was performed on the results. The statistical analysis show that there is no significant difference between the stability and moisture susceptibility of the CIR mixes with different RAP binder contents and gradations at same emulsion content. The regression analysis showed that the grading of the material had more impact on the dry stability than the binder content. It can be concluded that the quality of the grinding of the asphalt pavement during construction of cold in-place asphalt has direct effect on the initial performance of the road. Moreover, the performance tests on CIR mixes at different emulsion contents indicate that increasing emulsion content significantly improves the moisture susceptibility. This can be attributed to better coating of RAP aggregates at higher emulsion content and reduction in the infusion of moisture between aggregate surface and binder coating which can improve the adhesion between aggregate and asphalt binder.

The results of this study show that RAP asphalt binder is not fully activated at early curing stages of CIR mixes. However, its true contribution to long term performance of the Cold-Recycled pavements needs further investigation. Better understanding of the effect of RAP asphalt binder on the performance of the cold-recycled pavements is crucial in developing a standard mix design procedures in future.

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