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Exploring the Compactability and Workability of RAP

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INTRODUCTION

The use of asphalt materials has become a standard practice in the construction of pavements around the world. Traditional hot mix asphalt pavements are made of asphalt concrete, which is a combination of aggregate and asphalt binder that is heated, mixed, and placed on the roadway. In the past 50 years, the use of cold in-place recycling (CIR) of asphalt concrete pavements has become a prominent alternative in pavement rehabilitation (Cox, 2015). Instead of removing and replacing distressed pavement, CIR can eliminate significant distresses in pavements by recycling the in-place material, reducing costs and emissions from hauling virgin material to the jobsite.

CIR is a process by which existing asphalt concrete pavements are partially reclaimed, mixed with additives, placed, and compacted (Cox, 2015). Existing asphalt concrete pavement is removed, crushed, and graded to obtain proper aggregate sizes. This new material is referred to as reclaimed asphalt pavement, or RAP. The binder in CIR is asphalt emulsion. Emulsions consist of asphalt suspended in water and they do not require the addition of heat in order to adequately coat the RAP (Cox, 2015). After incorporation of asphalt emulsion with RAP, the mixture is placed back on the surface. The mixture is compacted and additional surface course construction may be performed before the structurally sound pavement is ready to be re-opened. It is important to note that the use of CIR is not appropriate in all circumstances, specifically in areas with substantial frost action, unstable subbase or subgrade, or when the bond between asphalt and aggregate has been broken in the existing pavement(Cox, 2015).

Inherently, CIR is an efficient rehabilitation system for asphalt concrete pavements. Since existing pavements are milled, remixed, and placed, there is little to no waste placed into landfills. In 1999, Oklahoma produced 200,000 tons of pavement millings, which, if not recycled, would be landfilled (Issa, 2001). In addition to reducing the waste sent to landfills, CIR is economically viable. In 1993, it was estimated that CIR saved $10,000 per kilometer as compared to complete pavement reconstruction (Cox, 2015).

In addition to asphalt emulsion, Portland cement or other cementitious materials can be used to increase performance of CIR. Previous studies have examined the use of supplementary cementitious materials (SCM) and their effect on strength and stability of CIR pavements. SCM's are defined as "an inorganic material that contributes to the properties of a cementitious mixture through hydraulic or pozzolanic activity, or both" (ASTM, 2016). The purpose of using an SCM's, such as Portland cement, is to reduce cost, account for different required characteristics, or to change unit weight, for example (Somayaji, 2001). A 1999 study examined the use of hydrated lime as an SCM with asphalt emulsion and indicated an increased unit weight, tensile strength, and resilient modulus (Cross, 1999). These results opened the door to using SCM's in order to achieve greater strength in CIR. Two years later, a study was performed to characterize CIR pavements with RAP bound with asphalt emulsion and Portland Cement. It was found that Portland cement increased Hveem stability while decreasing the amount of asphalt emulsion necessary to bind RAP (Issa, 2001). In 2015, different ratios of emulsions and SCM's were examined to determine the best balance to achieve optimal strength characteristics. It was found that single component binder systems (SCB), or one that uses asphalt only as a binder, had an "excess reserve capacity" to one type of distress while having "insufficient capacity" to another distress (Cox, 2015). Balancing a multiple component binder system (MCB) allows CIR pavements to have adequate capacity to resist several types of distresses, although this is not always economical (Cox, 2015). While there has been a great effort to characterize the effect of SCM's on hardened properties of CIR pavements, there has been limited effort to characterize the effect of SCM's on the compactability and workability of CIR.

Compactability is “the effort required to achieve consolidation of asphalt concrete” (Braham, et al., 2015). Workability is “the relative ease with which asphalt concrete can be mixed, handled, and placed” (Braham, et al., 2015). Compactability and workability are quantified by values such as workability energy index (CIR-WEI), compactability energy index (CIR-CEI), compaction densification index (CIR-CDI), and traffic densification index (CIR-TDI). CIR-WEI values indicate the energy required to compact a sample to 76% G_{mm}, or N_{76}. CIR-WEI values are inversely related to the energy required to compact a sample (Yeung and Braham, 2018). CIR-CDI values indicate the area under the densification curve from N_8 to the N_{76} (Yeung and Braham, 2018). CIR-CDI values are directly related to the energy required to compact a sample, meaning that as CIR-CDI values increase, so does the energy required to compact a sample. CEI and TDI values were not considered in this research.

Compactability and workability are characteristics that have been greatly studied in hot mix asphalt and warm mix asphalt, but have not been explored deeply in CIR. With the increasing use of CIR in pavement rehabilitation, studying compactability and workability of CIR is important because it may reveal more efficient construction methods or a more economical approaches to CIR. Because of the properties demonstrated by CIR pavements containing SCM, exploring the characteristics of compactability and workability will lead to a better understanding of the effects of SCM’s in CIR.

OBJECTIVES

The primary objectives of this research were to investigate the compactability characteristics of RAP using MCB approach and to determine the effect of an MCB approach on workability of lab created RAP.

MATERIALS AND METHODS

For this experimental plan, 36 tests were run on 18 samples with 6 different mixtures. The materials are listed in Table 1 and the experimental plan is listed in Table 2. The mix design for an asphalt emulsion stabilized CIR mixture was determined for RAP sampled from a local quarry. The gradation of RAP samples may be found in Table 3, with a graphical representation in Figure 1. The mix design was completed according the *AASHTO PP86-17* and *AASHTO MP31-17*. In order to isolate the influences of the two asphalt emulsions and the two SCM's, the same mixture proportions and RAP source were used for all samples.

Table 1: Material Matrix

Factor	**Level**
Emulsion Type	CMS-1 (Proprietary)
	CMS -1 (Commodity)
SCM (0.5% by weight)	Type I Portland cement
	Type C fly ash
	No SCM
Emulsion Content	2.75% (based on mix design)

Table 2: Experimental Plan

Variable	**Number of Options**	**Options**
Emulsion Type	2	Proprietary
		Commodity
SCM	3	Portland cement
		Fly ash
		No SCM
Testing Apparatus	2	Superpave Gyratory Compactor
		Direct Shear

Table 3: RAP Gradation

Sieve Size	% Passing	RAP Sample (g)
1/2	100%	0
3/8	96%	104
#4	63%	858
#8	45%	468
#16	-	1170
#30		
#50		
#100		
#200		
PAN		
Total		**2600**

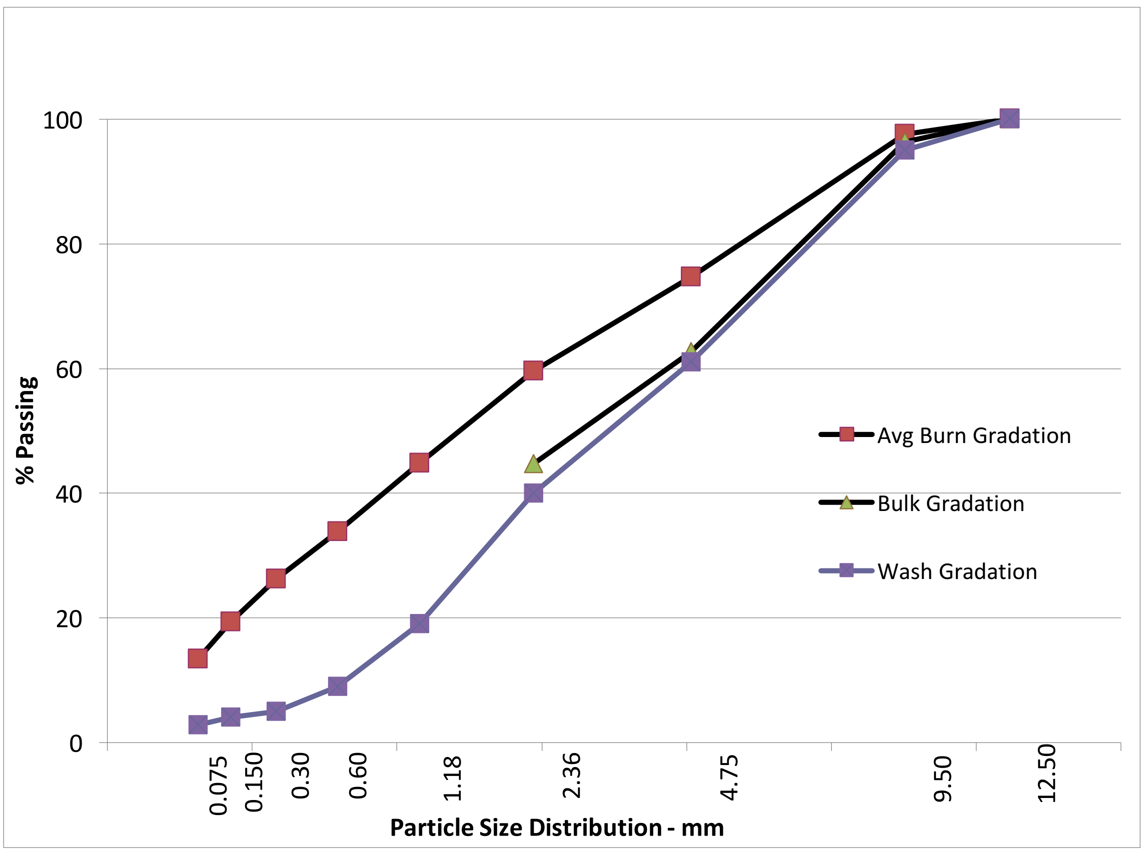

Figure 1: RAP Gradation

Sample Preparation Methods: RAP samples were batched and graded into (18) 2600 g samples, which would allow samples to fit in the direct shear apparatus as well as conserve RAP. Prior to sieving and batching, all RAP materials were dried in an oven at 60°C. This controlled water content during this evaluation. One day prior to compacting, anticipated field water content (6.8%) was added to samples, and samples were placed in containers and covered with plastic to retain water content. This water content was based on the moisture content of the RAP when received from the quarry, which mimics in-situ moisture, as well as an additional 2.0% by mass of water, which represents the amount of water expected to be added during the milling process.

Compaction Methods: RAP samples were placed in a bucket mixer and mixed for 30 seconds before the specific SCM was added, then mixed for one minute. Emulsion was slowly added while mixing, then mixed for one additional minute. In the case of samples which received no SCM, samples mixed for one minute after the addition of emulsion. Throughout mixing of all samples, a spoon was used to ensure uniform coating of the RAP. Upon the completion of mixing, samples were funneled into Superpave gyratory compactor molds, placed in the Superpave gyratory compactor and compacted to 30 gyrations. After compaction, samples were removed from the compactor, placed in protective molds that allowed for air flow, and placed into a 60°C oven to cure for 48 hours. After 48 hours, fully cured samples were removed from the oven and stored at room temperature until further testing was completed, as seen in Figure 2.

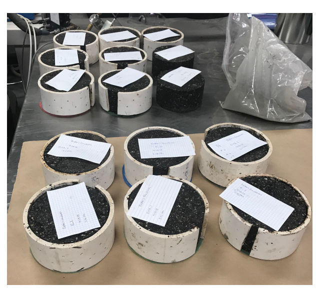

Figure 2: Samples in protective molds stored at room temperature

Bulk Specific Gravity Methods: Bulk specific gravity values were obtained according to the Corelok® method, *AASHTO T331-13 (2017).* After oven curing and storage at room temperature, samples were weighed. Samples were placed in vacuum seal bags, sealed, then weighed. Samples were then placed in a sling in a water bath, and were weighed. Samples were removed from the water bath, removed from vacuum seal bags, then weighed to ensure no water infiltrated the vacuum bag. In the case that water did infiltrate the bag, samples were placed back in their protective molds and allowed to dry out at room temperature for at least 24 hours before bulk specific gravity was repeated. Bulk specific gravity was calculated using recorded weights. Sample calculations may be found in the calculations section to follow.

Direct Shear Test Methods: The direct shear test mimics a hot mix asphalt bond strength test and is being evaluated for use in quantifying strength gain of asphalt emulsion CIR mixtures. This test is performed on a 22-kip load frame with a 5-kip load cell. In order to load the sample into the testing apparatus, a leveling block was placed under one side of the direct shear casing to ensure the sample was placed perpendicular to the shearing force, as seen in Figure 3. The top of the direct shear testing apparatus was placed on top of the sample to create a full casing around the circumference of the sample. The leveling block was removed, and the entire testing apparatus with sample were centered under the loading ram in the load frame, as seen in Figure 4. Modeled after the Marshall Stability test, a 2 inch per minute load rate was selected, with the load applied at the midpoint of the sample until failure.

Figure 3: Sample loaded into testing apparatus

Figure 4: Testing apparatus under loading ram

SAMPLE CALCULATIONS

Bulk Specific Gravity, G_{MB}

VARIABLE	SIGNIFICANCE	FORMULA	SAMPLE CALCULATION – PE_01
A	Wt. of Dry Core in Air before testing, g	--	2641.0
B	Wt. of Sealed Core in Air, g	--	2687.2
C	Wt of Sealed Core in Water, g	--	1289.1
D	Wt. of Dry Core in Air after testing, g	--	2641.1
E	Bag Weight, g	E = (B - A)	E=2687.2-2641.0 E=46.2
F	Bag Ratio	F = A / E	F=2641.0/46.2 F=57.165
G	Large Bag Volume Correction	G= (-0.00166*F+0.8596)	G=(-0.00166*57.165+0.8596) G=0.765
H	Total Volume	H = (E + D) – C	H=(46.2+26441.1)-1289.1 H=1398.2
I	Bag Volume	I = E / G	I=46.2/0.765 I=60.4
J	Sample Volume	J = H – I	J=1398.2-60.4 J=1337.8
K	Bulk Specific Gravity (Gmb)	K = A / J	K=2641.0/1337.8 K=1.974
L	Check: % wt. change (must be -0.08% to +0.04%)	L=(A-D)/A * 100%	L=(2641.0-2641.1)/2641.0 * 100% =0.0%

Theoretical Maximum Specific Gravity, G_{MM}

Calculation of G_{MM} was outside the scope of this project. G_{MM} was assumed to be 2.372 based on previous testing according to *AASHTO T-209-12 (2016).*

Percent G_{MM} Achieved Through Compaction, $\%G_{MM}$

VARIABLE	SIGNIFICANCE	FORMULA	SAMPLE CALCULATION – PE_01
$\%G_{MM}$	Percent G_{MM} achieved through compaction	$\%GMM = \frac{GMB}{GMM} * 100\%$	$\%GMM = \frac{1.974}{2.372} * 100\%$ $\%GMM = 83.2\%$

Workability Energy Index, CIR-WEI

VARIABLE	SIGNIFICANCE	FORMULA	SAMPLE CALCULATION – PE_01
CIR-WEI	Workability Energy Index	$CIR - WEI = \frac{\frac{\pi d^2}{4} * Pressure * (h_{n=0} - h_{76})}{N_{76}}$	$CIR - WEI = \frac{\frac{\pi 0.15^2}{4} * 599.2 * (90 - 85.6)}{2}$ $WEI = 23.3$

Shear Strength

VARIABLE	SIGNIFICANCE	FORMULA	SAMPLE CALCULATION – PE_01
τ	Shear Strength	$\tau = \frac{Peak\ Load\ (lb)}{Area}$	$\tau = \frac{3861.88\ lb}{\pi * 3\ in^2}$ $\tau = 136.59\ psi$

RESULTS AND DISCUSSION

Compaction

Using data collected during sample compaction in the Superpave Gyratory Compactor CIR-WEI were calculated for each sample. Sample calculations may be found in the sample calculation section. Since samples were compacted to a set number of gyrations rather than to a specific $\%G_{MM}$, CEI and TDI were not able to be calculated, since the target $\%G_{MM}$ for CEI and TDI were not achieved in 30 gyrations.

Table 4 includes final values used in analysis and calculations. Figure 5 offers a graphical representation of the average compaction curve for each sample type. It is noted that the presence of SCM's resulted in an increased $\%G_{MM}$, as seen in the curves that are shifted up relative to samples that contained emulsion only. This shift up indicates the samples were compacted to a higher density with fewer gyrations, thus indicating a more easily compacted mixture. It is seen in Figure 5 that samples reached 76% G_{MM} before 8 gyrations, so CDI calculations could not be performed.

Table 4: Calculated Compaction Values

Characteristic	Sample Name	G_{mm}	G_{mb}	Final $\%G_{mm}$	WEI	WEI St. Dev	Average Pressure (kPa)
Emulsion Only	CE_01	2.372	1.995	84.1	23.8	0.551	599.4
	CE_02	2.372	1.993	84.0	24.4		599.1
	CE_03	2.372	1.977	83.3	24.9		599.2
	PE_01	2.372	1.974	83.2	23.3	0.354	599.2
	PE_02	2.372	2.016	85.0	23.8		599.1
	Average		1.991	83.9	24.04		599.2
Emulsion and Fly Ash	CE_FA_01	2.372	2.025	85.4	23.8	0.346	599.3
	CE_FA_02	2.372	1.980	83.5	24.4		599.2
	CE_FA_03	2.372	2.012	84.8	24.4		599.3
	PE_FA_01	2.372	2.024	85.3	23.8	0.289	599.2
	PE_FA_02	2.372	2.014	84.9	23.8		599.1
	PE_FA_03	2.372	2.012	84.8	23.3		599.3
	Average		2.011	84.8	23.9		599.233
Emulsion and Portland Cement	CE_PC_01	2.372	2.092	88.2	21.7	1.848	599.9
	CE_PC_02	2.372	2.091	88.1	21.7		599.9
	CE_PC_03	2.372	2.057	86.7	24.9		599.2
	PE_PC_01	2.372	2.028	85.5	20.7	1.343	599.5
	PE_PC_02	2.372	1.983	83.6	22.8		599.3
	PE_PC_03	2.372	1.994	84.1	21.7		599.4
	PE_PC_04	2.372	1.992	84.0	23.8		599.3
	Average		2.034	85.7	22.5		599.5

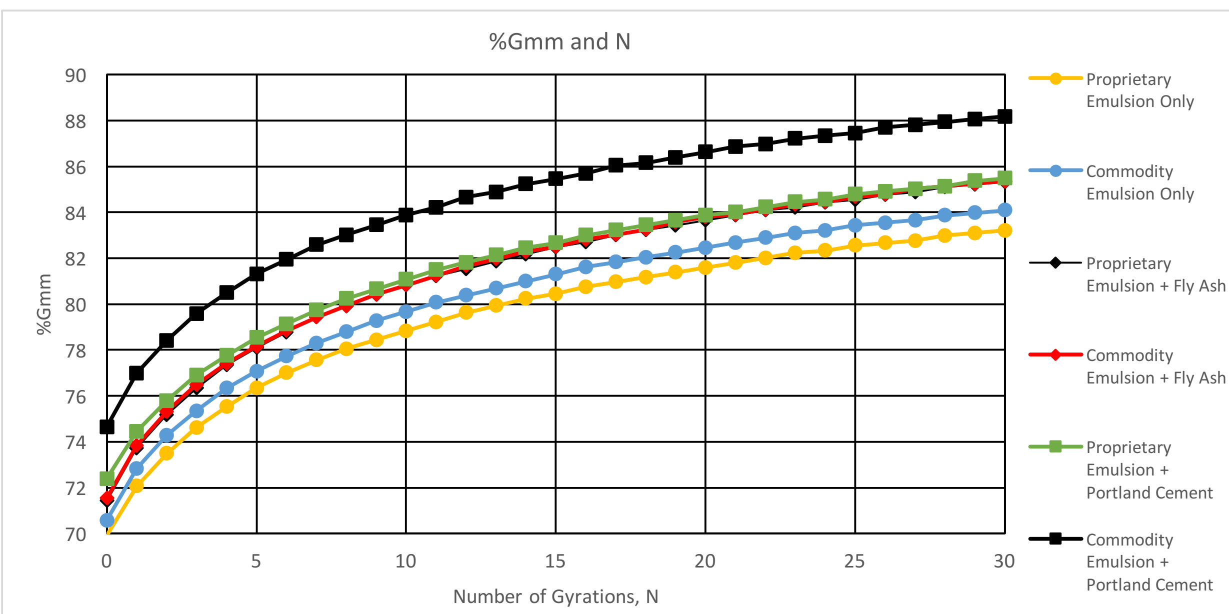

Figure 5: Compaction Curve

Figure 6 offers a direct comparison for average CIR-WEI values calculated for each sample type. Error bars were included to represent error among samples. Comparing average values only, it appears that samples containing fly ash behaved similarly to samples containing emulsion only. Since samples containing fly ash and samples containing emulsion only had increased CIR-WEI compared to samples containing Portland cement, less energy would be required for placing and compaction. But, when considering average values and error, it does not appear that there was a significant difference in CIR-WEI values among sample types.

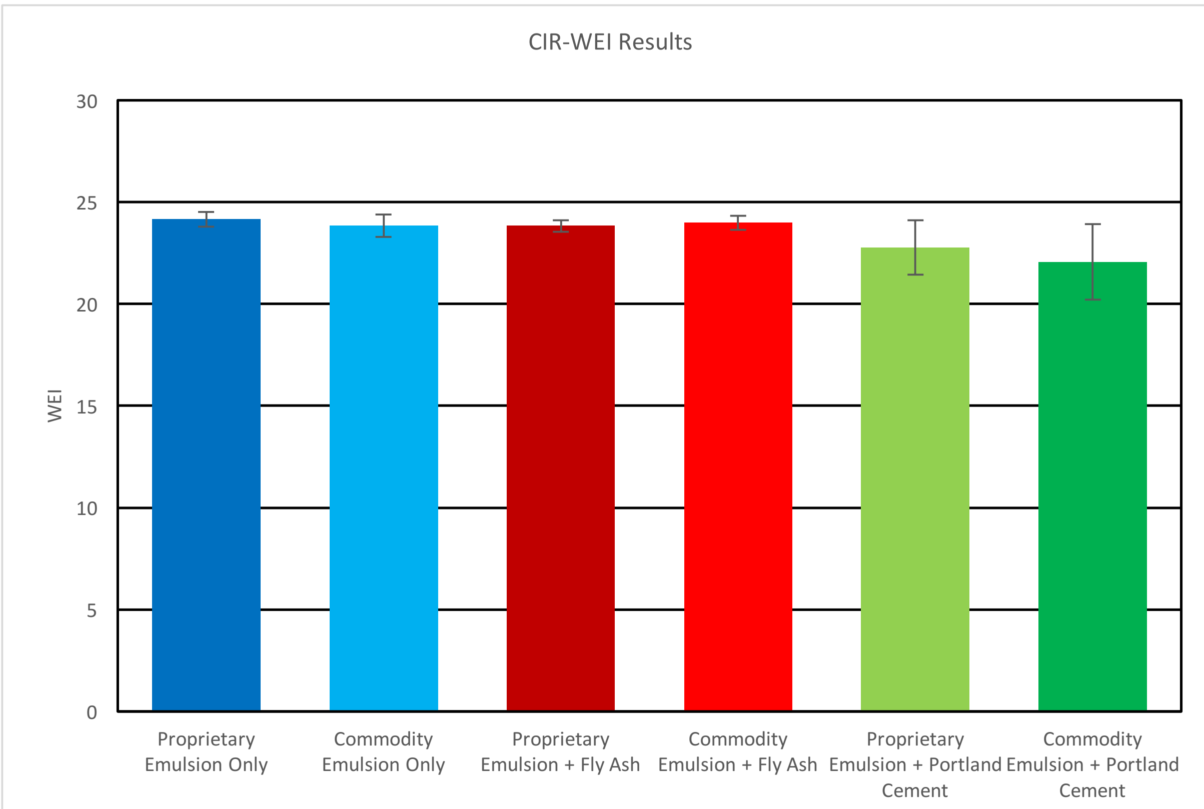

Figure 6: Average CIR-WEI values with error

Since there was no significant change in workability, it may be noted that the use of SCM's may be justified. Previous studies have shown performance benefits due to the presence of Portland cement such as early strength gain and resistance to moisture damage (Cox, 2015).

Additionally, previous studies have shown performace benefits due to the presence of fly ash such as early rutting and raveling prevention (Thomas, et. al, 2000).

Direct Shear

Using data collected from direct shear tests, direct shear strength was calculated for each sample. Sample calcultions may be found in the sample calculations section. Table 5 includes final values used in calculations and anaylsis. Figure 7 offers a direct comparison of average direct shear strengths. It appears that direct shear strengths are not significantly different for each sample type. The lack of siginificant difference may be due to the curing time of samples. Samples cured for over 30 days before direct shear testing could be performed. Benefits of an admixutre such as fly ash are most noteable in early stages (Thomas, et. al, 2000).

Table 5: Direct Shear Test Values

Direct Shear Test			
Sample ID	**Peak Load (lb)**	**Shear Strength (psi)**	**St. Dev. (psi)**
CE_01	3529.44	124.83	-
CE_02	3575.93	126.47	-
CE_03	3835.03	135.64	-
CE_Avg	3647	128.98	5.82
CE+FA_01	4092.53	144.74	-
CE+FA_02	3928.69	138.95	-
CE+FA_03	4011.10	141.86	-
CE+FA_Avg	4011	141.85	2.90
CE+PC_01	3816.56	134.98	-
CE+PC_02	3905.35	138.12	-
CE+PC_03	3578.56	126.57	-
CE+PC_Avg	3767	133.22	5.98
PE_01	3861.88	136.59	-
PE_02A	2405.33	85.07	-
PE_Avg	3134	110.83	36.43
PE+FA_01	3538.77	125.16	-
PE+FA_02	3474.55	122.89	-
PE+FA_03	4279.68	151.36	-
PE+FA_Avg	3765	133.14	15.83
PE+PC_01	3648.05	129.02	-
PE+PC_02	3614.82	127.85	-
PE+PC_03	3808.93	134.71	-
PE+PC_04A	3868.16	136.81	-
PE+PC_Avg	3735	132.10	4.34

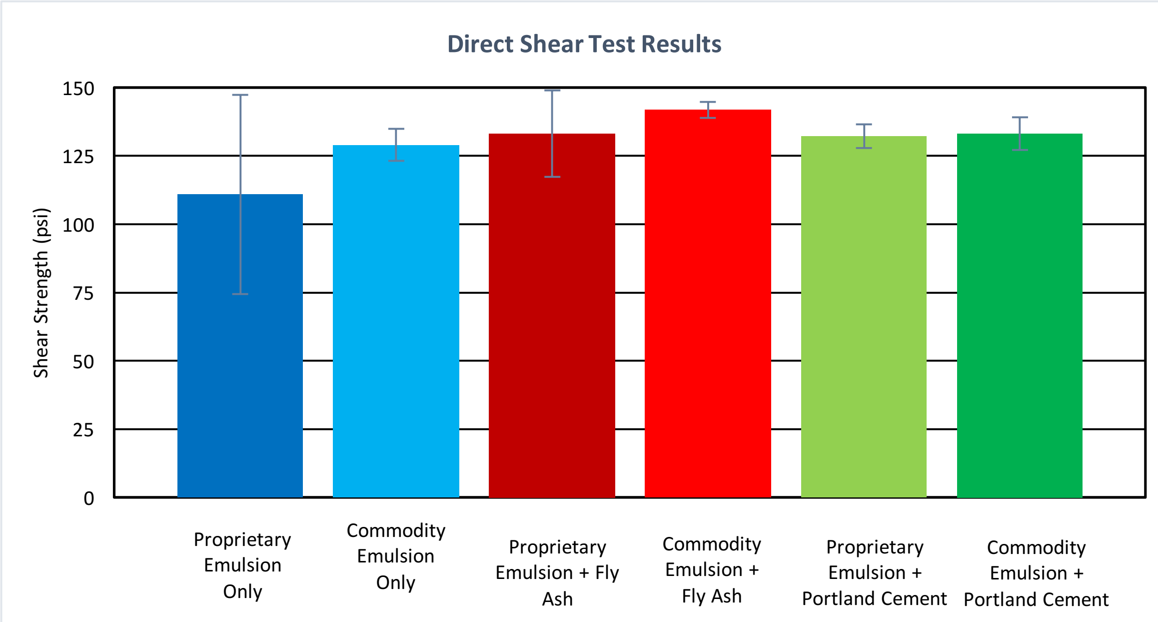

Figure 7: Average direct shear strength with error

Conclusions

Despite its economic and environmental benefits, the widespread use of Cold In-Place Recycling (CIR) is currently inhibited by a lack of laboratory testing and evaluation, specifically in the areas of compactability and workability of the reclaimed mixture stabilized with asphalt emulsion. The purpose of this study was to explore the influence of admixtures in CIR using modified Superpave Gyratory Compactor (SGC) compaction metrics.

The test methods in this study included compaction in a Superpave Gyratory Compactor, bulk specific gravity using the Corelok® method, and direct shear. These methods were selected to characterize compactability, workability, and shear strength. Workability was measured using the modified SGC metric of CIR-WEI.

Based on compaction testing, there was no significant change in the workability metric for samples containing SCM's. Since no significant adverse or beneficial change was noted in CIR-WEI, other strength tests may be performed on RAP samples containing SCM's to determine the advantages or disadvantages of a MCB approach. It can be noted that CIR-WEI values in this research are double that of previous research with similar parameters (Yeung and Braham, 2018).

The strength test performed in this study, direct shear test, revealed that the only statistically significant difference in strength was between samples containing commodity emulsion only and samples containing commodity emulsion and fly ash. There was no significant change in shear strength in all other samples, indicating that direct shear is not a characteristic that the presence of SCM's impacts. Further exploration of the effects of admixtures, such as Portland cement and fly ash, on the compactability, workability, shear strength, and other strength characteristics of MCB CIR will contribute to the growing body of knowledge surrounding CIR.

CIR is an inherently sustainable and economically viable process, since there is limited waste and reduced material input. A MCB approach to CIR adds another level of sustainability, specifically when fly ash is the SCM, since fly ash is a waste byproduct of the coal burning industry. Increased research in the area of CIR will only expand its body of knowledge, which may lead to increased implementation of sustainable, pavement recycling treatments.

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