Improve Material Inputs into Mechanistic Design for Reclaimed HMA & Recycled Concrete Aggregate (RCA) in Roadways

Task 2 – Data Collection

Revised Report Submission

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1. INTRODUCTION

4.3 million km (2.6 million miles) out of 6.6 million km (4.1 million miles) of total public roads are paved roads in the United States of America (Bureau of Transportation Statistics (BTS 2017) and more than 90% of the paved roads are flexible pavements (Copeland 2011). The main function of flexible pavements is distributing the vehicle loads to the layers beneath the asphalt surface layer (e.g. base, subbase, and subgrade layers). Thus, the characteristics and properties of these layers are very important for the long-term pavement performance (Little and Nair 2009, Tutumluer et al. 2015). Aggregate base layer is the first layer beneath the asphalt surface (Cosentino and Kalajian 2001; Yohannes et al. 2009). It is made of coarse-grained aggregates to provide a stiff and highly permeable layer (Schuettpelz et al. 2010, Haider et al. 2014, Cetin et al. 2014, Edil and Cetin 2015). The high stiffness of aggregate base layer improves the stability of the sublayers by improving the vertical load distribution (Zornberg 2017). Therefore, stiffer base course has less permanent deformation and increases the lifespan of the pavement (Edil et al. 2012a). Highway base layer is a very critical component of pavement structures. There are two primary functions of highway base layers: (1) acting as a foundation to provide adequate mechanical support to the asphalt or concrete layer to prevent fatigue and occurrence of rutting failures, and (2) providing adequate drainage to move the excessive infiltrated water out and away from the pavement structure. Materials used in highway base layer construction are responsible for distributing the wheel loads uniformly to the subgrade layer so they can protect the subgrade layer from excessive loading at a single location and ultimately increase the service life of the pavements (Yoder and Witzack 1975, Xiao et al. 2011). It is very well known that majority of the rutting failures occur due to lack of required mechanical properties of the materials used in the highway base layer construction (Tutumluer and Pan 2008, Xiao et al. 2011).

While large amounts of virgin unbound granular materials are used for the aggregate base layers in pavement constructions (Perkins et al. 2005, Haider et al. 2014, Hatipoglu et al. 2020), the lack of good quality material availability and high cost of virgin aggregates (VA) have made engineers to look for alternative sources such as recycled concrete aggregates (RCAs) and recycled asphalt pavements (RAPs). These materials additionally provide environmental benefits for being recycled materials. As a result, in this project alternative materials are being investigated to see if they meet the essential pavement performance criteria. The main focus of this project is to collect index and performance data of these two types of recycled base materials. Therefore, this task reports the properties of these materials used in such applications.

Department of transportations (DOTs) nationwide have been trying to implement the mechanistic pavement design approach (Rahn and Biehler 2008) for pavement design and analyses. The Mechanistic-Empirical Pavement Design Guide (MEPDG) represents a major improvement over its predecessors. However, accurate and reliable data first must be collected to take the advantage of such improvements in the pavement design. In this pavement design approach, pavement performance is evaluated based on mechanistically determined critical stresses, strains, temperatures, and moisture levels that are in turn the inputs to empirical prediction models for specific pavement distresses such as rutting, fatigue cracking, thermal cracking, and roughness for flexible pavements and cracking, faulting, and roughness for rigid pavements. Accurate characterization of the traffic, climate, and material input parameters is therefore important to ensure that the theoretical computation of pavement stresses, strains, temperatures, and moisture levels are accurate at the critical locations within the system. Depending on the desired level of accuracy of input parameter, three levels of input are provided from Level 1 (highest level of accuracy) to level 3 (lowest level of accuracy). Depending on the criticality of the project and the available resources, the designer has the flexibility to choose any one of the input levels for the design as well as use a mix of levels.

The material parameters required for pavement foundation materials including unbound granular materials, subgrade, and bedrock may be classified in one of three major groups: (1) pavement response model material inputs, (2) Enhanced Integrated Climatic Model (EICM) material inputs, and (3) other material inputs. Pavement response model materials input required are resilient modulus (Mr) used for quantifying the stress dependent stiffness of unbound materials under moving wheel loads. Material parameters associated with EICM are those parameters that are required and used by the EICM models to predict the temperature and moisture conditions within a pavement system. These inputs include Atterberg limits, gradation, and saturated hydraulic conductivity.

This task reports the collected data for RCA and RAPs used in highway base layers and provide recommendations about how to use this data for pavement design and analysis.

1.1. BACKGROUND

Use of recycled materials promotes sustainability in roadway construction by reducing consumption of energy and emission of greenhouse gases associated with mining and production of natural aggregates (Lee et al. 2010 and Lee et al. 2011). Recycled materials often manifest mechanical behavior that is distinct from that of natural aggregate due to the composition and the nature of particulate characteristics. The most widely used recycled aggregates in roadway construction are recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA) (Edil et al. 2012a). The performance of a pavement system mostly depends on stiffness of the pavement structure under specified traffic loads and environmental conditions. RAP and RCA have comparable stiffness to natural aggregates that are currently used in roadway base course applications (FHWA 2008, Guthrie et al., 2007, Edil et al. 2012a). Hence, their performance should be evaluated based upon their relative engineering or index properties.

In order to obtain recycled asphalt pavement (RAP), old asphalt pavement surfaces are milled to a specific depth (depending on the asphalt course thickness) and then processed (Edil 2011). In simple terms, RAP is a mixture of aged bitumen and aggregate, which is obtained as a by-product of pavement milling (Taha et al. 1999). On the other hand, RCA was obtained via crushing of the existing hardened concrete of old pavement surfaces or other structures (e.g. buildings and bridges) (Edil et al. 2012a).

RAP and RCA can be either used at the same construction site or stockpiled for future applications. Producing and using them at the same construction site can help to reduce the cost and the duration of the construction. In fact, up to 30% of cost savings could be achieved by in-place recycling for a recycled aggregate generation (Edil 2011).

The properties of RAP or RCA as an unbound aggregate are certainly depending on several factors that relate back to the production of asphalt or concrete as well as the processes followed during the production of RAP or RCA. Some of these factors are listed below:

- The type of the road (interstate highway, arterial highway, or parking lot) that is milled may affect the binder content of the produced RAP since different bituminous content are used in different asphalt mixtures.
- The regional differences in location of the milled road may result in different RAPs and RCAs due to different geological composition and formation of aggregates.
- Processing operation that is used to create RAP and RCA may affect the grain size distribution of these materials due to the different opening sizes of the screens used by the different milling operation stations.

- The time of exposure of RAP and RCA to atmospheric conditions during stockpiling may affect the stiffness of the binder content of RAP as asphalt changes its properties when exposed to drastic temperatures (cold or hot) for a long period of time (Ullah and Tanyu 2019) and carbonation of remaining cement content in RCAs (Bestgen et al. 2016).
- The type of concrete, quality of raw materials, water/cement ratio, coarse/fine aggregate ratio, age of concrete, compaction of concrete, temperature, relative humidity and curing of concrete can affect the strength of the recycled concrete all of which come from the origin of RCA.

1.2. DATA ON RCA AND RAP PROPERTIES

Material characteristics such as mineralogy, gradation, angularity, texture, and durability are different for each RCA and RAP materials, and these differences affect the engineering properties of them (Tutumluer 2013, Tan et al. 2014). The index properties of RAP and RCA are also highly affected by several factors such as the aggregate source, the aggregate type, and the type of crushing operations. While determining the properties of these recycled materials before the pavement design and construction is preferred, it may be costly and take a long time to be completed for DOTS. Therefore, it is important to establish a database with the information collected from previous studies which would provide some insight information about the boundaries and average properties of these materials and can be used by DOTs during pavement analyses and designs. Table 1 summarizes the list of the RCA/RAP data collected from the literature. It also shows the number of available data for each characteristic along with the corresponding data source.

Approximately 50 different studies were examined to create Table 1. The RCA and RAP materials for the available data was captured for the states of Minnesota, Colorado, Michigan, California, Texas, Ohio, New Jersey, Wisconsin, Illinois, Montana, Virginia, Florida, Tennessee, Maryland, New Mexico, Washington, Utah and Rhode Island. The laboratory data of more than 40 different recycled samples were collected in terms of geomechanical properties. Most of the samples used in the studies were 100% recycled materials, while there were also some blended RCA-RAP materials with natural aggregates at different mixture ratios.

TABLE 1. LIST OF THE COLLECTED DATA AND CORRESPONDING RESOURCES

Ref.	**Location**	**Type of Material**	**Grain Size Distribution**	**Atterberg Limits**	**Compaction**	**Hydraulic Conductivity**	**Shear Strength**	**CBR**	**Resilient Modulus**	**R Value**
Edil et al. (2012a)	MN, MI, CO, CA, TX, OH, NJ, WI	Aggregate Class 5 (MN)	1		1	1			26	
		Blend (50%RCA 50% Class5)	1		1	1			2	
		RAP	7		7	7			96	
		RCA	7		7	7			96	
		RPM	2		2	2			4	
Edil et al. (2012b)	WI	RPM	1	1	1				1	
Edil et al. (2012c)	MN	RPM	1		1			1	1	
Tutumluer et al. (2015)	IL	60%RCA+ 40% RAP	1				6		6	
		100% RAP	1		1			1	6	
Locander (2009)	CO	RAP	11	11	11	11			45	11
Mokwa and Peebles (2005)	MT	RAP CBC#1	3		3	3				
		RAP CBC#2	3		3	3				
		RAP CBC#3	3		3	3	24			48
		RAP pitrun	3		3	3	24			48
Ullah and Tanyu (2019)	VA	RAP	4	5				16	21	
Saeed (2008)	FL	RAP	3		3		3			
Bennert et al. (2000)	NJ	DGABC	1		1				1	
		RAP	1		4		3		4	
		RCA	1		4				4	
Kim et al. (2005)	MN	RAP	4		4				16	

Ref.	**Location**	**Type of Material**	**Grain Size Distribution**	**Atterberg Limits**	**Compaction**	**Hydraulic Conductivity**	**Shear Strength**	**CBR**	**Resilient Modulus**	**R Value**
Huang and Dong (2014)	TN	RAP	1		3				9	
Mijic et al. (2019)	MD	RAP	7		7	7				
Ullah et al. (2018)	VA	RAP	4	4	4				PD=11	
Edil et al. (2017)	MN	RAP	1		1				2	
		RCA	2		2				4	
Hasan et al. (2018)	NM	RAP	3		1				16	
Abdelrahman and Noureldin (2014)	MN	RAP			3				9	
Cosentino and Bleakley (2013)	FL	RAP						3	PD=3	
Cosentino et al. (2013)	FL	RAP	1		8			8		
Wu et al. (2012)	WA	RAP	1		5	5			20	
Puppala et al. (2012)	TX	RAP	1		1				5	
Attia et al. (2013)	MN	RAP							PD= 6	
Soleimanbeigi and Edil (2015a)	WI	RAP	1		2				7	
Soleimanbeigi and Edil (2015b)	WI	RAP	1		1	1				
		RCA	1		1	1				

Ref.	Location	Type of Material	Grain Size Distribution	Atterberg Limits	Compaction	Hydraulic Conductivity	Shear Strength	CBR	Resilient Modulus	R Value
Soleimanbeigi et al. (2015)	CA, TX, NJ, MI, CO, MN	RAP	4		4					
		RCA	4		4					
Kang et al. (2011)	MN	RAP				4	4		4	
		RCM	4			4	4		4	
Camargo et al. (2013)	WI	RPM	1		1			1	1	
Attia and Abdelrahman (2010a)	MN	RAP			11				12	
Attia and Abdelrahman (2010b)	MN	RAP	6	6	12				11	
Guthrie et al. (2007)	UT	RAP	4	4	4					
Bradshaw et al. (2016)	RI	RAP	7		7				7	
Alam et al. (2010)	MN	RAP	5						5	
Attia and Abdelrahman (2011)	MN	RAP			7				4	
Bennert and Maher (2005)	NJ	RAP	1			8	1	8	4	
		RCA	1			8	1	8	4	

Ref.	Location	Type of Material	Grain Size Distribution	Atterberg Limits	Compaction	Hydraulic Conductivity	Shear Strength	CBR	Resilient Modulus	R Value
Bestgen et al. (2016)	Eastern USA	RCA	2		2			13	24	
Tutumluer et al. (2012)	IL	RCA	3		3			3	3	
Natarajan et al. (2019)	MN	RCA	4		4					
Mahedi and Cetin (2020)	TX, IA, MN	RCA	5		5					
Chen et al. (2013)	CA, CO, MI, MN, WI, TX	RCA	7		7	7				
Diagne et al. (2015)	WI	RCA	1		1	1			3	
Cetin et al. (2020)	MN	RCA	3	3	6	3			3	
Total	United States of America	RCA	47	3	47	32	5	24	153	0
		RAP	92	31	126	57	66	38	316*	107

Notes: *It only represents resilient modulus of materials and permanent deformations were not counted for this number. PM= Recycled pavement material; CBC= Crushed base course; RCM= Recycled concrete material; DGABC= Dense graded aggregate base course; PD= Permanent Deformation; CBR= California Bearing Ratio; R-Value= Measures the response of compacted aggregates to a vertically applied pressure under specific conditions. Class 5 is an aggregate base layer specification from MnDOT (2018) report.

2. PHYSICAL PROPERTIES OF RAP AND RCA

2.1. GRADATION CHARACTERISTICS

Gradation of the aggregates affects the engineering properties of granular materials such as hydraulic conductivity, shear strength, stiffness, and frost-susceptibility (Saeed 2008). Original aggregate type, milling operations, and the crushing methods affect the gradation of RAP and RCA (Cosentino and Kalajian 2001).

The first material characteristics for the database was selected as the index properties, which mainly consists of the gradation of aggregates. Gradation characteristics database include gravel, sand, silt and clay contents, effective diameter sizes (D_{60}, D_{30} and D_{10}), and coefficient of uniformity (C_u) and coefficient of curvature (C_c). Approximately 190 different aggregate materials including blends with natural aggregate were included in the gradation database.

It was observed that the gradations of RAPs were generally similar to natural aggregates; however, depending on the method used, RAPs were likely to contain lower fines content (Chesner et al. 1998). Per MnDOT guideline and applications, RAPs can be considered as a Class 7 aggregate based on their comparable gradation curves whereas RCA can be considered as Class 5 aggregate based on their comparable gradation curves (LRRB 2016).

Asphalt content (~ 4.5% - 6%) and trapped air between asphalt coating and aggregate particles cause lower specific gravity values for RAP than that of natural aggregates (Cosentino et al. 2003). RCA also has a relatively lower specific gravity than natural aggregates due to the presence of mortar in RCA matrix (Snyder et al. 1994). This is well shown in our database when comparing the specific gravities of the recycled materials with natural aggregates (Appendix A and Table 2). The G_s of RAP ranges from 2.19 to 2.87 with the median value of 2.4 while G_s of RCA is between 2.12 and 2.7 with the median value of 2.39.

94.1% is the highest gravel percent reported for RCA in Mahedi and Cetin (2020) while Edil et al. (2017) reported the lowest gravel content (31.8%) for RCA. On the other hand, Alam et al. (2010) showed 4% gravel content for a RAP material which was the lowest gravel percent in the database. Locander (2009) reported the highest gravel percent for a RAP material which contained 75% gravel. Finally, the median gravel percent of RAP and RCA is reported to be 45% (Guthrie et al. 2007) and 51% (Diagne et al. 2015), respectively.

The highest sand content in RCA was reported to be 64.9% (Edil et al. 2012a) while Mahedi and Cetin (2020) used a RCA with 4.9% sand which was the lowest sand percent in the database. The highest and lowest sand contents for RAP materials were 97% and 28.1%, respectively. At last, the median value of sand content is 54% and 46.3% for RAP and RCA, respectively.

12.8% is the highest fines percent for RCA (Edil et al 2012a) while 0.1% is the lowest fines percent as reported in Mahedi and Cetin (2020). On the other hand, RAP’s lowest fines content is 0% in Alam et al. (2010) study while Camargo et al. (2013) reported highest fines content in RAP with 11%. In summary, the median value of fines percent is 1% and 2.8% for RAP and RCA, respectively.

Table 2. summarizes the gradation table in Appendix A by providing maximum, minimum and median value of RAPs and RCAs according to the database.

Appendix A reports the specific gravities and gradation characteristics (sand and fines percent are shown along with D_{10}, D_{30}, D_{60}, C_c and C_u) of the materials for each study. According to Appendix A, all of the RAPs and RCAs are classified as coarse-grained soils. Since most of the materials had fines content lower than 12%, they were all classified either well-graded gravel (GW) and poorly graded gravel (GP) or well-graded sand (SW) and poorly graded sand (SP)-SW.

TABLE 2. INDEX PROPERTY RANGES OF RCA AND RAP

Characteristics	RAP			RCA		
	Lower Limit	Median	Upper Limit	Lower Limit	Median	Upper Limit
% Gravel	3	45	68.1	31.8	51	94.1
% Sand	28.1	54	97	4.9	46.3	64.9
% Fines	0	1	11	0.1	2.8	12.8
D_{10} (mm/inch)	10^{-1}/ $3.9x10^{-3}$	$5x10^{-1}$/ $1.96x10^{-2}$	1/ $3.93x10^{-2}$	10^{-1}/ $3.9x10^{-3}$	$2.3x10^{-1}$/ $9x10^{-3}$	$4.3x10^{-1}$/ $1.7x10^{-2}$
D_{30} (mm/inch)	$8x10^{-2}$/ $3.1x10^{-3}$	1.5/ $6x10^{-2}$	4.9/ $1.9x10^{-1}$	$2x10^{-1}$/ $7.9x10^{-3}$	1.2/ $4.72x10^{-2}$	6.5/ $2.56x10^{-1}$
D_{60} (mm/inch)	$1.5x10^{-1}$/ $5.9x10^{-3}$	4.82/ $1.89x10^{-1}$	10.4/ $4.09x10^{-1}$	$6x10^{-1}$/ $2.36x10^{-2}$	6.8/ $2.67x10^{-1}$	16.3/ $6.42x10^{-1}$
C_u	5	10.65	40	2.1	32	66
C_c	0.21	1.2	8	0.14	1.4	6
G_s	2.19	2.395	2.87	2.12	2.39	2.7

Notes: 52 gravel, sand and fines contents data were collected for RAPs from different sources, while 30, 27 and 27 data were used to determine the lowest, median and highest values of D_{10}, D_{30} and D_{60} for RAPs, respectively. 35 C_u, 37 C_c, and 38 G_s data were available to derive lower,median and upper limits of RAPs. 34 gravel, sand and fines contents data were collected for RCAs from different sources, while 19, 17 and 17 data were used to determine the lowest, median and highest values of D_{10}, D_{30} and D_{60} for RCAs, respectively. 29 C_u, 29 C_c, and 32 G_s data were available to derive lower,median and upper limits of RCAs.

2.2. COMPACTION CHARACTERISTICS

The general trend of Proctor compaction tests shows that RAP and RCA have lower maximum dry unit weight than natural aggregates (Figure 1, Figure 2, Figure 3 and Figure 4). Table 3 summarizes the compaction characteristics (MDU and OMC) of RCA and RAP materials collected for the database. MDU of RAP ranges between 17.2 kN/m^3 (110 pcf) and 24.1 kN/m^3 (155 pcf) with the median value of 19.6 kN/m^3 (126 pcf). The limits of MDU for RCA is 18.3 kN/m^3 (118 pcf) and 21.7 kN/m^3 (140 pcf) with the median of 19.7 kN/m^3 (127 pcf). OMC of RAPs ranges between 4% and 10.7% with the median to be 6.05% while OMC of RCA ranges between 6.1% and 14.8% with the median of 10.8%. Figures 3 and 4 show that the voids in RAP matrix cannot be filled effectively because of low fines contents which yields to a lower maximum dry unit weight (Locander 2009; Blankenagel and Guthrie 2006).

RAP possesses hydrophobic properties due to the asphalt coating around aggregate particles and this contributes RAP materials to have lower optimum water content (Figure 5 and Figure 6). On the other hand, RCA shows hydrophilic properties due to concrete mortar residues thus a higher optimum moisture content is reported as a result of higher water absorption capacity of RCA (Figure 7 and Figure 8) (Edil et al. 2012a, Nokkaew et al. 2012, Sayed et al. 1993, Rahardjo et al. 2010). In addition, the hydration and cementation of dehydrated cement particles in RCA may cause a reduction in the dry unit weight of RCA. Furthermore, higher fines contents in RCA cause a higher optimum water content due to an increase in the surface area and absorption capacity of aggregate and cement particles (Jayakody et al. 2012). On the other hand, lower maximum dry unit weights of RAP may be due to their lower specific gravities caused by asphalt content and low fines contents (Guthrie et al. 2007, Locander 2009).

The reduction in the maximum dry unit weight (MDU) of recycled aggregate-natural aggregate mixtures is directly proportional to the RAP and RCA contents in the mixtures (Taha et al. 1999). Higher rate of reductions in the maximum dry unit weights were observed with an increase in recycled aggregate contents in the mixtures (Bennert et al. 2000). Moreover, using more RAP content in the RAP-natural aggregate mixtures caused further reductions in the optimum water content (Locander 2009) while use of a higher amount of RCA in the RCA-natural aggregate mixtures caused an increase in the optimum moisture content (OMC) (Bennert et al. 2000).

According to our database, the compaction results were mostly obtained from materials compacted at modified Proctor compaction energy. Therefore, it is recommended to use modified Proctor compaction data for analyses.

TABLE 3. COMPACTION CHARACTERISTICS RANGES OF RCA AND RAP

Characteristics	RAP			RCA		
	Lower Limit	Median	Upper Limit	Lower Limit	Median	Upper Limit
MDU (kN/m^3)/(pcf)	17.2 (110)	19.6 (126)	24.1 (155)	18.3 (118)	19.7 (127)	21.7 (140)
OMC (%)	4	6.05	10.7	6.1	10.8	14.8

Notes: MDU=Maximum dry density, OMC=optimum moisture content. 46 and 35 MDU and OMC data were collected for RAPs and RCAs, respectively. Number of samples collected for each parameter are presented in parantheses.

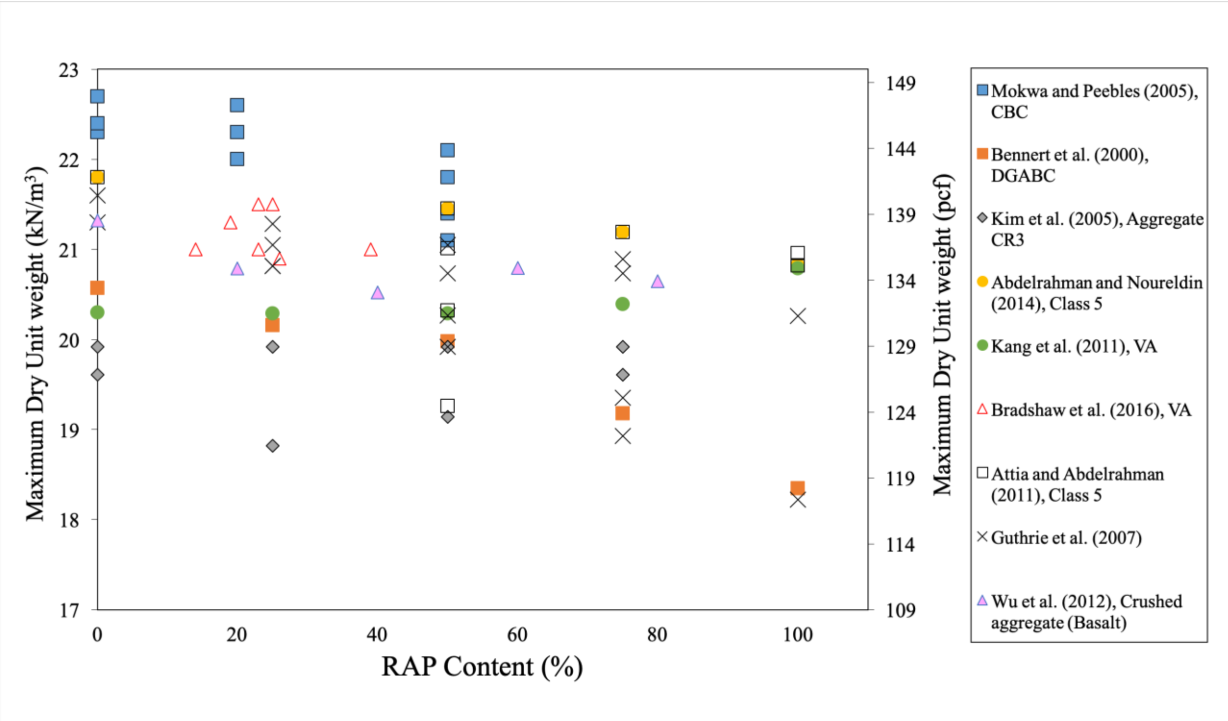

FIGURE 1. MAXIMUM DRY UNIT WEIGHT (MDU) VERSUS RAP CONTENT

Notes: CBC= Crushed base course; DGABC= Dense graded aggregate base course; CR3= County Road 3; VA= Virgin aggregate

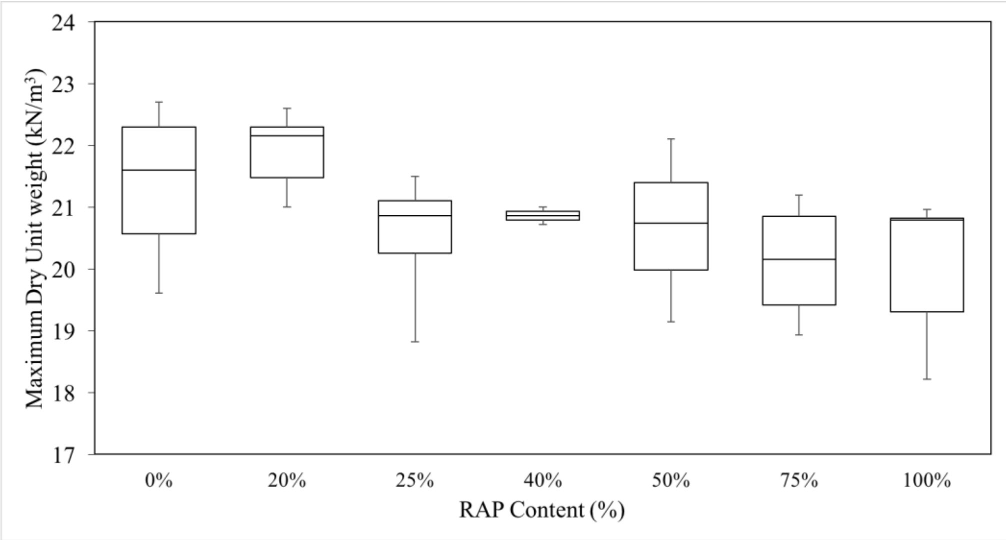

FIGURE 2. MAXIMUM DRY UNIT WEIGHT (MDU) VERSUS RAP CONTENT (WHISKER PLOT)

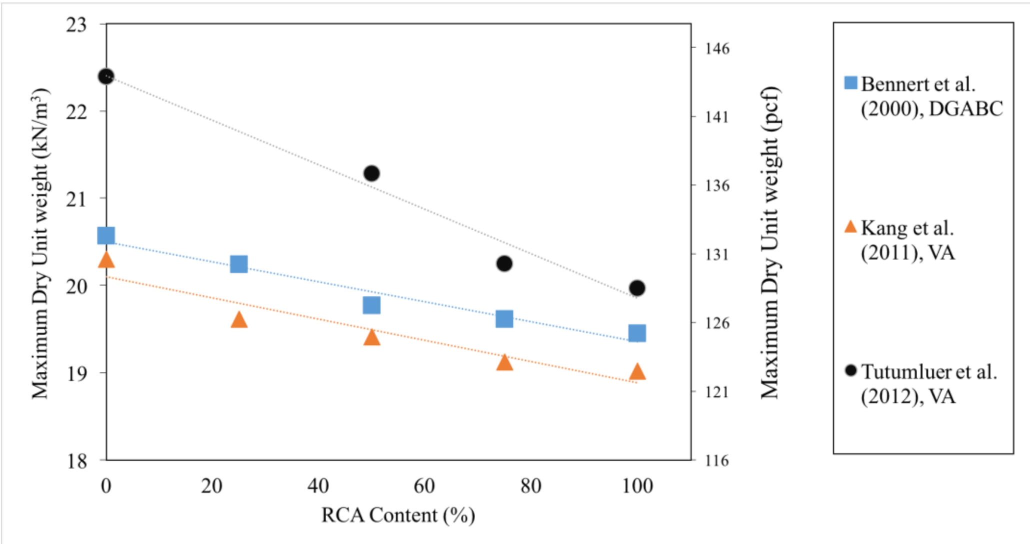

FIGURE 3. MAXIMUM DRY UNIT WEIGHT (MDU) VERSUS RCA CONTENT

Notes: DGABC= Dense graded aggregate base course; VA= Virgin aggregate

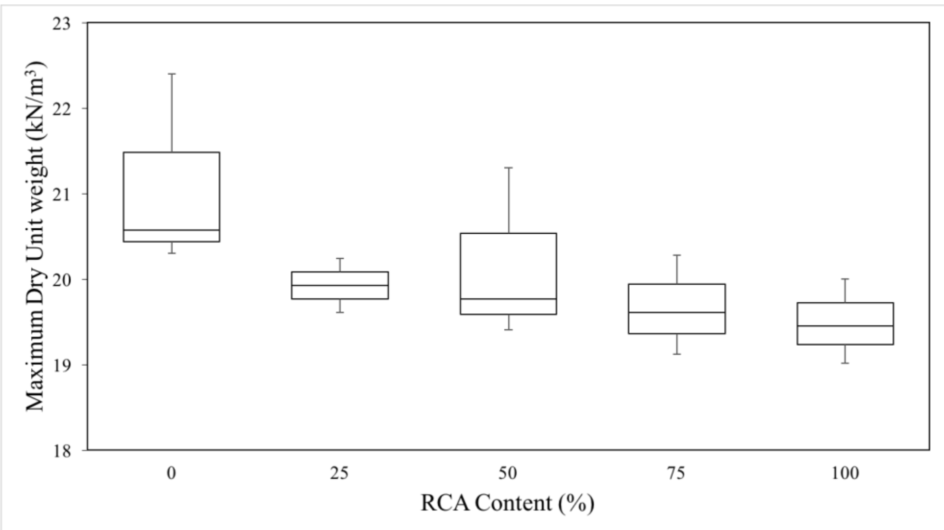

FIGURE 4. MAXIMUM DRY UNIT WEIGHT (MDU) VERSUS RCA CONTENT (WHISKER PLOT)

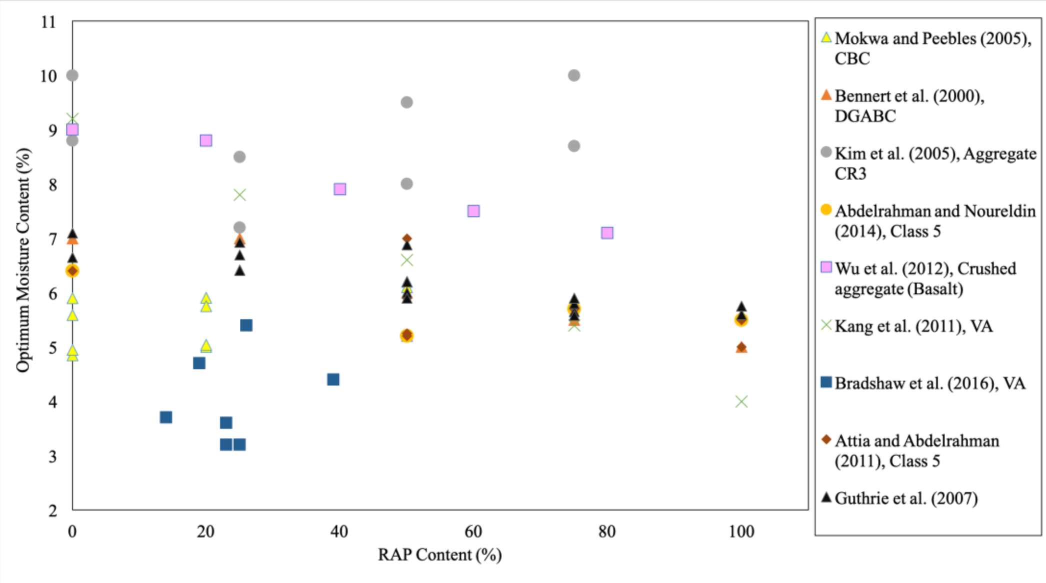

FIGURE 5. OPTIMUM MOISTURE CONTENT (OMC) VERSUS RAP CONTENT

Notes: CBC= Crushed base course; DGABC= Dense graded aggregate base course; CR3= County road 3; VA= Virgin aggregate

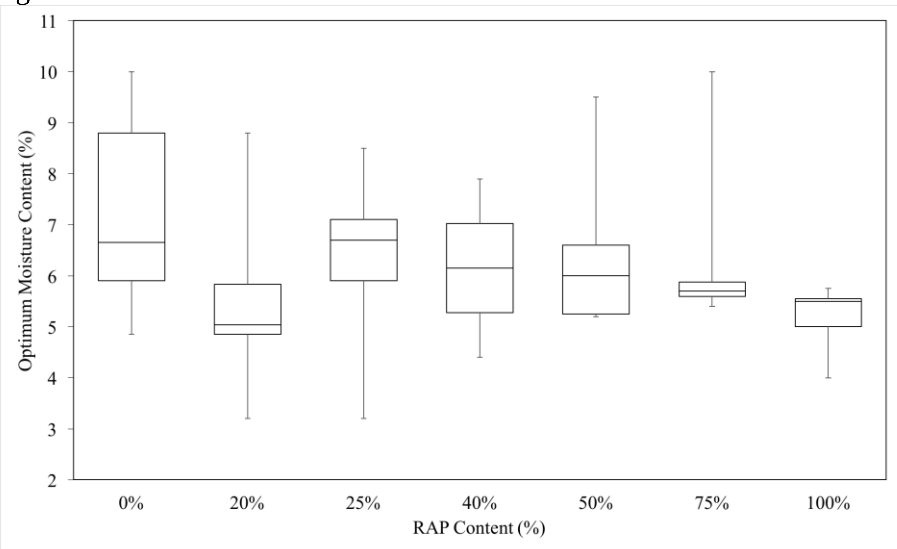

FIGURE 6. OPTIMUM MOISTURE CONTENT (OMC) VERSUS RAP CONTENT (WHISKER PLOT)

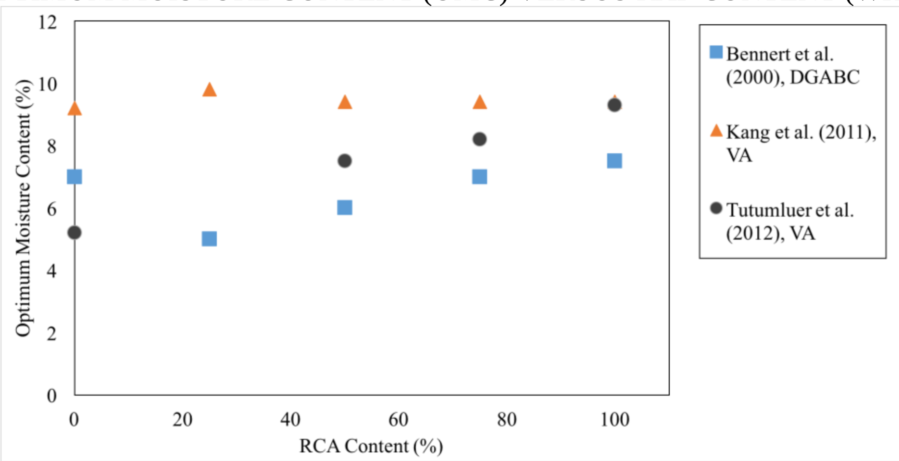

FIGURE 7. OPTIMUM MOISTURE CONTENT (OMC) VERSUS RCA CONTENT

Note: VA= Virgin aggregate; DGABC= Dense graded aggregate base course

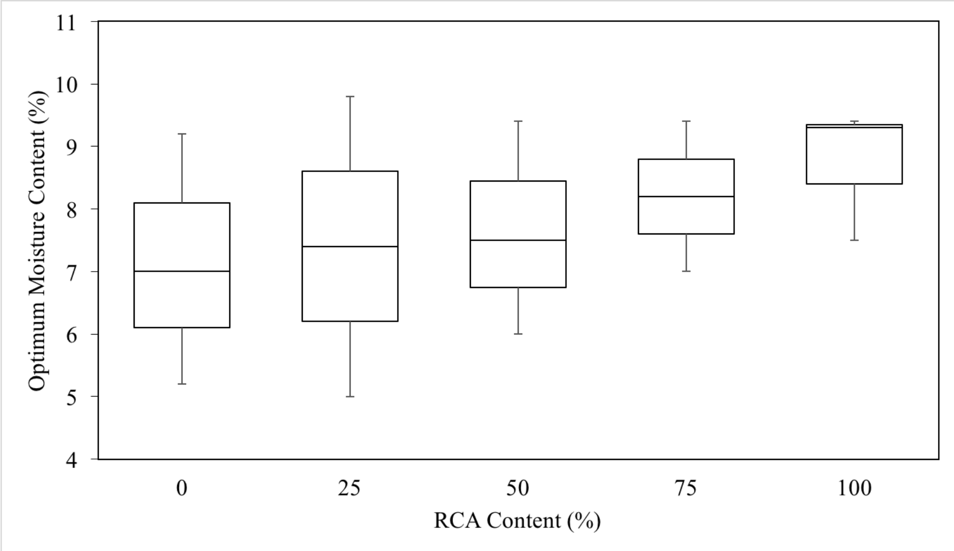

FIGURE 8. OPTIMUM MOISTURE CONTENT (OMC) VERSUS RCA CONTENT (WHISKER PLOT)

It is stated by Kim et al. (2007) that gyratory compactor provided better results to simulate the in-situ conditions. Figure 9 shows that the gratory compaction results simulate the actual field results better than the Proctor compaction results in terms of moisture content and dry unit weight (Kim et al. 2007).

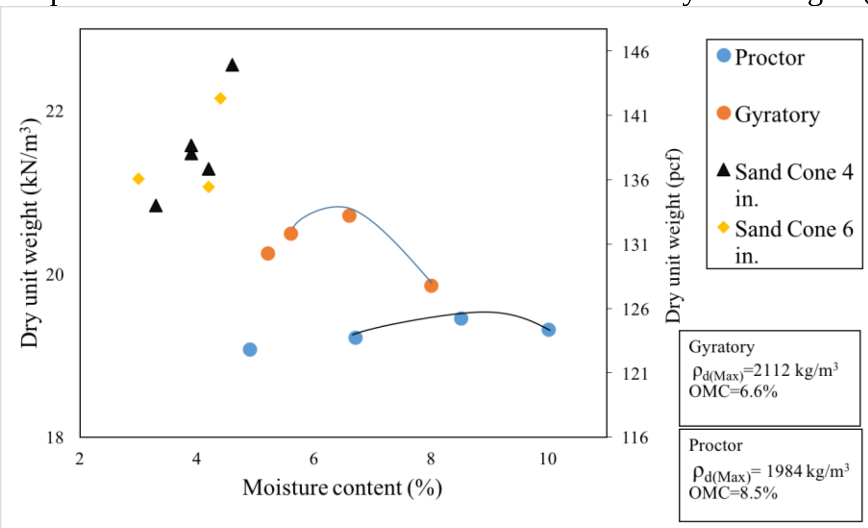

FIGURE 9. THE EFFECT OF COMPACTION METHOD ON THE DEGREE OF THE COMPACTION

Binding quality improves between aggregate particles due to softening of asphalt binder at higher temperatures. Therefore, the compaction characteristics of RAP changes with temperature (Soleimanbeigi and Edil 2015b). For example, the dry unit weight of the specimens increased about 3.5% when compacted at 49°C (120°F) than the ones compacted at 21°C (70°F) (Montemayor 1998, as cited in Cosentino and Kalajian 2001).

2.3. PLASTICITY CHARACTERISTICS

Most of the plasticity index of RAP and RCA were reported as non-plastic (NP) (Locander 2009, Ullah and Tanyu 2019, Edil et al. 2012a, Mijic et al. 2019, Ullah et al. 2018, Edil et al. 2012b, Guthrie et al. 2007, and Cetin et al. 2020. Attia and Abdelrahman (2010a) tested the liquid limit (LL) of 100% RAP and 75% RAP and reported LL to be 26 and 25, respectively. They also reported LL to be 19, 20, 25 and 30 for different 50% RAPs mixed with Class 5 aggregate. Class 5 is a typical base course material classification used in pavements by MnDOT. More detailed information about Class 5 can be found at MnDOT grading and base manual (MnDOT 2016).

3. MECHANICAL AND HYDRAULIC PROPERTIES OF RAP AND RCA

Index properties, the aggregate type, and asphalt/mortar content of RAP and RCA affect their engineering properties significantly (Thakur and Han 2015 and Hiller et al. 2011). Thus, it is important to study the components and the engineering properties of the aggregates for constructing high-quality pavements as recycled aggregates are obtained from different sources (Gonzalez and Moo-Young 2004). Some specifications (AASHTO 2002, Greenbook 2009, ASTM 2016) limit the content of an impurity, e.g., crushed clay brick, unless its presence improves the engineering properties of aggregate base course (Edil et al. 2012a). Hydraulic conductivity, stiffness, strength, shear strength and permanent deformations are discussed and summarized in this section.

3.1. HYDRAULIC CONDUCTIVITY

One of the main functions of aggregate base layers is to provide an adequate drainage and prevent capillary action to increase the service life of pavements (Cedergren 1988). An increase in the pore water pressure in the aggregate base layers causes a reduction in the stiffness of aggregate base layers (Edil et al. 2012a). Hydraulic properties of aggregates are affected by gradation characteristics (e.g. sand, fines content and D_{10}). Fine particles fill up the voids and reduce drainage properties of aggregates (Cosentino et al. 2003). Saturated hydraulic conductivity (k_{sat}) and soil-water characteristics curve (SWCC) are the two parameters that should be evaluated for pavement designs (Nokkaew et al. 2012). Saturated hydraulic conductivity is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient and it is used as a parameter for drainage design while SWCC can be used to determine the matric suction of aggregates at different moisture contents then it can be used to predict the modulus of aggregate base layers (Gupta et al. 2004, Ba et al. 2013).

As mentioned in the previous section, RAP shows hydrophobic properties while RCA shows hydrophilic properties (Edil et al. 2012a; Rahardjo et al. 2010). Due to the hydrophobicity of RAP, it tends to have higher k_{sat} than RCA (Nokkaew et al. 2012). Thus, if the gradations are similar, RAP tends to provide a better drainage layer than RCA (Edil et al. 2012a; Hoppe et al. 2015).

Mokwa and Peebles (2005) and Cosentino et al. (2003) reported an increase in hydraulic conductivity with higher RAP content in the RAP-natural aggregate mixtures. Kang et al. (2011) also showed 100% RAP had a higher hydraulic conductivity than natural aggregates. On the other hand, Wu et al. (2012) indicated that the hydraulic conductivity of base course materials decreased by the addition of RAP. After porosity analysis using X-ray scanning, it turned out that the 80% RAP had less air voids than the crushed aggregate specimens which may have been the cause for observing low hydraulic conductivity. According to Bennert and Maher (2005), RAP-natural aggregate blends with an increase in RAP content from 25% to 75% lowered the hydraulic conductivity of the mixture to almost less than 3.5×10^{-6} m/s (4.2×10^{-2} ft/hr) while 100% RAP had a hydraulic conductivity value of approximately 5.64×10^{-5} m/s (6.7×10^{-1} ft/hr). Kang et al. (2011) showed that addition of 25% RAP in aggregates improved the saturated hydraulic conductivities of the aggregate mixtures since RAP was a coarser material than that of natural aggregates used in that particular study. However, with a further increase in RAP contents, the saturated hydraulic conductivities of the mixtures reduced. It was concluded that a reduction in the hydraulic conductivity may have been due to the that dense packing of the RAP-natural aggregate mixtures. Thus, it lowered the saturated hydraulic conductivity of the mixtures.

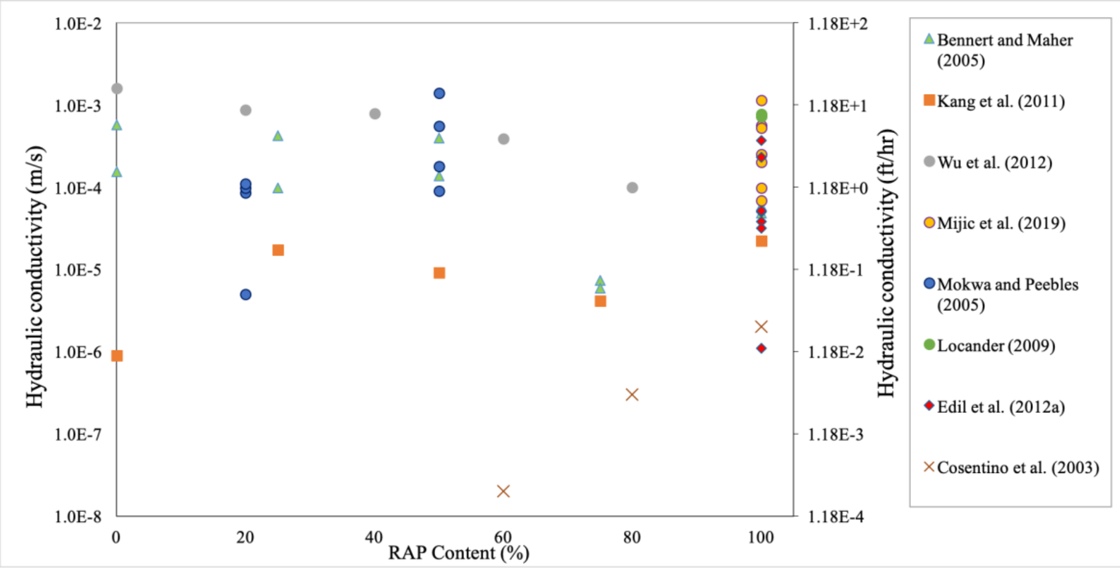

FIGURE 10. HYDRAULIC CONDUCTIVITY VERSUS RAP CONTENT

Bennert and Maher (2005) showed that RCA-natural aggregate blends with an increase in RCA content from 25% to 75% of total weight lowered the hydraulic conductivity of the blend to approximately 50% while the hydraulic conductivity of the RCA was 10^{-6} m/s (0.000145 ft/hr).

According to Kang et al. (2011), hydraulic conductivity of natural aggregates increased with addition of RCA up to 50% by weight. However, further addition of RCA caused a reduction in hydraulic conductivity. The RCA alone had higher hydraulic conductivity than that of natural aggregate, while the 50% RCA-50% natural aggregate mixture had the highest hydraulic conductivity with in all blends.

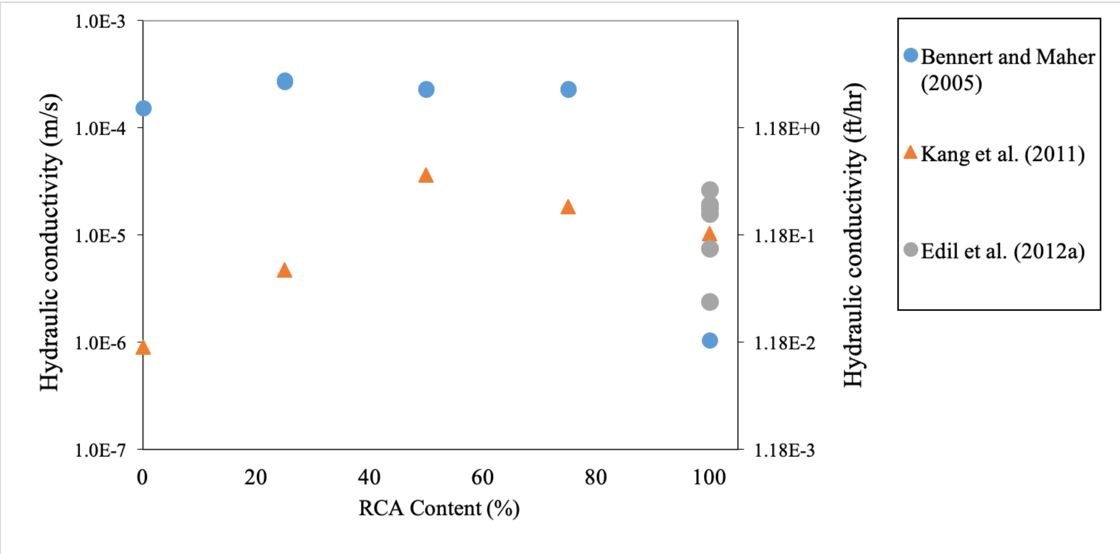

FIGURE 11. HYDRAULIC CONDUCTIVITY VERSUS RCA CONTENT

To evaluate the relationship between hydraulic conductivity and gradation of RAP materials, Figure 12 is presented with 8 data of hydraulic conductivity of 100% RAP from different studies. D_{10} and percent fines are expected to have major influence on hydraulic conductivity. Low D_{10} means higher fine particles, which is expected to clog the pores in the material matrix and reduce air voids. Thus, it causes lower hydraulic conductivity. However, Figure 12 confirms that hydraulic conductivity of RAP increases when D_{10} values increases with few exceptions (e.g. D_{10} = 0.4 mm).

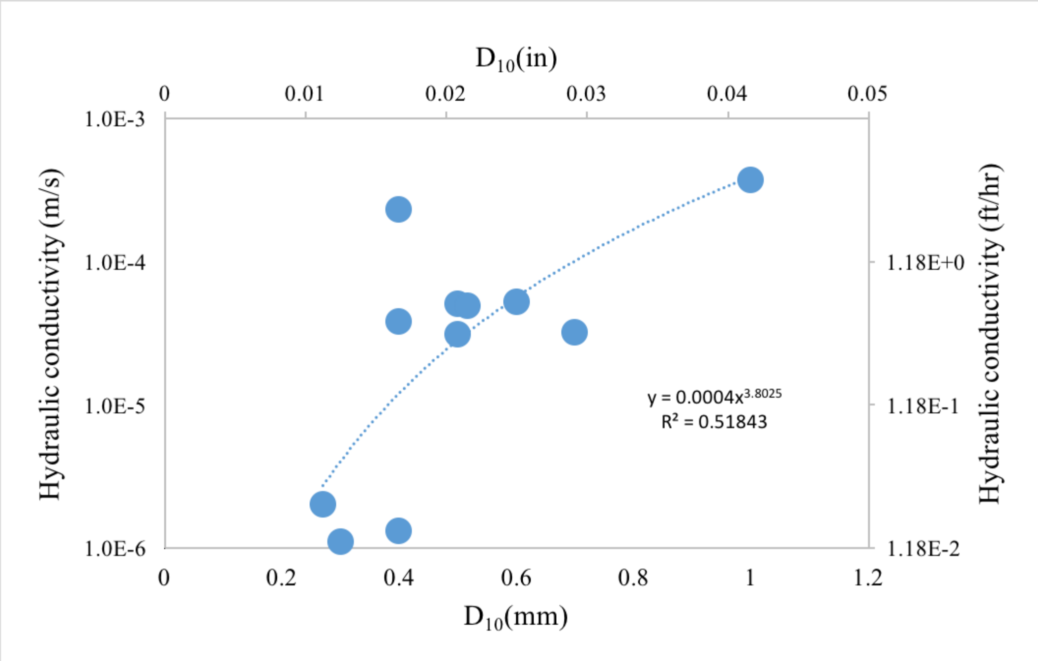

FIGURE 12. HYDRAULIC CONDUCTIVITY VERSUS D_{10} OF 100% RAP

According to Figure 13, there is a decreasing trend for the hydraulic conductivities of RAP materials as fines content increases.

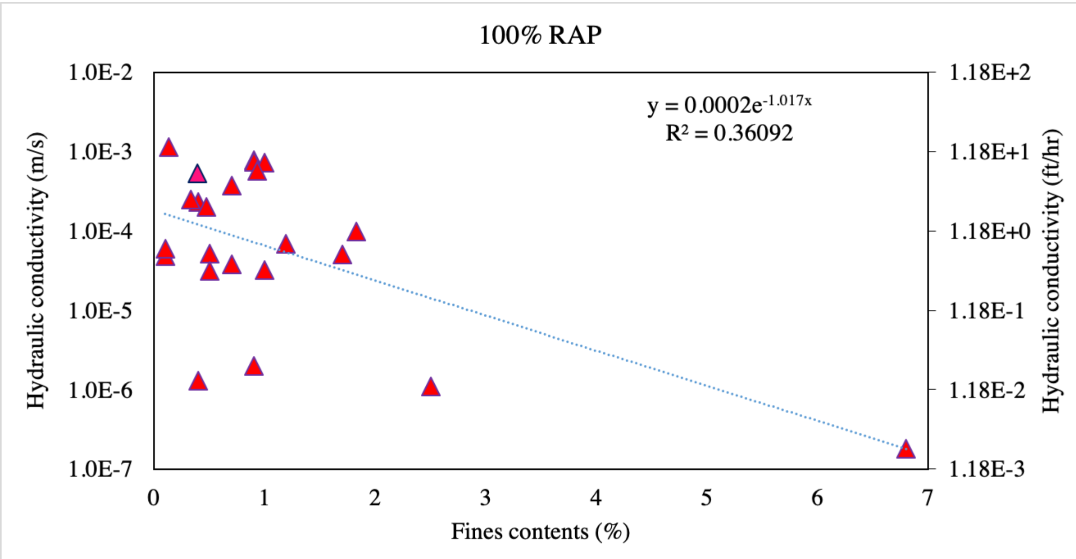

FIGURE 13. HYDRAULIC CONDUCTIVITY VERSUS FINES CONTENT OF 100% RAP

Figure 14 shows the relationship between hydraulic conductivity of different RAP blends and their corresponding fines contents. The hydraulic conductivities of different crushed base course materials mixed with RAP materials at 20% and 50% RAP were collected from Mokwa and Peebles (2005).

Hydraulic conductivity of 100% RAP ranges between 1.8×10^{-7} m/s (2.1×10^{-3} ft/hr) and 1.1×10^{-3} m/s (1.7×10^{-1} ft/hr) with the median of 6. 9×10^{-5} m/s (1×10^{-2} ft/hr) according to our database.

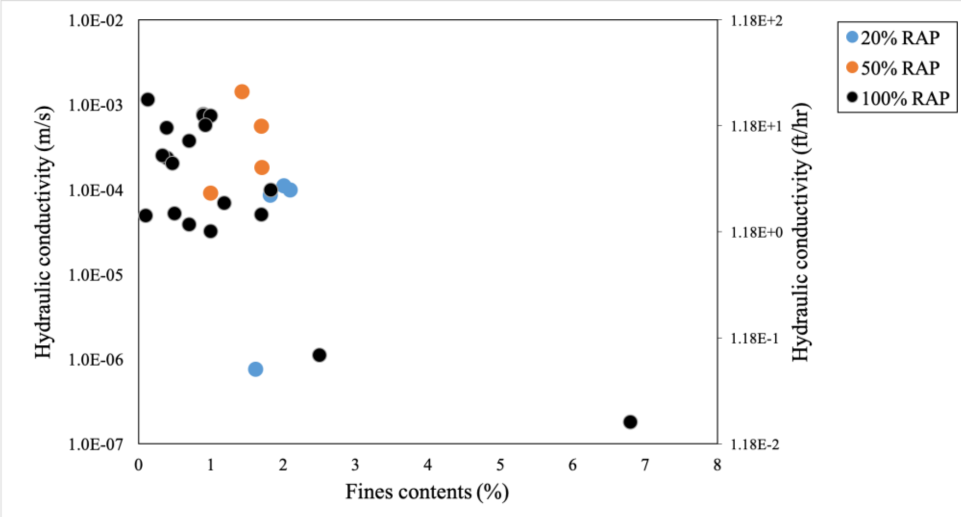

FIGURE 14. HYDRAULIC CONDUCTIVITY VERSUS FINES CONTENT OF DIFFERENT RAP BLENDS

In Figure 15, there are 11 different hydraulic conductivity data of 100% RCA with corresponding fines content. On the other hand, no trend was observed between hydraulic conductivity and fines content of the RAP materials. Hydraulic conductivities of RCAs ranged between 1.05×10^{-6} m/s (1.2×10^{-2} ft/hr) and 1.2×10^{-3} m/s (1.7×10^{-1} ft/hr) with the median of 1.7×10^{-5} m/s (2.5×10^{-3} ft/hr) according to our database.

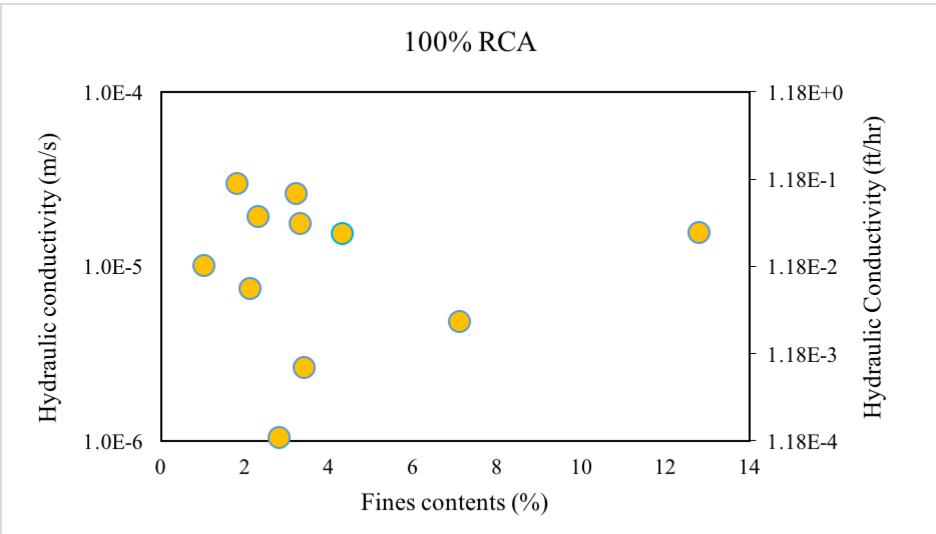

FIGURE 15. HYDRAULIC CONDUCTIVITY VERSUS FINE CONTENT OF 100% RCA

3.2. STRENGTH

The California Bearing Ratio (CBR) of base materials is an indication of their mechanical characteristics under vertical loading (traffic) and is determined as the ratio of the penetration resistance of the base material to that of a standard crushed stone. The CBR has been used by pavement engineers to characterize the strength of materials for designing pavements (Thakur and Han 2015). The minimum CBR values of the aggregate base and subbase layers should be 80 and 60, respectively (Jayakody et al. 2012; Ooi et al. 2010). In Florida, lime rock Bearing Ratio (LBR) which is a modified version of conventional CBR test, is commonly used (Cosentino et al. 2003). In addition to the specified minimum CBR values, LBR should be at least 100 (LBR = 1.25 x CBR) for aggregate base layers (FDOT 2018).

The database showed that the CBR values of 100 % RAP ranged from 18 to 68 with the median to be 28 while CBR of 100% RCA was between 58 to 169 with the median 146.

3.2.1. IMPACTS OF SELECTED INDEX PROPERTIES ON CBR

Gravel-to-sand (G/S) ratio and fines contents were selected to investigate their effects on CBR of RAP and RCA materials. Figures 16 and 17 reveal that there is not a specific trend between CBR of 100% RAP versus fines content and/or gravel to sand ratio; however, it is not possible to draw any conclusion due to lack of the data.

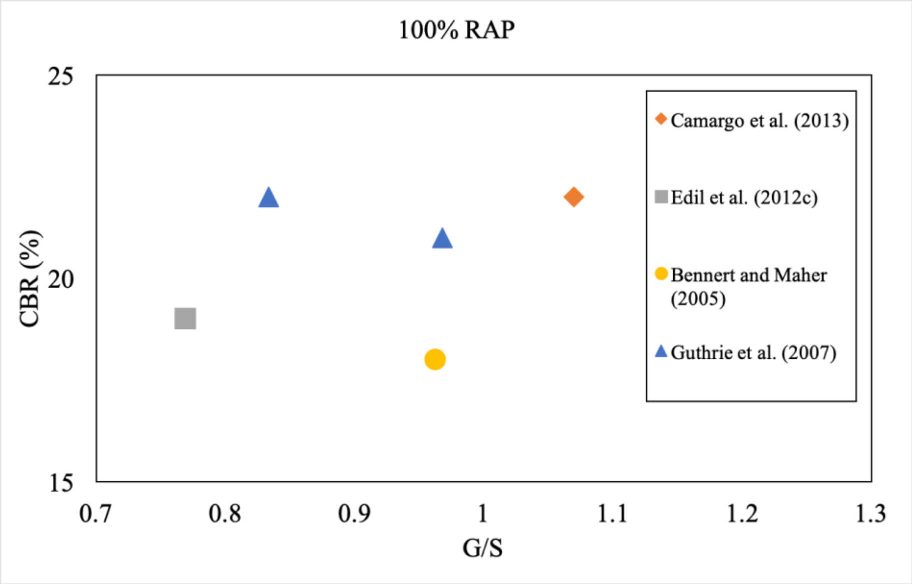

FIGURE 16. CBR VERSUS GRAVEL TO SAND RATIO OF 100% RAPS

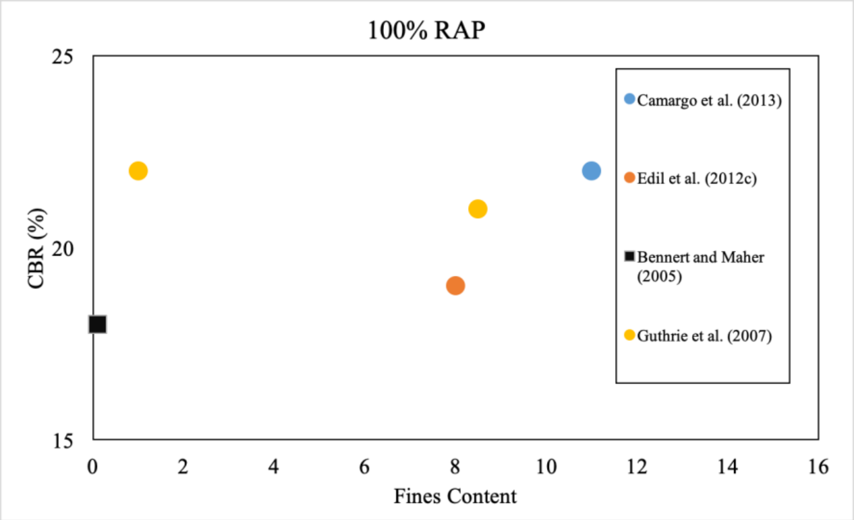

FIGURE 17. CBR VERSUS FINES CONTENT OF 100% RAP SAMPLES

According to Figures 18 and 19, there is also not a specific trend between CBR of 100% RCA and fines content or gravel to sand ratio; however, it is not possible to draw any conclusion due to lack of data.

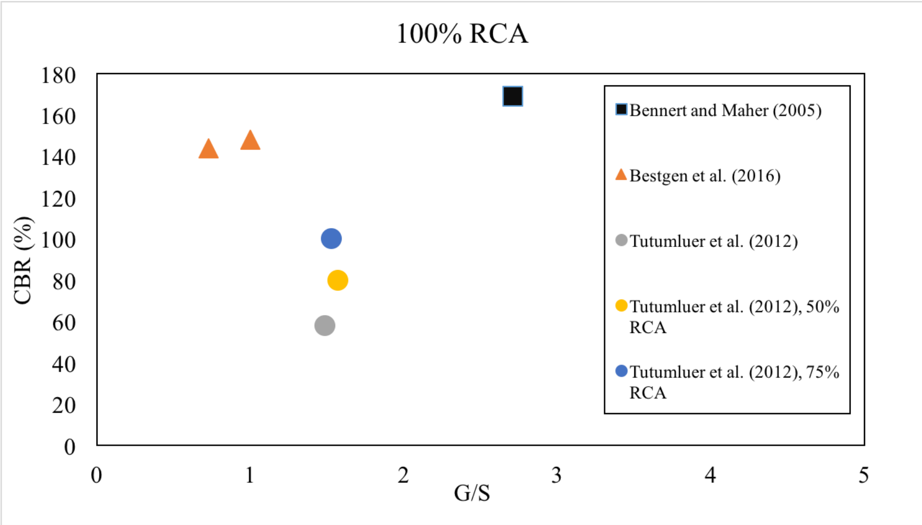

FIGURE 18. CBR VERSUS GRAVEL TO SAND RATIO OF RCA SAMPLES

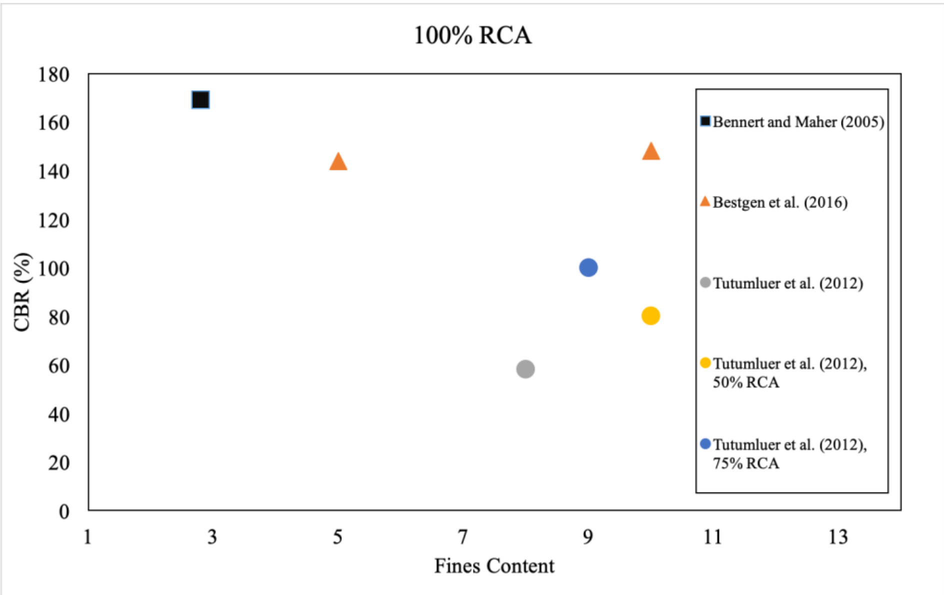

FIGURE 19. CBR VERSUS FINES CONTENT OF RCA SAMPLES

3.2.2. IMPACTS OF RAP/RCA CONTENTS ON CBR

In general, RAP has lower CBR than natural aggregates. In addition, increasing the RAP content in the RAP-natural aggregate mixtures reduces the CBR (Bennert and Maher 2005; Guthrie et al. 2007). Figure 20 clearly shows that CBR of RAP-natural aggregates decreases with higher RAP contents in the mixture. The asphalt coating around the particles may be the reason for CBR reduction in the presence of RAP since asphalt coating reduces the particle bonding and interlocking mechanism of aggregate particles (Ooi et al. 2010; Taha et al. 1999). In addition, a lower fines content of RAP may leave unfilled voids (open-graded structure), which may result in lower CBR (Sayed et al. 1993). Cosentino et al. (2003), Bennert and Maher (2005), Ullah and Tanyu (2019), Cosentino and Bleakley

(2013) and Guthrie et al. (2007) conducted CBR tests on blended RAP-natural aggregate specimens, all of which except Cosentino et al. (2003), reported a decrease in CBR with an increase in RAP content. On the other hand, Cosentino et al. (2003) observed that the CBR of the mixtures first increased with an increase in RAP content in the blend up to a certain level (~RAP content is 80%) and then started decreasing.

Depending on the physical, chemical and morphological characteristics of RAP and/or moisture contents used for blends, different trends could be observed in different applications (Thakur and Han 2015). Figure 20 reports the type of each material that is blended with RAP. Natural aggregate, lime rock (LR), base material, dense graded aggregate base course (DGABC) and fine sand were used to blend RAPs.

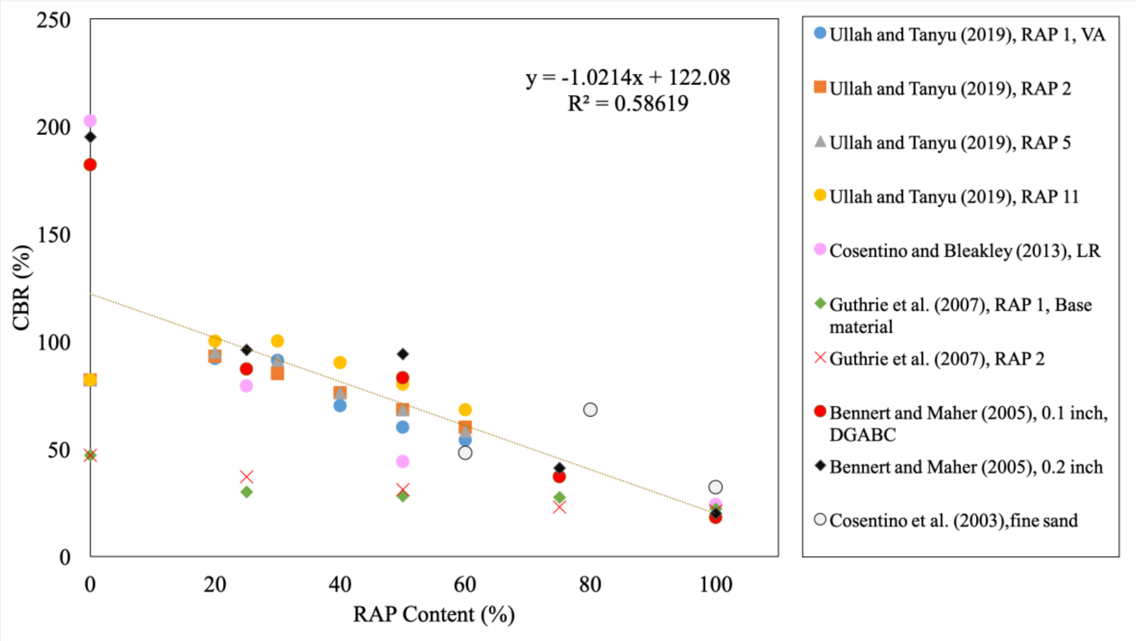

FIGURE 20. CBR VERSUS RAP CONTENT

Notes: VA= Virgin aggregate; LR= Limerock; DGABC= Dense graded aggregate base course

The literature review showed that compacting RAP at a relatively higher temperature increased its dry unit weight which led to an increase in the LBR values. For instance, RAP that was compacted at 49°C (120°F), the range of LBR was increased from 25-50 to 42-125 (Montemayor 1998). On the other hand, higher ambient temperature decreases the LBR of RAP after compaction, while higher LBR values were observed at lower ambient temperatures due to asphalt material hardening (Cosentino and Kalajian 2001).

It was observed that the CBR of RCA materials (either soaked or unsoaked) had different trends in different studies. While lower CBR values were seen for unsoaked RCA materials compared to natural aggregates, this trend was opposite when they were soaked (Jayakody et al. 2012). The reason of different behaviors of RCA could be due to the presence of dehydrated cement content. Relatively higher CBR values can be observed with longer soaking period since more cementitious reactions could occur with longer curing periods (Poon et al. 2006; Garach et al. 2015; Bestgen et al. 2016).

To investigate the CBR behaviors of natural aggregate-RCA mixtures, Figure 21 and 22 are presented. These figures show that there is not a discernible trend between CBR and RCA contents. Figure 22 shows normalized CBR versus RCA content. Normalized CBR is obtained by dividing the CBR of each RCA blend by the CBR of 100% RCA of the same study.

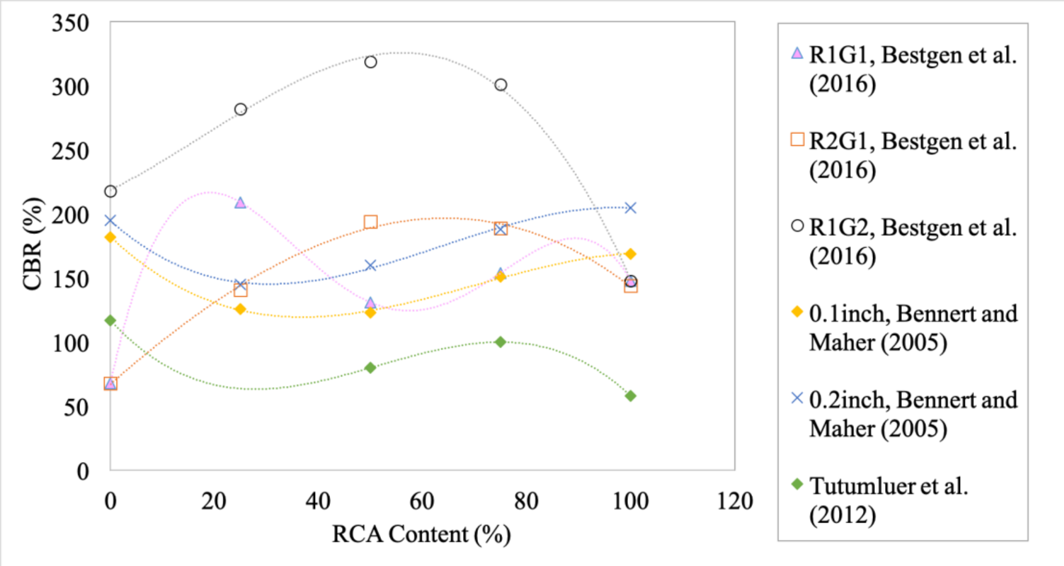

FIGURE 21. CBR VERSUS RCA CONTENT

Notes: The CBR value corresponding to 0.1 and 0.2 inches of penetration was used in Bennert and Maher (2005) study

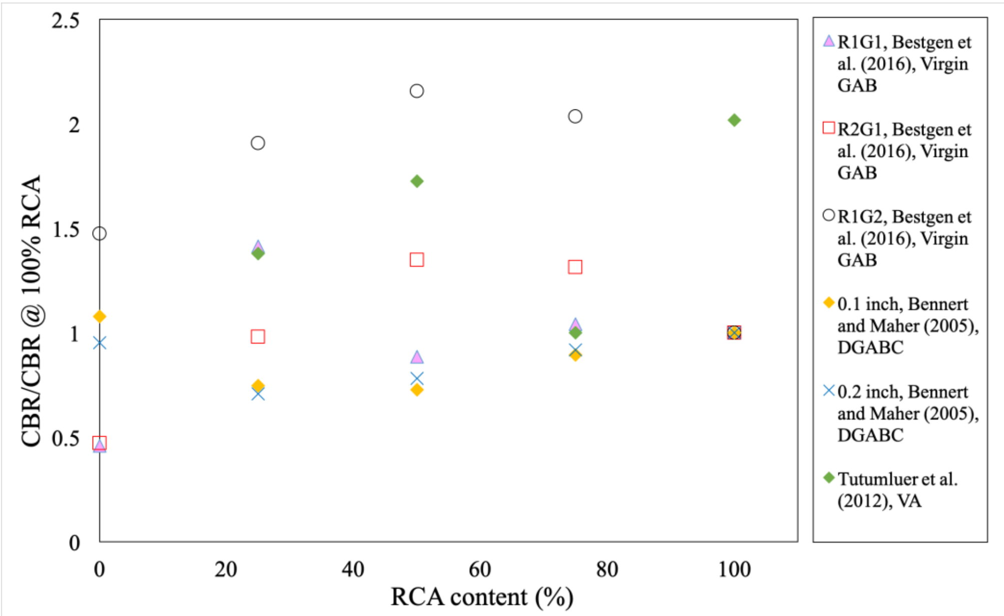

FIGURE 22. NORMALIZED CBR VERSUS RCA CONTENT

Notes: Virgin GAB= Virgin graded aggregate base; DGABC= Dense graded aggregate base course; VA= Virgin aggregate

3.3. STIFFNESS

Resilient modulus (M_r) is a fundamental material property used to analyze stiffness of materials under different conditions such as moisture, density, and stress level. The 1993 American Association of State Highway and Transportation Officials (AASHTO) flexible pavement design method and the current Mechanistic-Empirical Pavement Design Guide (MEPDG) use M_r to define subgrade and base stiffness for pavement systems. Mr is defined as a ratio of applied axle deviator stress and axle recoverable strain. M_r of RAP and/or RCA materials depends on several factors including moisture content, freeze-thaw cycles, density, stress history, aggregate type, RAP or RCA type, gradation, temperature, asphalt content in RAP, type of stabilizing agent and curing time (Thakur and Han 2015, Bestgen et al. 2016).

M_r plays an important role in pavement design. Therefore, most of the studies have reported M_r as a stiffness characteristic. In addition to the summary resilient moduli (SM_R) values, k_1, k_2, k_3, k_6 and k_7 were provided in the database. Summary resilient moduli (SM_R) were reported at a bulk stress of 208 kPa and octahedral stress of 48.6 kPa for base materials as recommended by NCHRP 1-28A.

As RAP content increases, M_r gets higher while the plastic strain increases. More than 400 M_r data investigating the resilient modulus of RAP, RCA or blends were collected for the database. It also includes the M_r data of these materials that were tested at different environmental conditions including different temperatures, freeze-thaw cycles, and moisture contents (Appendix B).

Overall, it was observed that RAP and RCA in the base course had higher M_r than that of well-graded natural aggregates. The SM_r reported in the database for RAP was between 168 MPa (24366 psi) and 400 MPa (58015 psi) with the median value to be 261.5 MPa (37927 psi). The SM_r of RCA ranged between 123.4 MPa (17897 psi) and 370 MPa (53664 psi) with the median value of 183 MPa (26541 psi) according to the database.

3.3.1. EFFECTS OF INDEX PROPERTIES ON STIFFNESS OF RCA AND RAP

Figure 23 presents summary resilient modulus of RAP versus gravel-to-sand (G/S) ratio to investigate the effects of index properties on corresponding stiffness. Figure 24 shows that SM_r of RAP is lower at higher G/S ratios. This indicates that RAP with higher sand content would have higher SM_r in general.

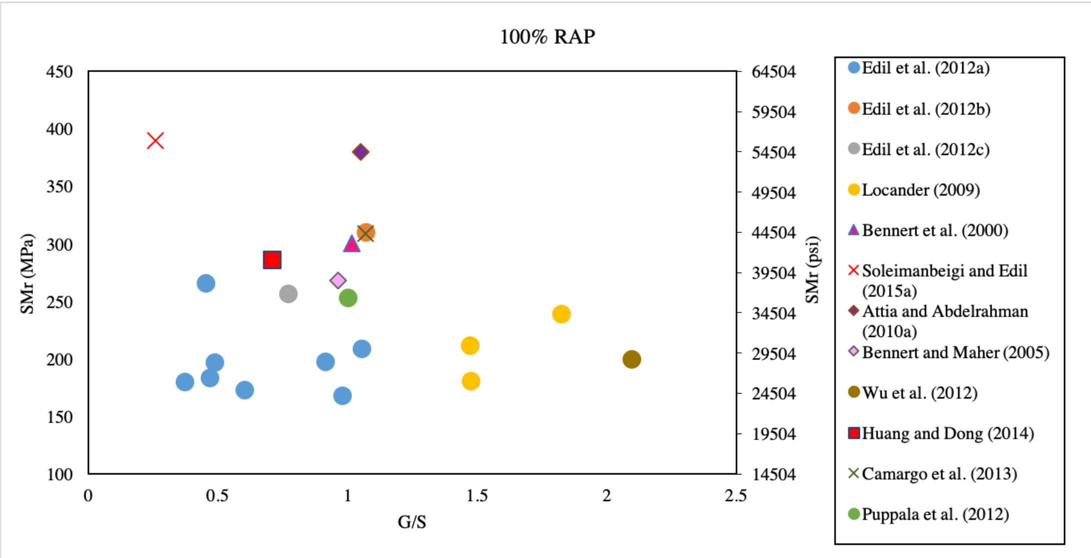

FIGURE 23. SM_R AND GRAVEL TO SAND RATIO OF 100% RAPS

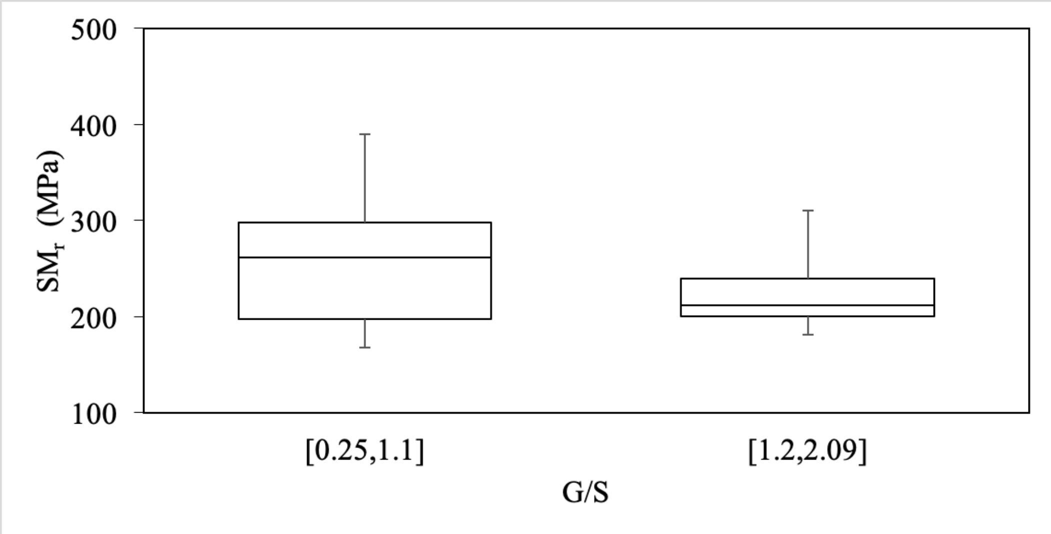

FIGURE 24. SMR VERSUS GRAVEL TO SAND RATIO OF 100% RAPS (WHISKER PLOT)

Figure 25 and Figure 26 show that there is no correlation or trend between SM_r and fines content of RAPs (within the typical ranges observed in this study).

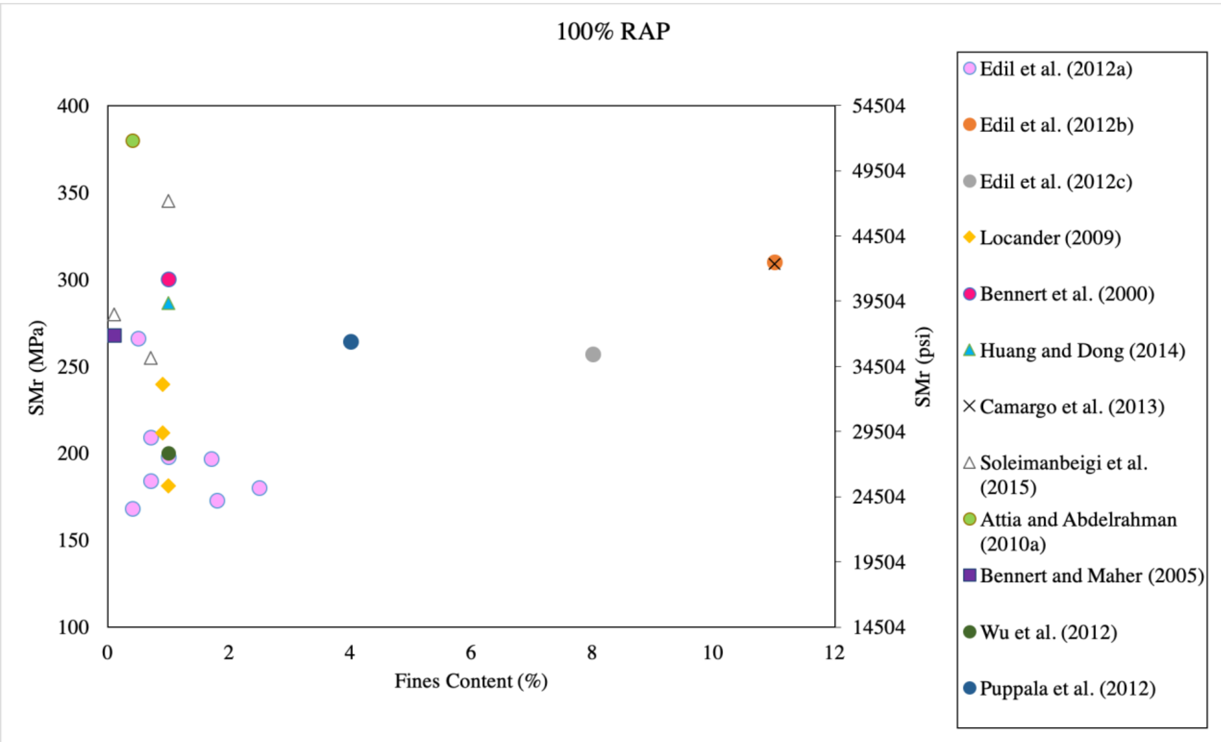

FIGURE 25. SMR VERSUS FINES CONTENT OF 100% RAPS

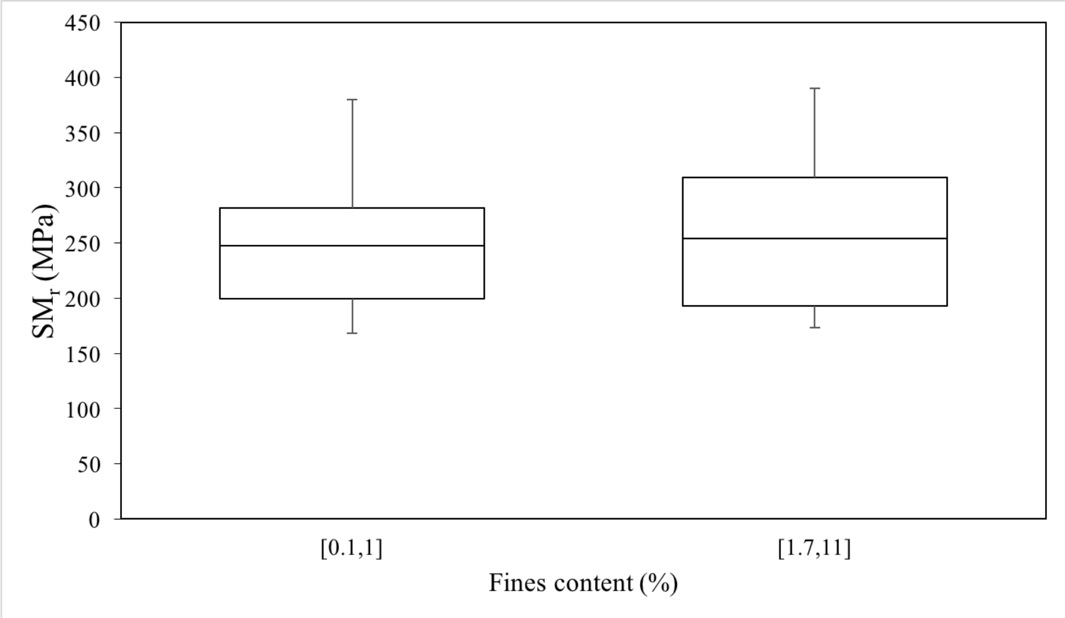

FIGURE 26. SMR VERUS FINES CONTENT OF 100% RAPS (WHISKER PLOT)

The trend between SM_r of RCA and corresponding G/S ratios were not as significant as the ones observed for RAPs. However, it was observed that an increase in SM_r of RCAs when G/S ratio was higher.

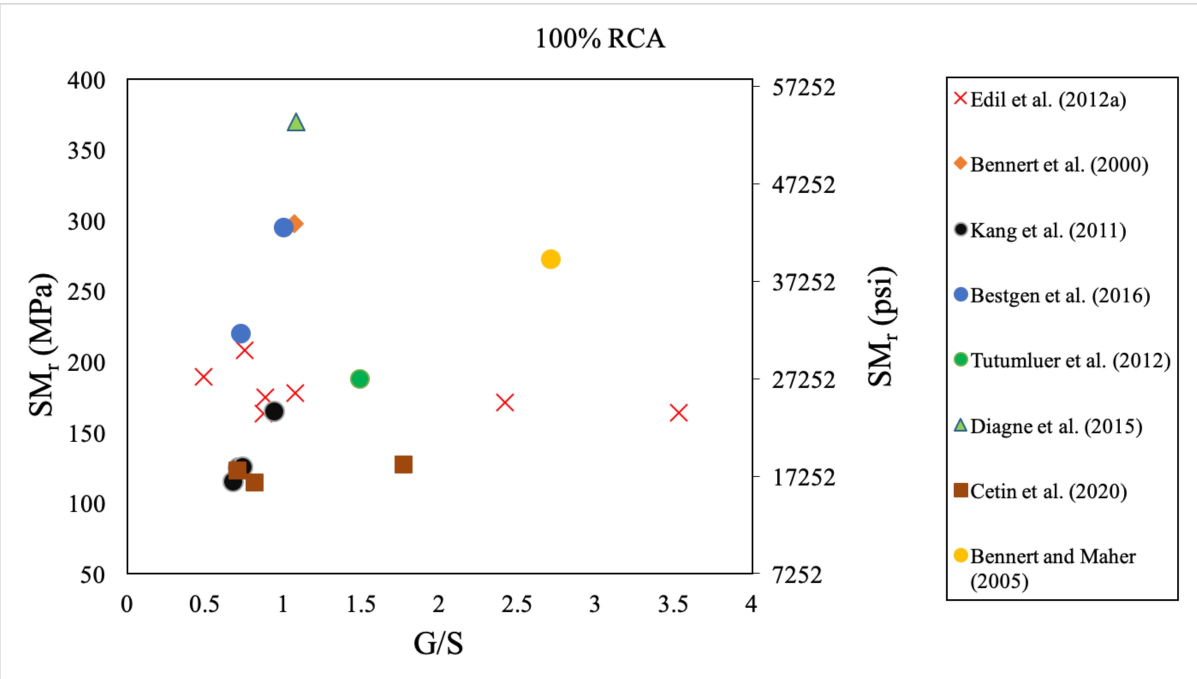

FIGURE 27. SMR VERSUS GRAVEL TO SAND RATIO OF 100% RCAS

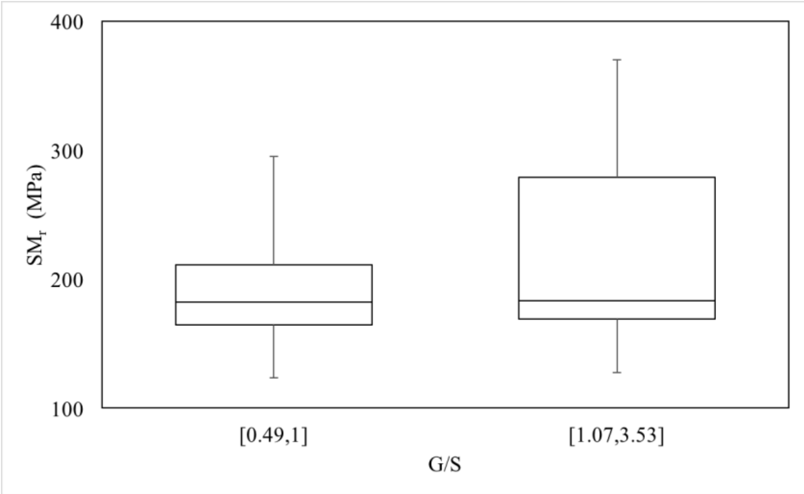

FIGURE 28. SM_R VERSUS GRAVEL TO SAND RATIO OF 100% RCAS (WHISKER PLOT)

According to Figures 29 and 30, there is a slight decrease in SM_r of RCAs as fines content increases. However, this was not consistent with some other studies such as Bestgen et al. (2016).

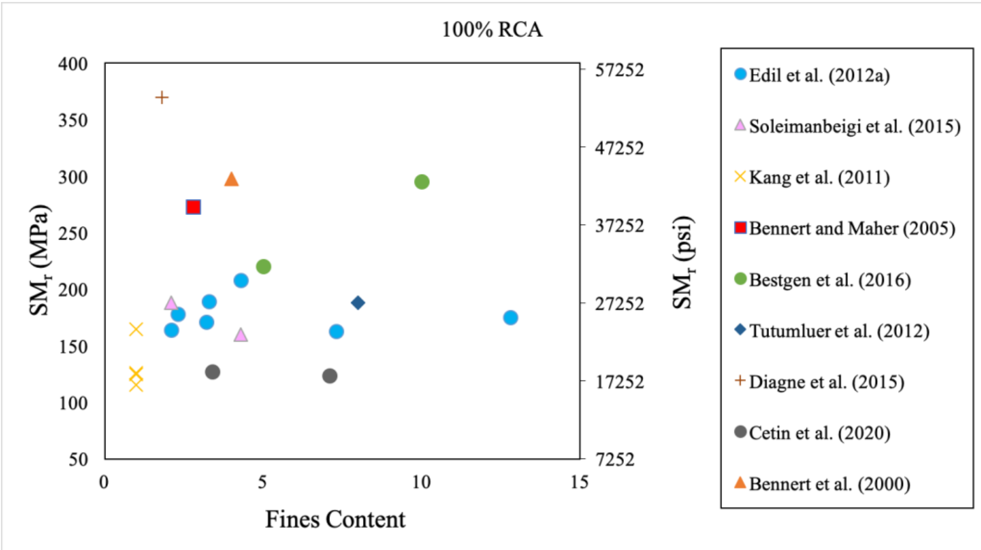

FIGURE 29. SM_R VERSUS FINES CONTENT OF 100% RCAS

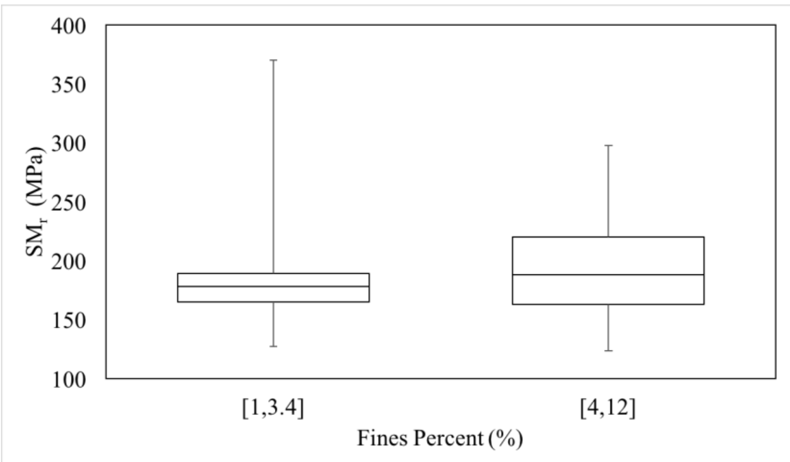

FIGURE 30. SM_R VERSUS FINES CONTENT OF 100% RCAS (WHISKER PLOT)

The maximum dry unit weight (MDU) and optimum moisture content (OMC) of RAP from different studies were plotted against the corresponding summary resilient modulus (SM_r) of the corresponding RAP materials (Figures 31 and 33). To better understand these scatter plots, Figures 32 and 34 are shown as whisker plots. However, no significant trend was observed between MDU and SM_r of RAP materials (Figure 32). There was a slight decrease in SM_r of RAPs with an increase in OMC (Figure 33).

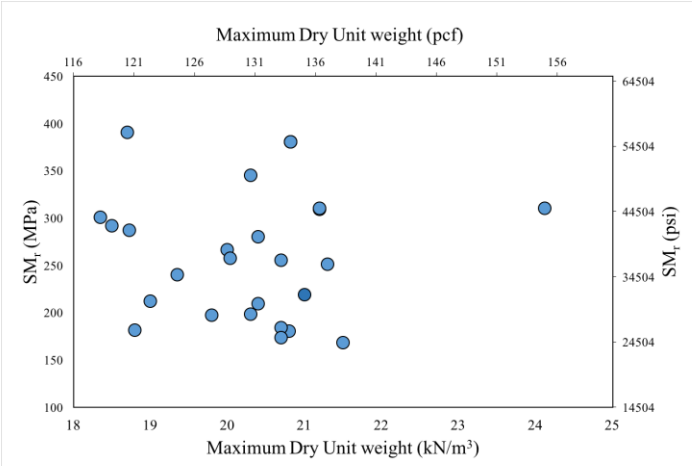

FIGURE 31. SM_R VERSUS MAXIMUM DRY UNIT WEIGHT OF 100% RAP

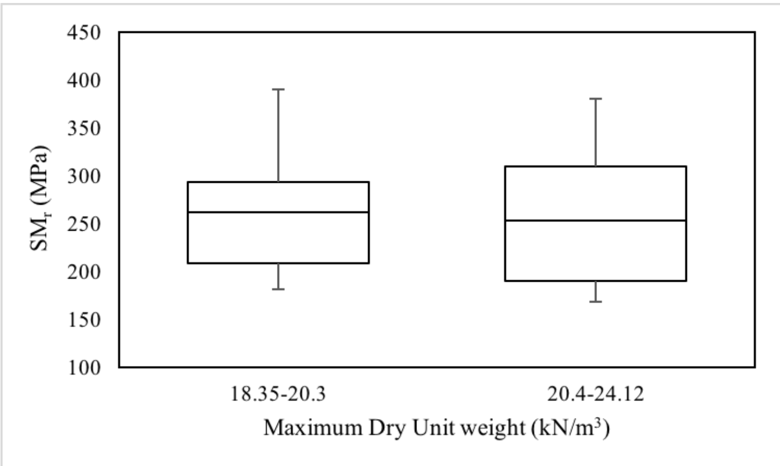

FIGURE 32. SM_R VERSUS MAXIMUM DRY UNIT WEIGHT OF 100% RAP (WHISKER PLOT)

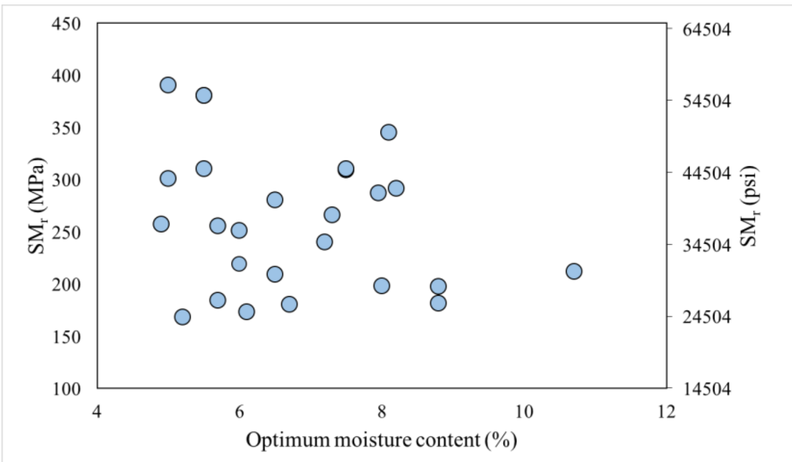

FIGURE 33. SM_R VERSUS OPTIMUM MOISTURE CONTENT OF 100% RAP

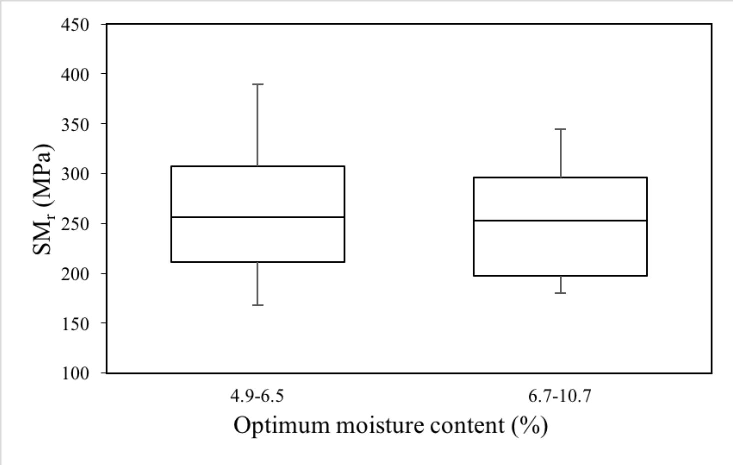

FIGURE 34. SM_R VERSUS OPTIMUM MOISTURE CONTENT OF 100% RAP (WHISKER PLOT)

D_{30} and D_{60} of RAPs were plotted against their corresponding SM_r values in Figures 35 and 37, respectively. According to Figure 36, RAPs with higher D_{30} tend to have higher SM_r. Similar trend was also observed in Figure 38. It shows that SM_r of RAPs are higher when they have higher D_{60} values.

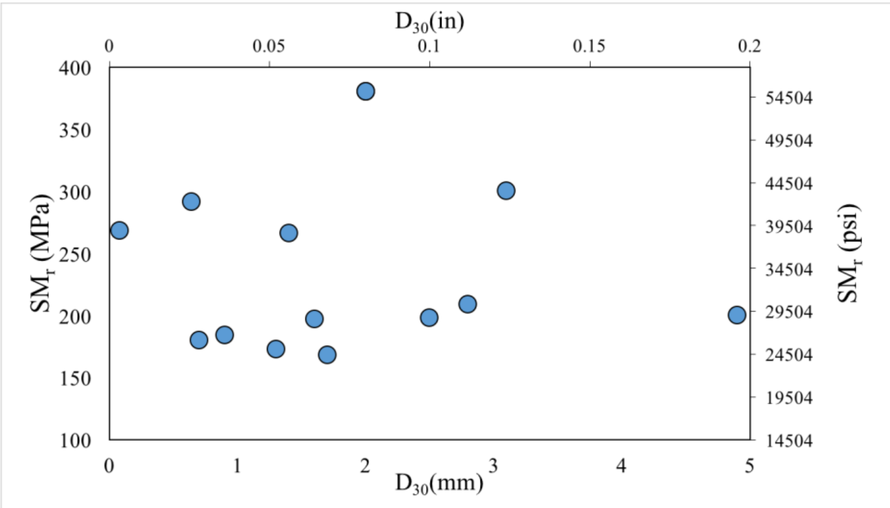

FIGURE 35. SM_R VERSUS D_{30} OF 100% RAP

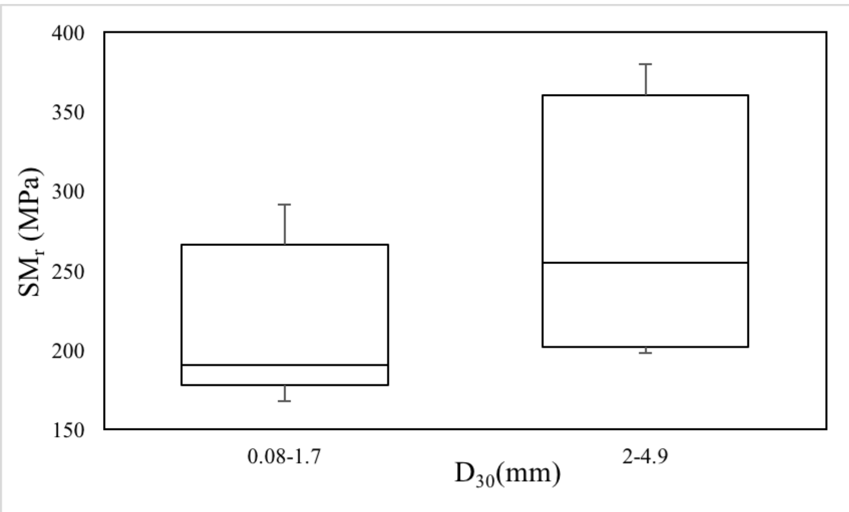

FIGURE 36. SM_R VERSUS D_{30} OF 100% RAP (WHISKER PLOT)

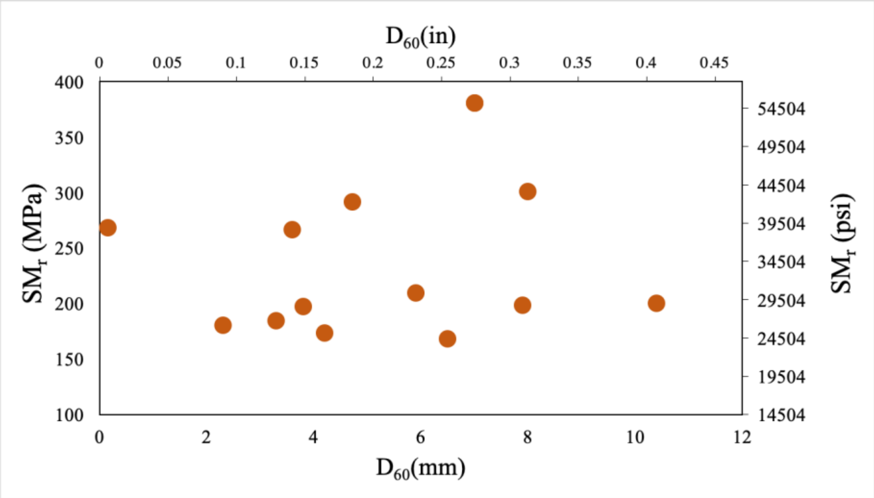

FIGURE 37. SM_R VERSUS D_{60} OF 100% RAP

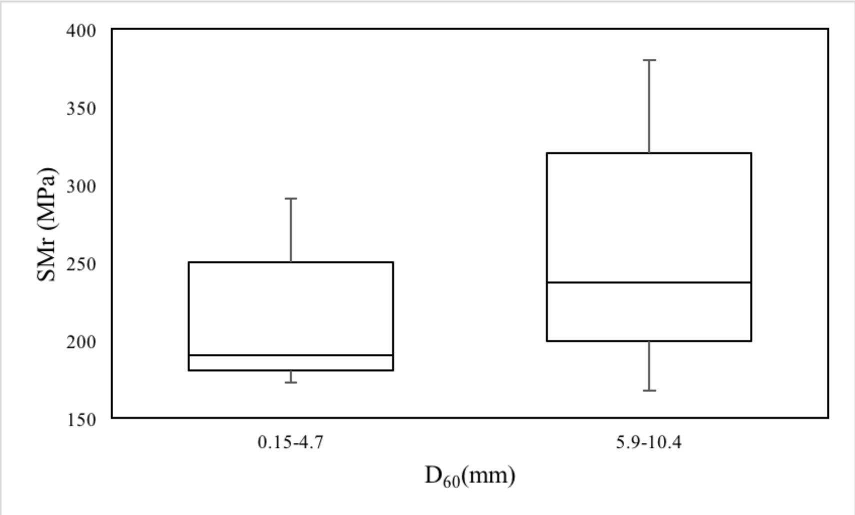

FIGURE 38. SM_R VERSUS D_{60} OF 100% RAP (WHISKER PLOT)

Coefficient of curvature (C_c) should be between 1 and 3 for well-graded gravel and sand. Figures 39 and 41 show variation of SM_r of RAPs with their corresponding C_c values. Based on the data collected, it was observed that SM_r of RAPs were higher when C_c of RAPs were lower than 1 ($1>C_c$) and higher than 3 ($C_c>3$). It means that poor graded RAP may have higher SM_r. Figure 42 shows that an increase in C_u yields some increase in SM_r).

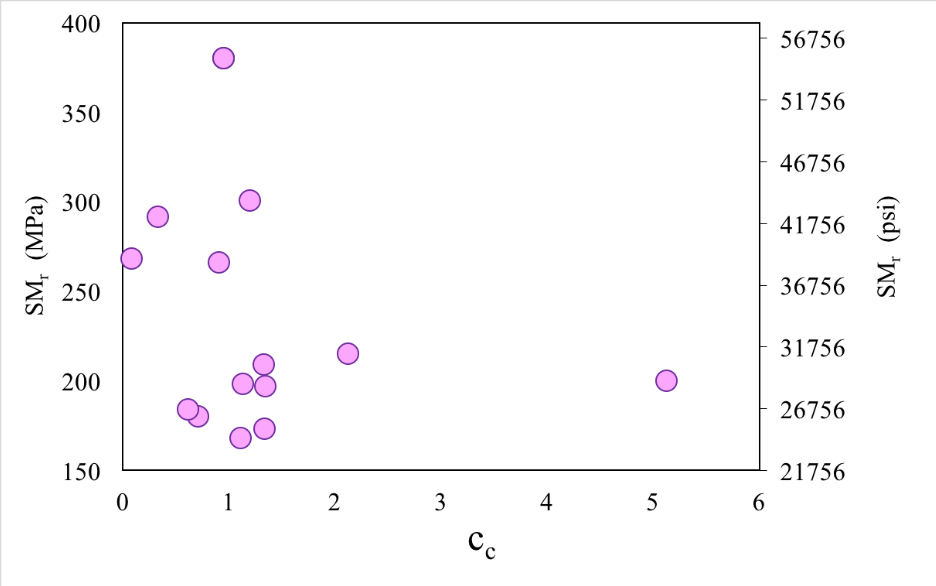

FIGURE 39. SM_R VERSUS C_C OF 100% RAP

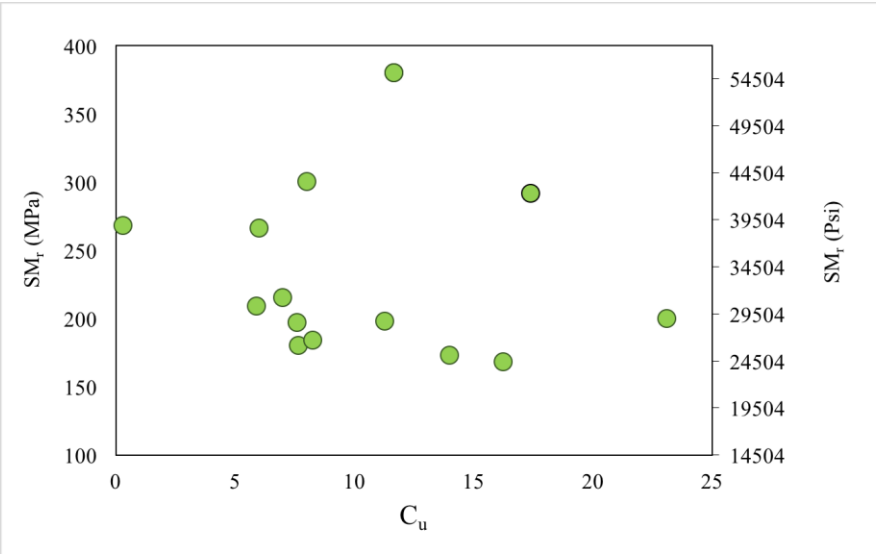

FIGURE 40. SM_R VERSUS C_U OF 100% RAP

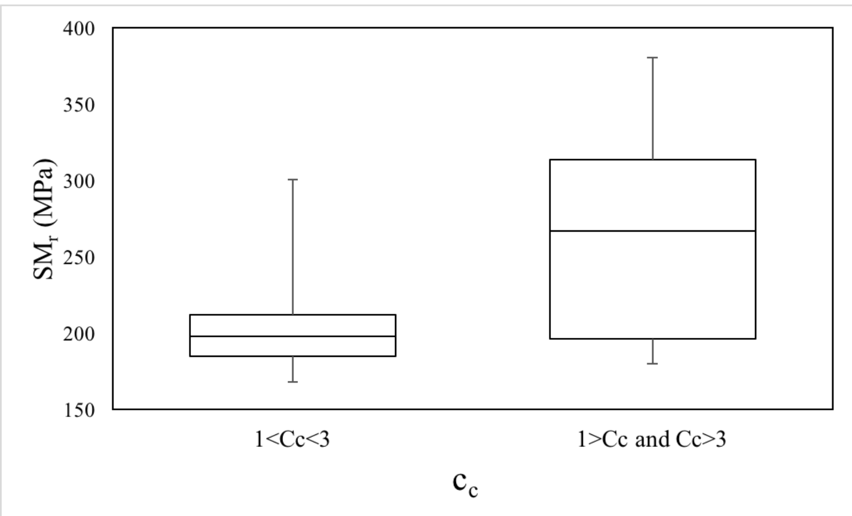

FIGURE 41. SM_R VERSUS C_C OF 100% RAP (WHISKER PLOT)

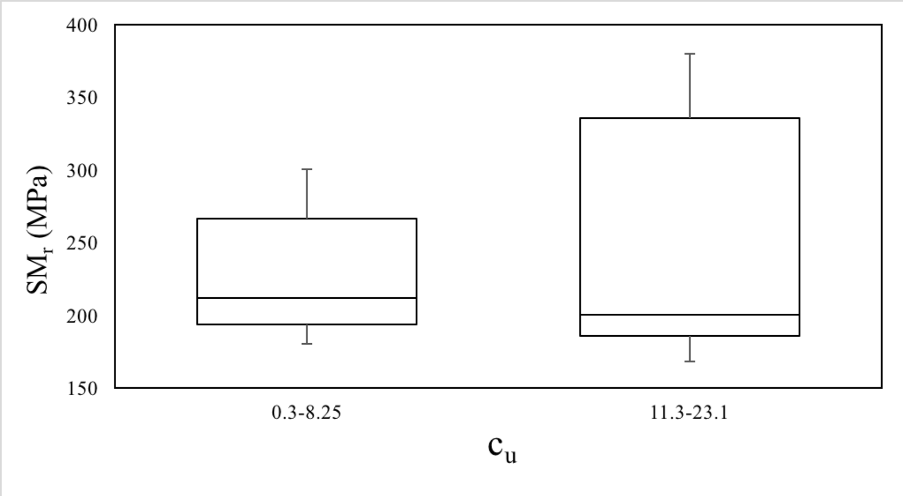

FIGURE 42. SM_R VERSUS C_U OF 100% RAP (WHISKER PLOT)

RCA materials compacted at higher MDU are likely to have higher SM_r values(Figures 43 and 44). Higher OMC results in a reduction in SM_r of RCAs. The OMC of RCA ranged from 6.1% to 11.9% while their corresponding SM_r changed between 370 MPa (53664 psi) and 124MPa (17984.7 psi) (Figures 45 and 46). Figures 47, 48, 49 and 50 shows that no correlations are observed between D_{30} and D_{60} characteristics of RCAs and the corresponding SM_r values.

The MDU of RCA ranged from 18.9 kN/m^3 (121.4 pcf) to 20.9 kN/m^3 (134.4 pcf) while their corresponding SM_r changed between 370 MPa (53664 psi) and 124MPa (17985psi) (Figures 43 and 44).

According to Figure 51 and 52, well-graded RCA yields higher SM_r than that of poorly-graded ones. The SM_r of RCA with C_c between 1 and 3 tended to be higher than the ones with C_c ($1>C_c$) smaller than 1 or higher than 3 ($C_c>3$). Higher C_u values in RCAs could result in higher SM_r (Figure 54).

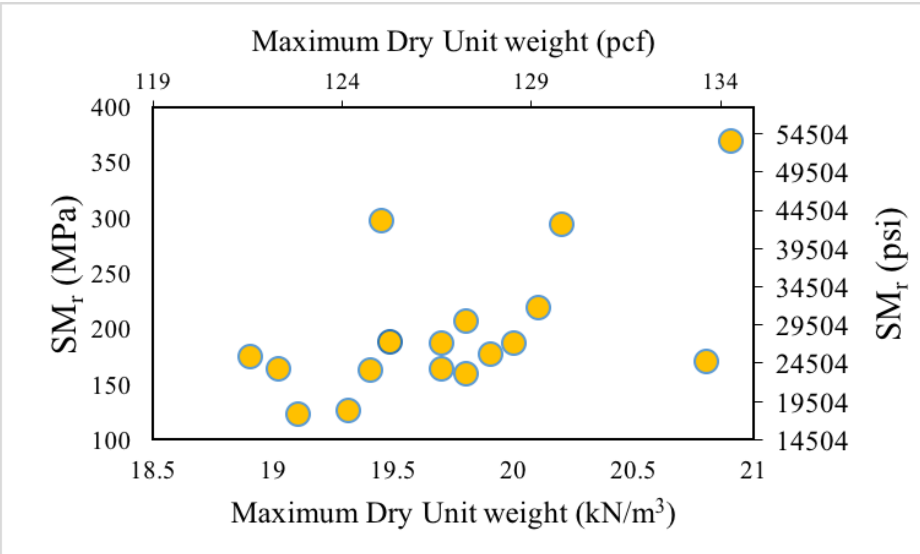

FIGURE 43. SM_R VERSUS MDU OF 100% RCA

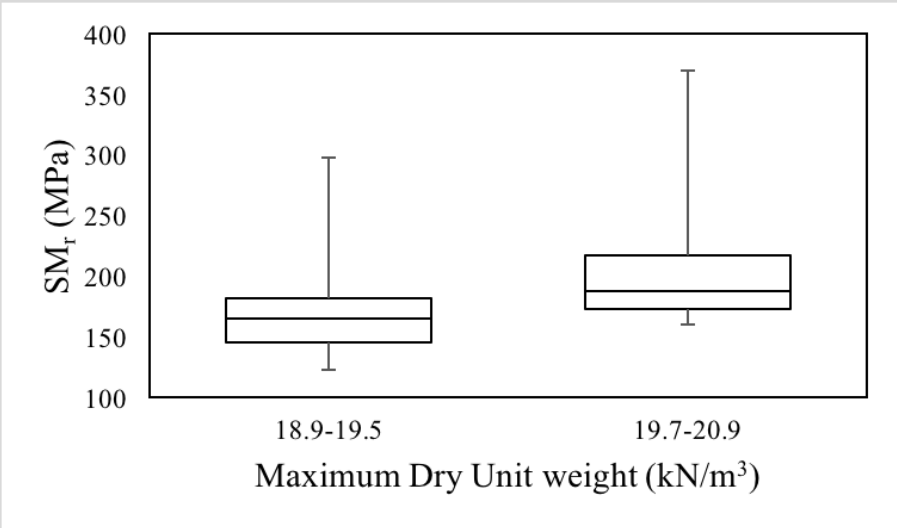

FIGURE 44. SMR VERSUS MDU OF 100% RCA (WHISKE PLOT)

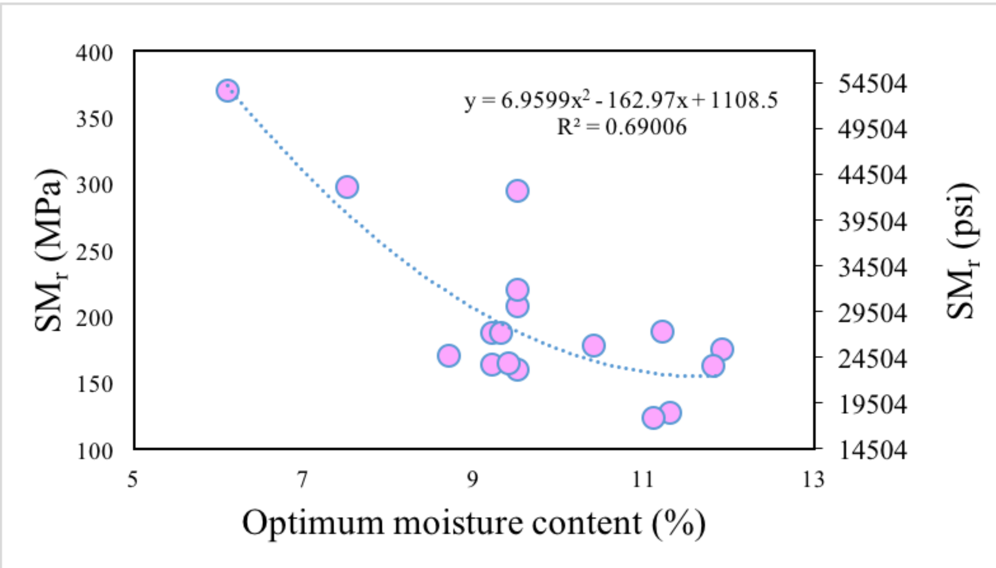

FIGURE 45. SMR VERSUS OPTIMUM MOISTURE CONTENT OF 100% RCA

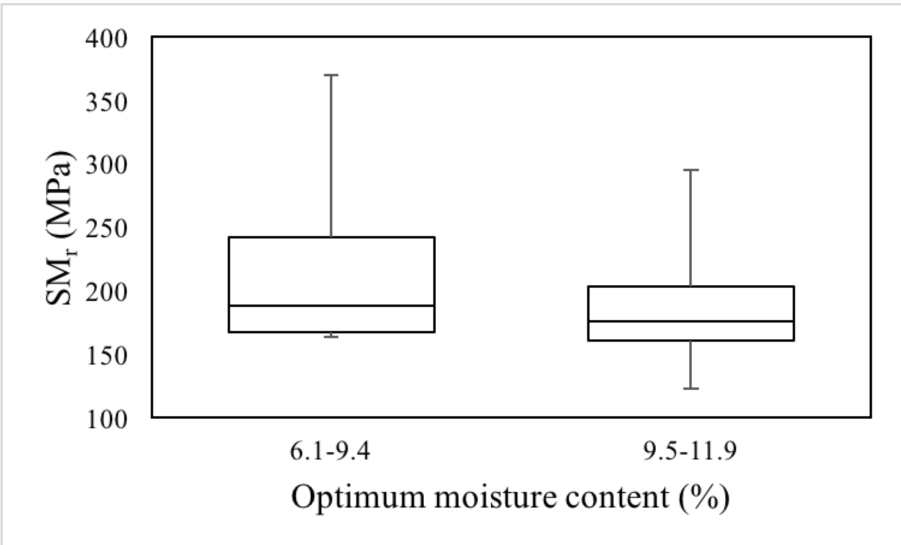

FIGURE 46. SMR VERSUS OPTIMUM MOISTURE CONTENT OF 100% RCA (WHISKER PLOT)

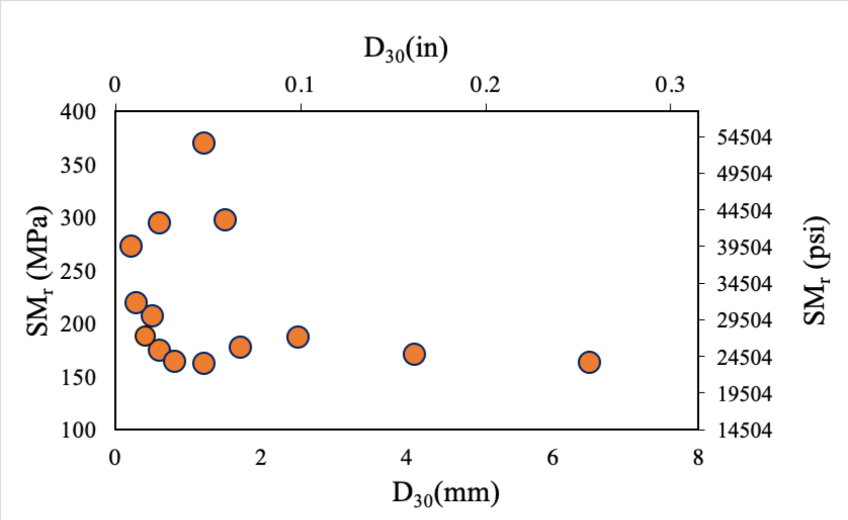

FIGURE 47. SM_R VERSUS D_{30} OF 100% RCA

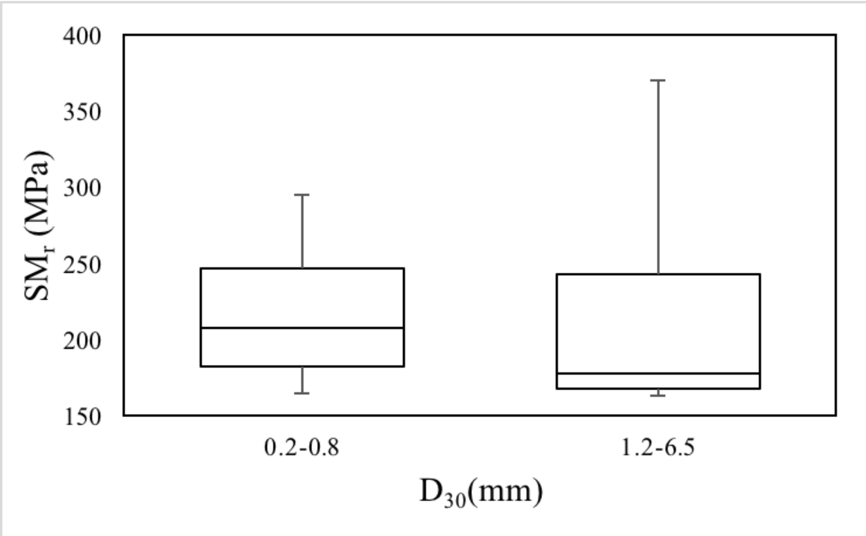

FIGURE 48. SM_R VERSUS D_{30} OF 100% RCA (WHISKER)

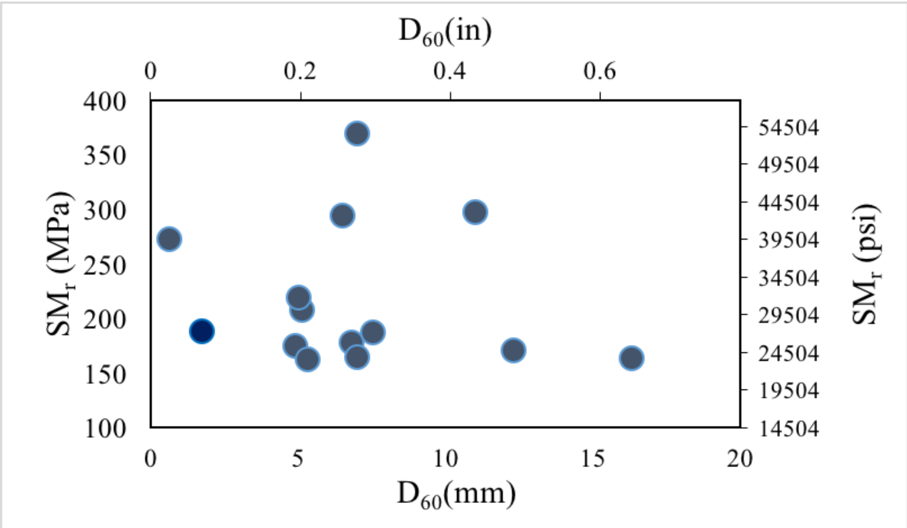

FIGURE 49. SM_R VERSUS D_{60} OF 100% RCA

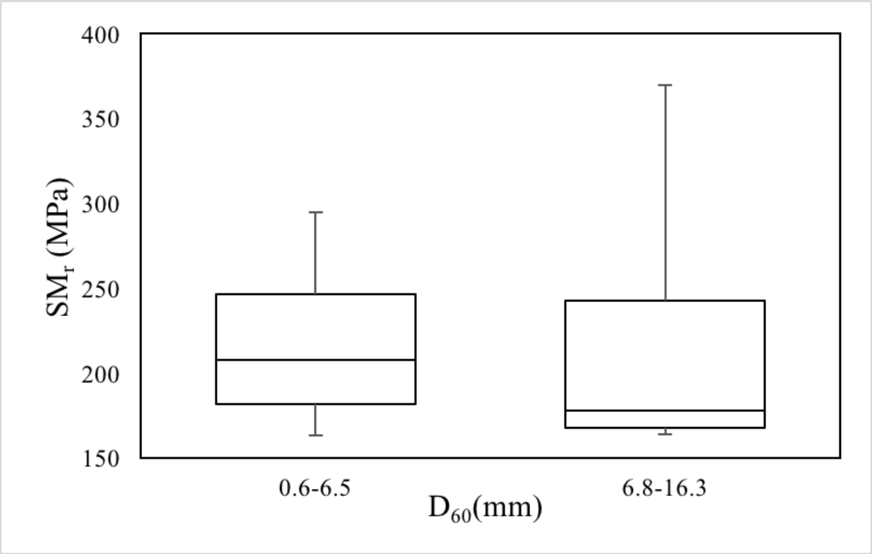

FIGURE 50. SM_R VERSUS D_{60} OF 100% RCA (WHISKER PLOT)

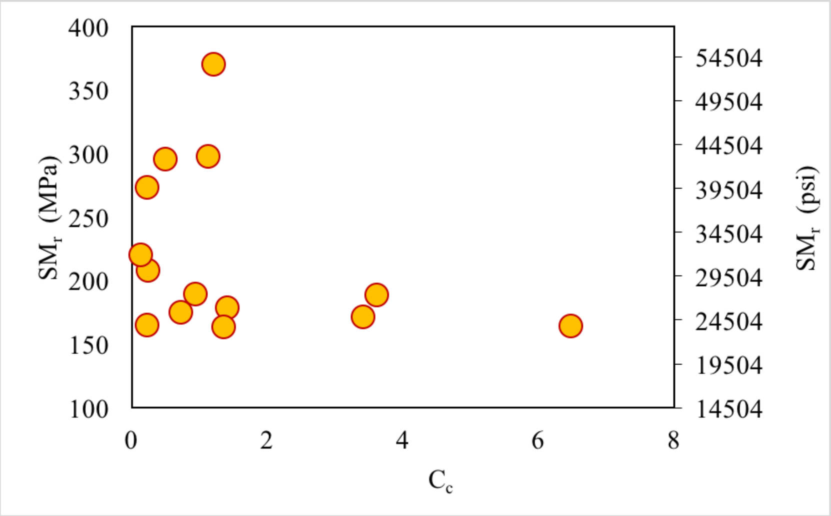

FIGURE 51. SM_R VERSUS C_C OF 100% RCA

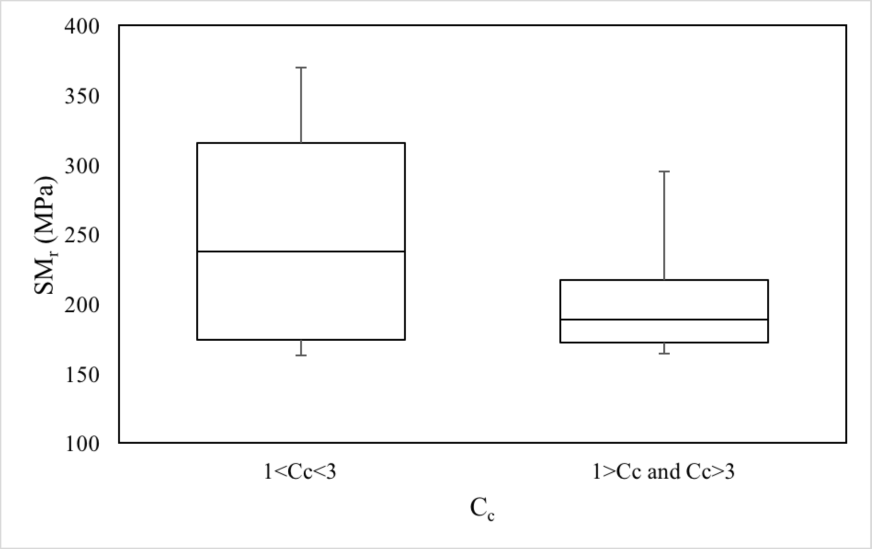

FIGURE 52. SM_R VERSUS C_C OF 100% RCA (WHISKER PLOT)

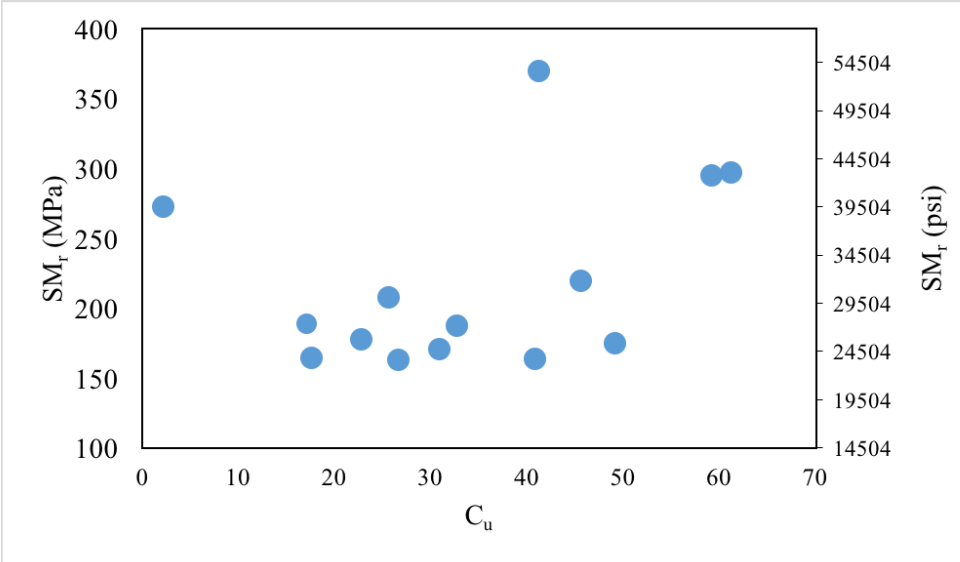

FIGURE 53. SM_R VERSUS C_U OF 100% RCA

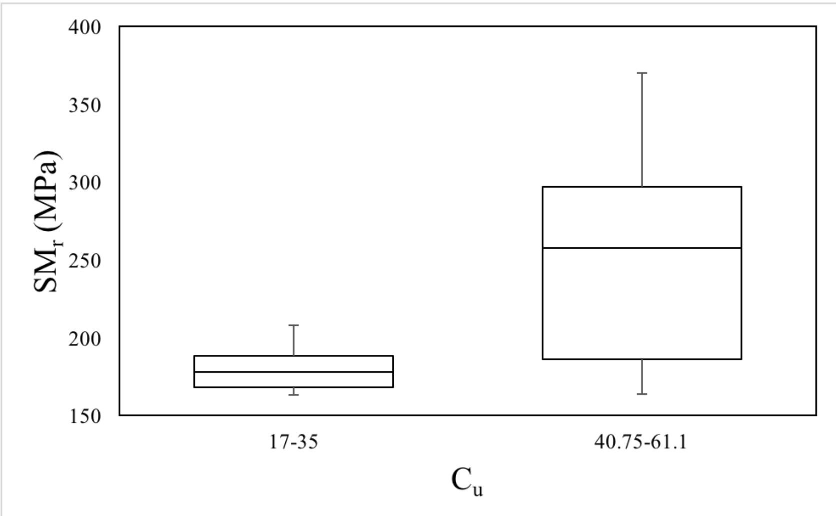

FIGURE 54. SM_R VERSUS C_U OF 100% RCA (WHISKER PLOT)

3.3.2. TEMPERATURE EFFECTS ON RAP AND RCA STIFFNESS

RAP is sensitive to temperature due to its asphalt content, which is a temperature-sensitive material. On the other hand, RCA and natural aggregates are not as sensitive to temperature changes as RAP (Wen et al. 2011; Soleimanbeigi et al. 2015). The SM_r of RAP-natural aggregate mixtures reduces as temperature increases (Soleimanbeigi et al. 2015). However, Soleimanbeigi and Edil (2015b) claimed that RAP could undergo a thermal preloading process. Thus, it would have higher stiffness at higher temperatures (Read and Whiteoak 2003, Wen et al. 2011). Thermal conditioning in this context means inducing elevated temperature to RAP during compaction process. The induced elevated temperature increases compressibility of RAP, thus reducing the void space in the material. When the temperature drops, the compacted RAP is expected to have higher stiffness and strength due to reduction in void space. Therefore, it is important to know the proper thermal conditioning for RAP during compaction when used as a base course (Soleimanbeigi and Edil 2015b).

Edil et al. (2012a) and Soleimanbeigi et al. (2015) conducted M_r tests on Colorado, Texas and New Jersey RAP at 7°, 23°, 35°, 50°C (44.6°, 73.4°, 95° and 122°F) and it was observed that SMr of all

RAP materials decreased with an increase in temperature (Figure 55). Soleimanbeigi and Edil (2015b) showed that SM_R of RAP was also affected by the compaction temperature. SM_r of RAPs increased when RAPs were compacted at higher temperatures and then cooled and tested for resilient modulus as shown in Figure 55. Figure 56 shows the normalized SM_r of RAP versus different temperatures. SM_r of RAP at different temperature was divided by the SM_r of RAP at 23°C (73.4°F) of each RAP study. There was a decreasing trend with higher temperature except for the New Jersey and Colorado RAP from Soleimanbeigi et al. (2015) which had a slight increasing trend.

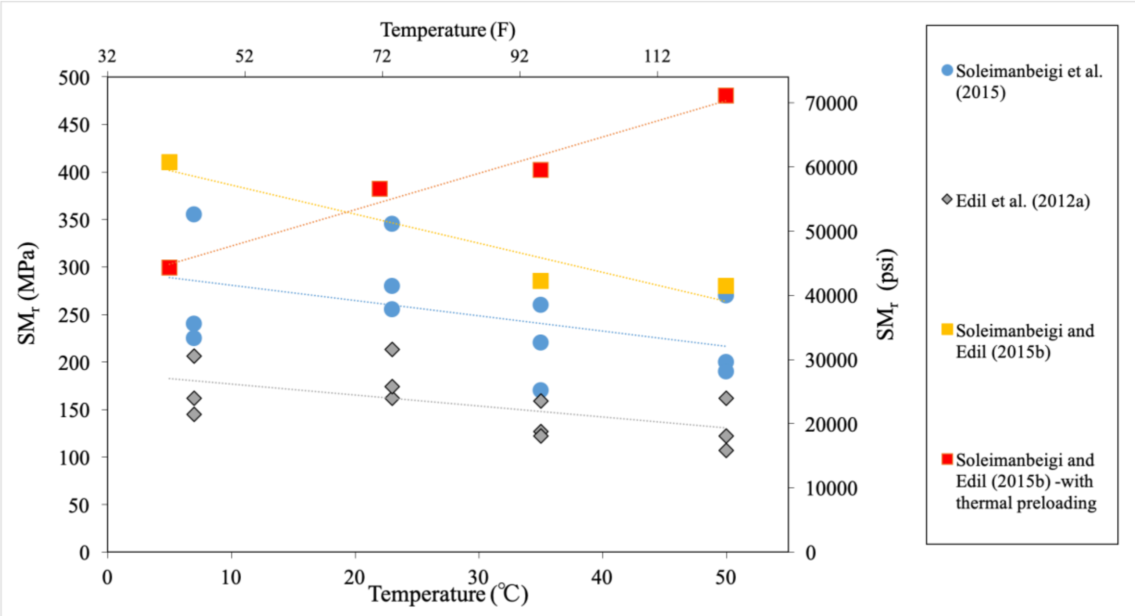

FIGURE 55. SM_R VERSUS TESTING TEMPERATURE OF 100% RAPS

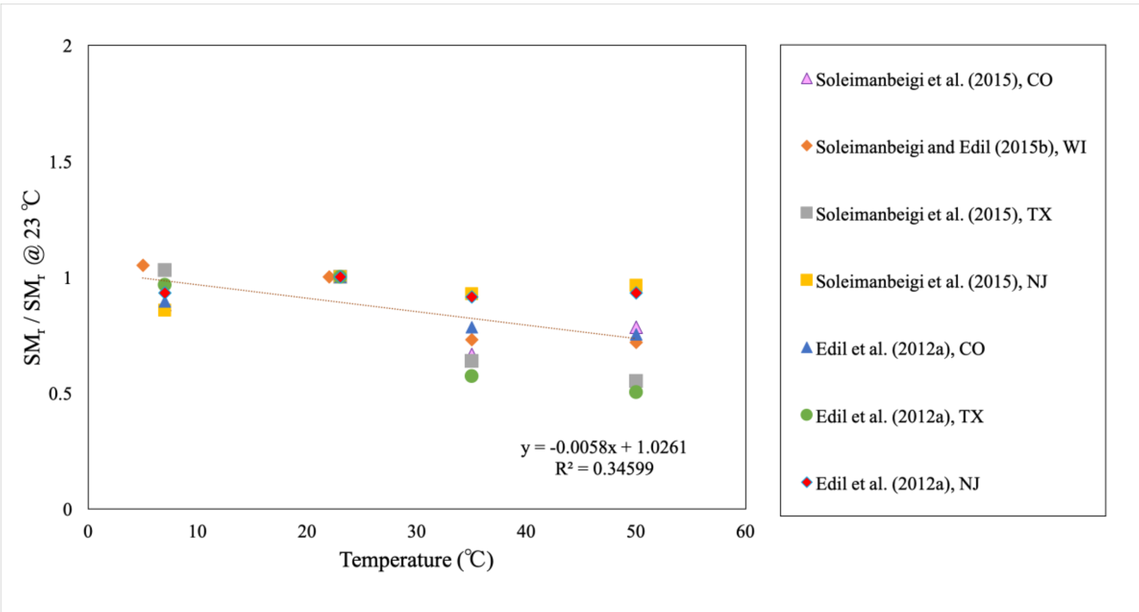

FIGURE 56. NORMALIZED SM_R VERSUS TEMPERATURE OF 100% RAPS

On the other hand, Figure 57 shows that RCA is not temperature-dependent. Moreover, Figure 58 shows the normalized SM_r–Temperature data that were tested at different temperatures. The SM_r of RCA at different temperature was divided by the SM_r of the same RCA at 23°C (73.4°F). The low R^2 value in Figure 58 reveals that there is no relationship between SM_r of RCA and temperature conditions during testing. Figure 59 also shows that SM_r of RCA is independent from the temperature as the whisker plots do not indicate any visible trend. However, the SM_r of RCA at 50°C (122°F) had generally lower SM_r than that of tested at 7°C (44.6°F).

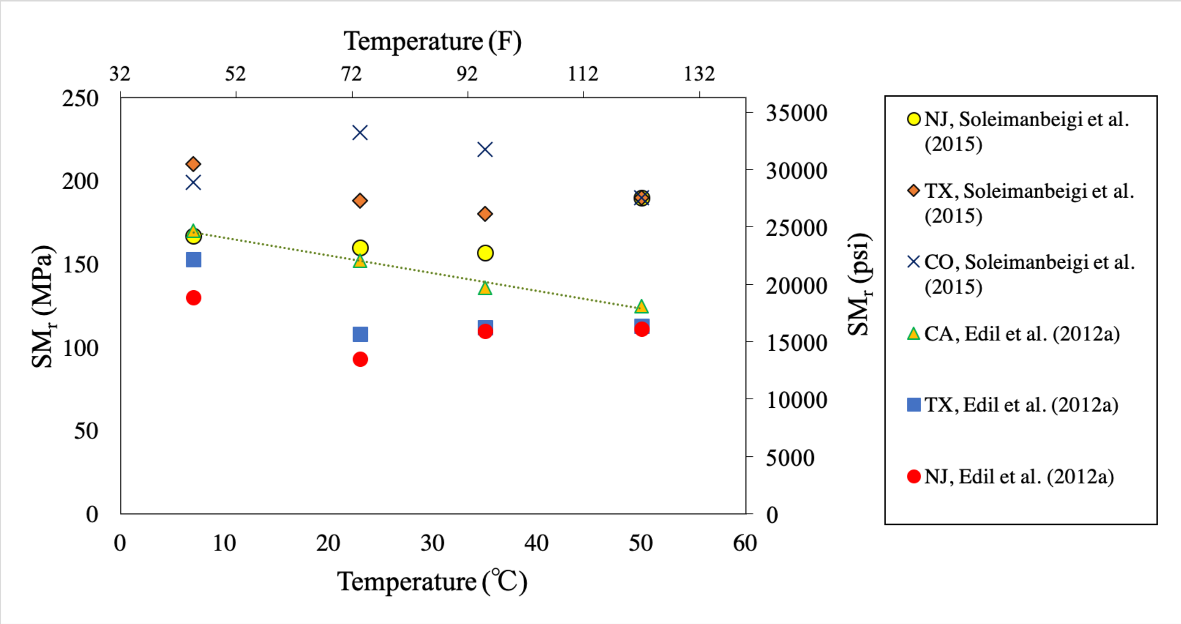

FIGURE 57. SM_R VERSUS TEMPERATURE OF 100% RCA

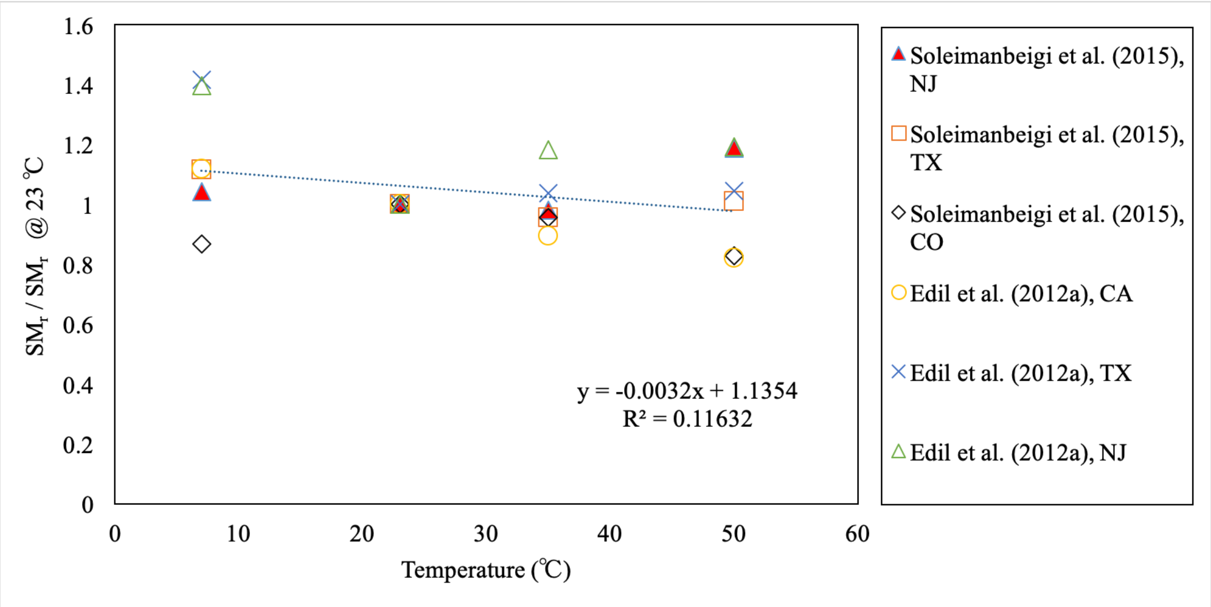

FIGURE 58. NORMALIZED SM_R VERSUS TEMPERATURE OF 100% RCA

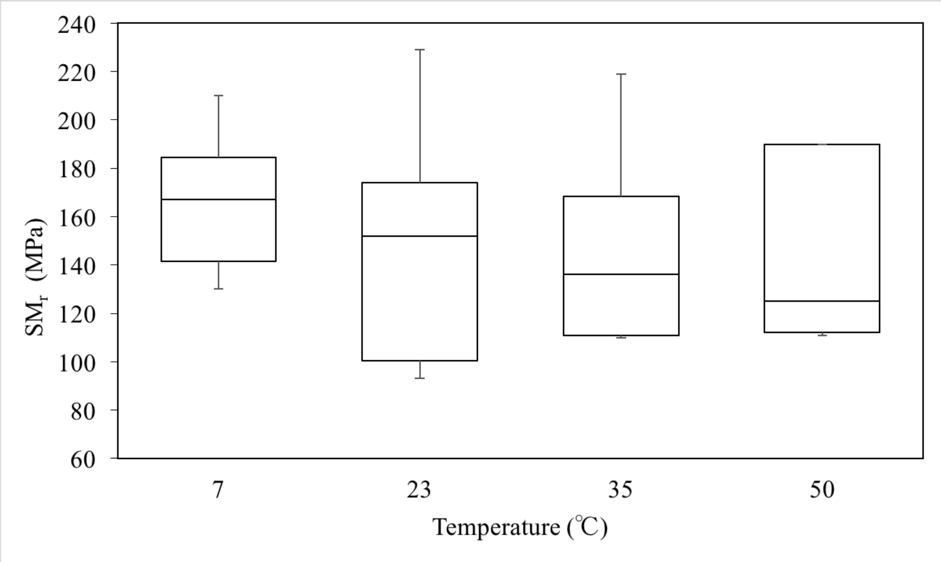

FIGURE 59. SM_R VERSUS TEMPERATURE OF 100% RCA (WHISKER PLOT)

According to Figure 60, an increase in moisture content of RAPs causes a decrease in SM_R. Attia and Abdelrahman (2010b) conducted research on Minnesota's 100% RAP and 50% RAP-natural aggregate mixture. In both cases a reduction in SM_r was observed as the OMC of the specimens increased. In addition, Edil et al. (2012a) tested the RAP samples from Texas and Ohio and concluded that as OMC increased, SM_r of these materials decreased. Resilient modulus test following the NCHRP 1-28A, procedure 1A was conducted with test samples at different moisture contents, as defined by testing matrix.

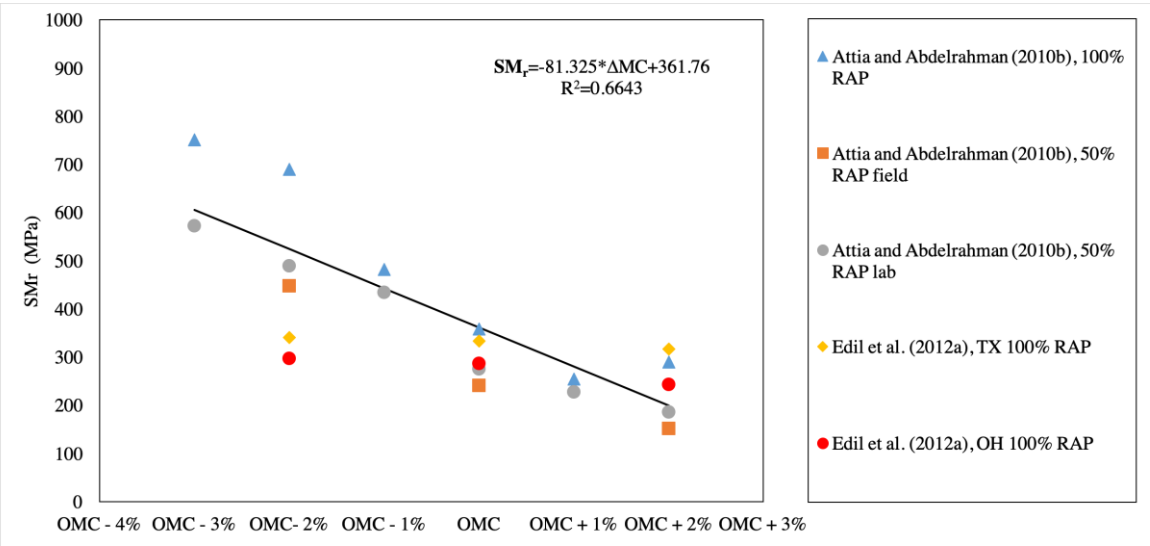

FIGURE 60. SM_R VERSUS OMC OF 100% RAPS

Notes: Samples were compacted at different moisture contents to achieve maximum dry density.
OMC-2%= 2% dry of OMC; OMC+2%= 2% wet of OMC; ΔMC= Percent change in the OMC, for example, ΔMC=+2 in the equation for SM_r of OMC+2%

3.3.3. RESILIENT MODULUS BLENDS OF RAP AND RCA WITH NATURAL AGGREGATES

The use of a higher amount of RAP and RCA increased the stiffness of the RAP-natural aggregates and RCA-natural aggregates mixtures (Bennert et al. 2000). However, there were several exceptions.

For instance, Bestgen et al. (2016) did not observe a consistent increase in the SM_r of the natural aggregates when they were mixed with RCA until RCA contents reached to 75% by weight in the mix design.

An increase in RAP content lead to an increase in SM_r (Figure 61). The SM_r of 100% RAP ranged between 170 MPa (24656.4 psi) (Kim et al. 2005) and 417 MPa (60480.7 psi) (Attia and Abdelrahman 2010a), while the SM_r of 100% RCA varied from 164 MPa (23786.2 psi) to 297 MPa (43076.2 psi).

Ullah and Tanyu (2019) conducted resilient modulus tests on 3 different RAP (RAP 1, RAP2, and RAP3) that were mixed with natural aggregates at 20%, 30%, 40%, 50%, 60% by weight. The SM_r of natural aggregate in this study was 141.1 MPa (20450 psi). The minerals in parent rock of all the RAPs were plagioclase and pyroxene. This study showed that RAP 1 with a high binder content (5.6-5.8%) resulted in the highest SM_r in RAP-natural aggregate mixture, while the RAP 2 with the lowest binder content had the lowest SM_r. Overall, this study claimed that the binder contents of RAP samples had a slight impact on the SM_R of blends when the blends had low RAP percentages and low binder contents. This paper indicated that, parent rock had the most impact on SM_r on the RAP and RAP-natural aggregate mixtures. For instance, RAP materials with plagioclase and pyroxene had a higher SMr than those made of quartz, muscovite, biotite, and amphibole.

Attia and Abdelrahman (2010a) tested Minnesota Class 5 (Class 5) and RAP-natural aggregate blends consisting of 50% RAP + 50% Class 5, 75% RAP + 25% Class 5, and 100% RAP material. Attia and Abdelrahman (2011) determined that RAP-natural aggregate blends were generally less sensitive to bulk stress and more sensitive to confining pressure. They showed that materials with 50% RAP would have SM_r of 265 MPa (38435 psi) while SM_r of 75% RAP blends was 210 MPa (30458 psi). 100% RAP had a SM_r of 400 MPa (58015.1 psi) which was higher than any blends. Bulk stress in this study was calculated as it is defined in the previous studies. It is the sum of the σ_d and 3 times σ_3.

Alam et al. (2010) collected the RAP materials from millings of the 2001 rehabilitation project on Mn/ROAD Cell-26 constructed in 1994. This cell was located on the low volume roadway which had been subjected to 20,000 vehicles per day (Mulvaney and Worel 2002). These RAP materials were mixed with natural aggregates at the following rates by weight 30%, 50%, 70% and 100% and were subjected to M_r tests. This study determined that SM_r increased with an increase in RAP content from 154 MPa (22335.8 psi) at 30% RAP to 270 MPa (39160.2 psi) at 100% RAP.

Bradshaw et al. (2016) studied two different types of RAP and natural aggregate blends. The materials included cold recycled RAP blends that were prepared off site and RAP blends that were generated in situ during full depth reclamation (FDR). The SM_r of the cold recycled RAP blends (14– 39% RAP content) was between 120 MPa (17404.5 psi) and 502 MPa (72808.9 psi). The possible reason for slightly higher SM_r of these blends that those of RAP blends in the literature could be the differences in aggregate composition and/or particle shape. The SM_r of the FDR-RAP blends (57–71% RAP content) ranged from 171 MPa (24802 psi) to 578 MPa (83832 psi) which were higher than the SM_r of the cold recycled RAP blends. This could be due the higher RAP contents used in these blends. In addition, more shear softening and permanent strains were observed for the FDR-RAP mixtures as compared to the cold recycled RAP blends.

Kang et al. (2011) tested recycled materials and natural aggregates. RAP was collected from highway 61 in Minneapolis. Natural aggregates were collected from a pit south of Jordan, MN. RAP and RCA were mixed with natural aggregates at 25%, 50% and 100% by weight. SM_r of blends in this study increased with an increase in RAP content. However, generally the reported SM_r was smaller than any other study ranging from 90 MPa (13053 psi) at 25% RAP blend to 192 MPa (27847 psi) at 100% RAP.

Abdelrahman and Noureldin (2014) conducted research on one source of RAP supplied by the Minnesota Department of Transportation (DOT) from a trunk highway. This RAP was blended with Class 5 base aggregates (Minnesota DOT) at 50%, 75%, and 100% RAP. According to the results, SM_r values changed from 289 MPa (41916 psi) at 50% to 262 MPa (38000 psi) at 75% RAP mixture. It was reported that the SM_r of 100% RAP was 330 MPa (47863 psi) which was the highest among all the blends.

Kim et al. (2005) obtained the reclaimed materials from County Road (CR) 3 in central Minnesota. An in situ blend, a mixture of 25%, 50% and 75% RAP and crushed aggregate, pure RAP and pure aggregate materials were taken separately during FDR. This was the only study that reported similar SM_r for different blends. 100% RAP had SM_r of 170 MPa (24656 psi).

Wu et al. (2012) obtained crushed aggregate (basalt) from POE Asphalt Paving, Inc. (Pullman, Wash.) and RAP from the Fairmount Road construction site in Pullman. To eliminate the effect of gradation, one single gradation was selected meeting the Washington State Department of Transportation (DOT) specifications for crushed surfacing base course material for all percentages of RAP used in the study. This study showed a constant value for blends from 20% to 60% around 200 MPa (29008 psi) whereas 80% RAP blend had a SM_r of 550 MPa (79771 psi) which was considered an outlier.

Bennert and Maher (2005), conducted M_r tests on RAP and RCA blended with dense graded aggregate base course (DGABC) material from the Central region of New Jersey since the quarried material did not exist naturally in southern New Jersey. The ratios of blends for testing were 25%, 50% and 75% along with the 100% RAP or RCA and 100% DGABC. It reported an increasing trend with higher RAP contents from 25% (202 MPa- 29225 psi) to 50% (234 MPa- 33895 psi) and from 75% (214 MPa- 31009 psi) to 100% RAP (268 MPa- 38870 psi). SM_r of 50% RAP was observed to be higher than that of blend mixed with 75% RAP.

Hasan et al. (2018) collected the subgrade soils and the RAP from the interstate 40 (I-40) construction site at the mile post of 141 near Albuquerque, New Mexico and the RAP material was supplied from the stockpile. They reported SM_r of 175MPa (25382 psi) at 25% RAP and SM_r of 290 MPa (42061 psi) at 75% RAP.

Bennert et al. (2000) conducted research on 25%, 50%, 75% and 100% RAP blended with dense graded aggregate base course (DGABC) in the state of New Jersey. This study reported an increasing trend in SM_r as RAP content increased. It also showed that the 25% RAP blend had 187 MPa (27122 psi) stiffness which was 300 MPa (43555 psi) for 100% RAP.

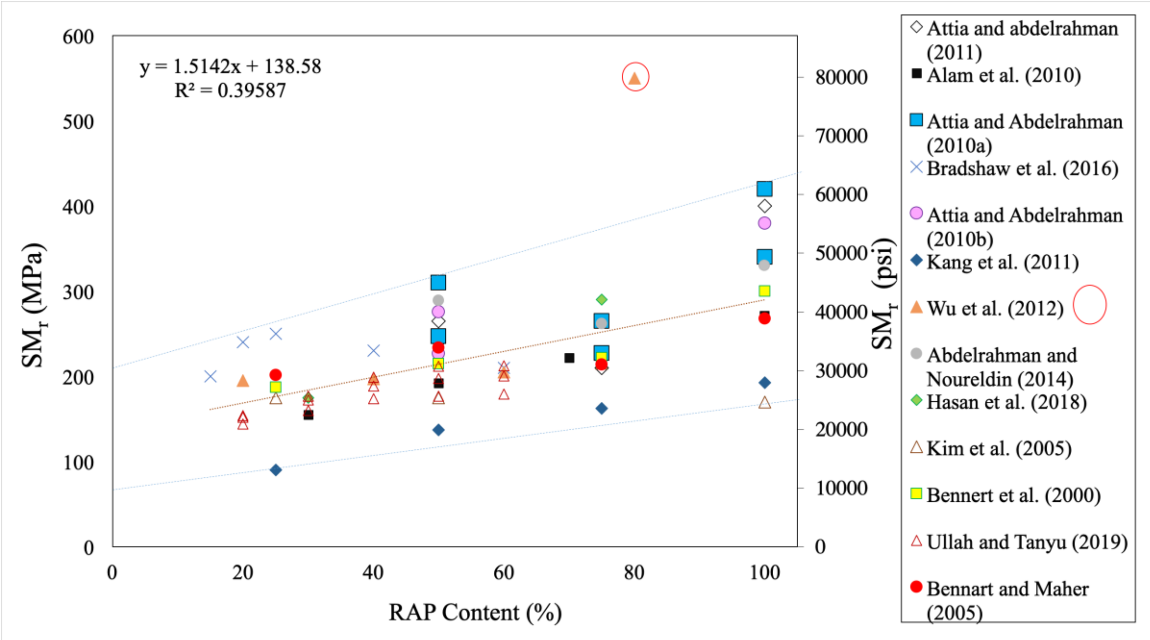

FIGURE 61. SM_R VERSUS RAP CONTENT

Figure 62 shows the normalized SM_r of each RAP blend to the SM_r of the corresponding RAP alone and it is observed that SM_r of RAP mixtures increase with an increase in RAP contents. Figure 63 also confirms this trend more clearly.

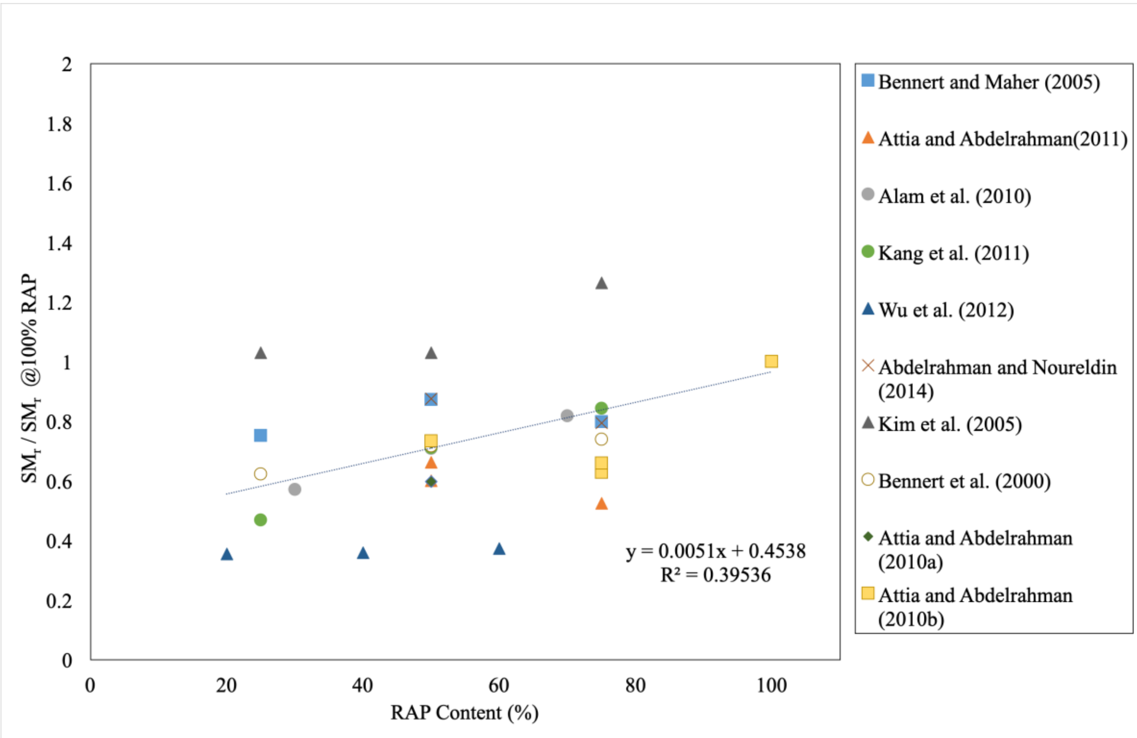

FIGURE 62. NORMALIZED SM_R VERSUS RAP CONTENT

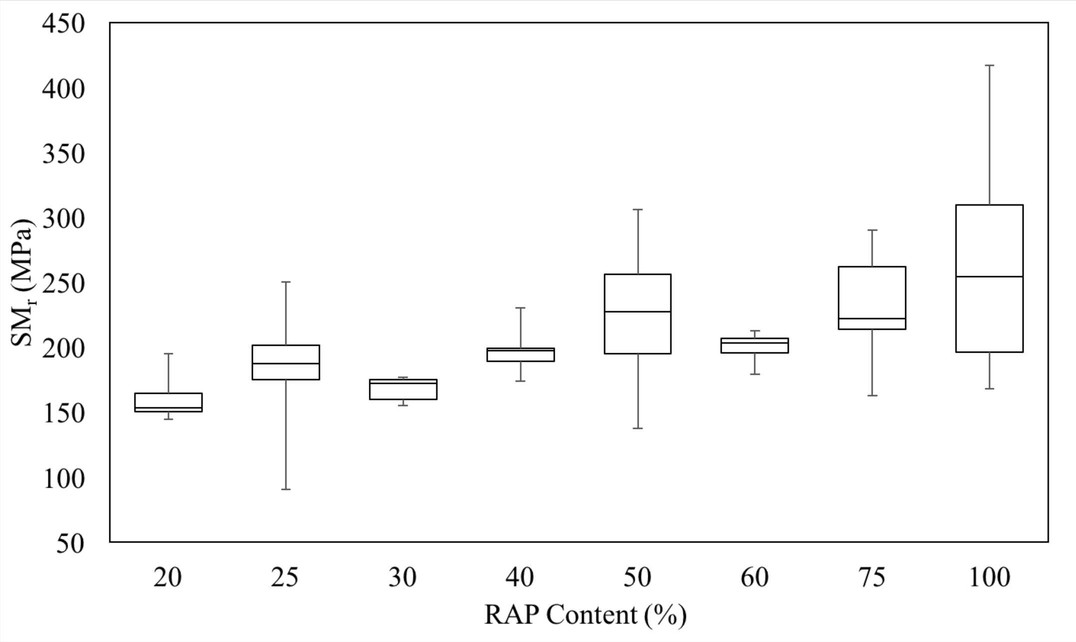

FIGURE 63. SM_R VERSUS RAP CONTENT (WHISKER PLOT)

Furthermore, Figure 64 shows that RCA content and SM_r relationship is not very straight forward as the one observed between the RAP content and SM_r. According to Bestgen et al. (2016), the presence of higher CaO content in RCA materials led to higher SM_r values than the natural aggregates. CaO initiates the cementitious reaction in the aggregate matrix which can improve the mechanical properties of RCA materials. However, database contained 18 different RCA-natural aggregate mixtures and it was observed that each of these mixtures had different trends. Bestgen et al. (2016) tested four different natural aggregate materials with two different RCAs. RCAs were mixed with natural aggregates at 25%, 50%, 75% and 100% ratios by weight. Overall, the mixtures presented a slight increase in SM_r when 25% RCA was increased to 50%. All of the mixtures showed an increase trend in SM_r with RCA content going from 25% to 75% with a few exceptions. RCA had higher SM_r than the RCA-natural aggregate mixtures and the natural aggregates alone. Nevertheless, overall trend was that 100% RCA had a higher summary resilient modulus than any other mixtures and natural aggregates (Figure 65). Figure 66 shows the normalized SM_r values of each blend of RCA (Normalized SM_r means the ratio of the SM_r value of each RCA blend to the corresponding SM_r value of 100% RCA).

Figure 67 indicates that no specific trends are observed between the SM_r of 50% and 75% RCA-natural aggregate blends. The number of available data for SM_r of RCA was lower than those available for RAP. For 100% RCA and 50% RCA, 23 and 11 data points were available, respectively. The lowest number of available data was 10 for 25% and 75% RCA blends. Overall, Figure 67 also confirms that 100% RCA has a higher resilient modulus than any blends and natural aggregates.

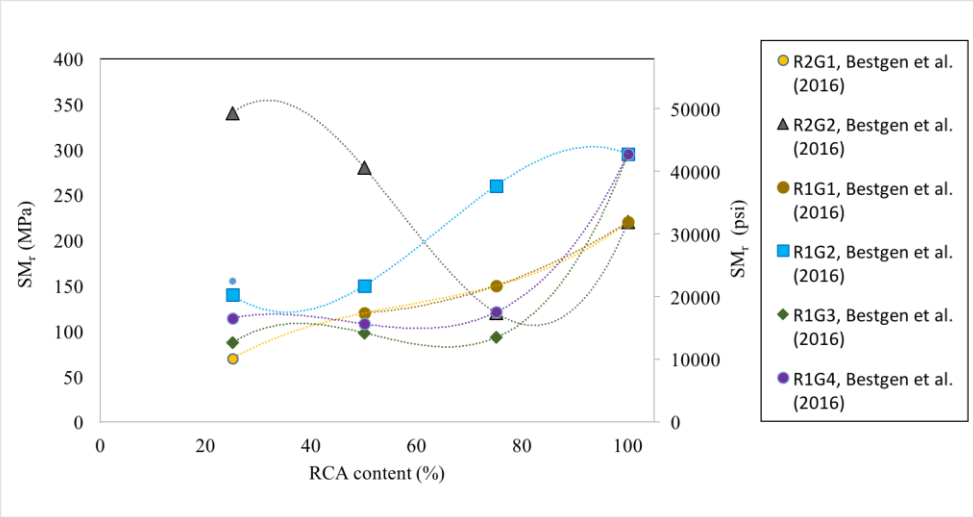

FIGURE 64. SM_R VERSUS RCA CONTENT

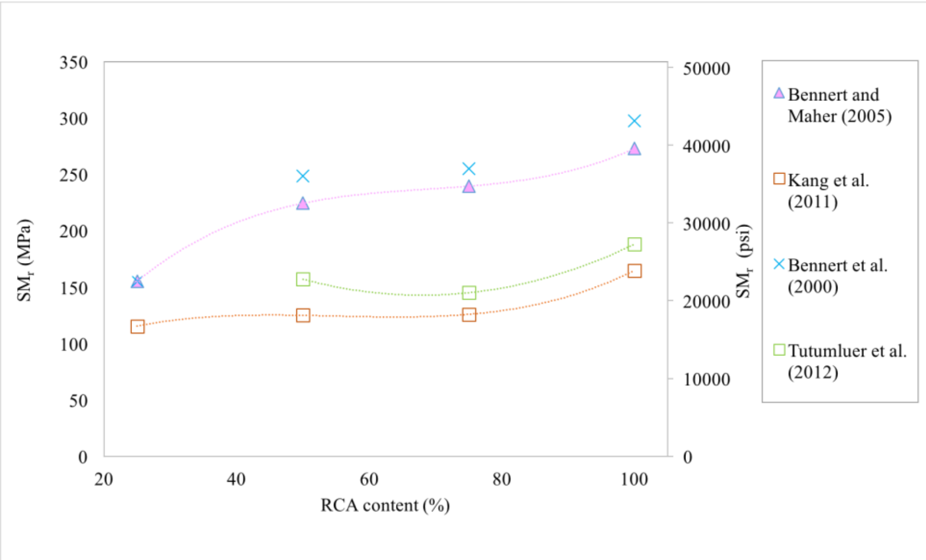

FIGURE 65. SM_R VERSUS RCA CONTENT

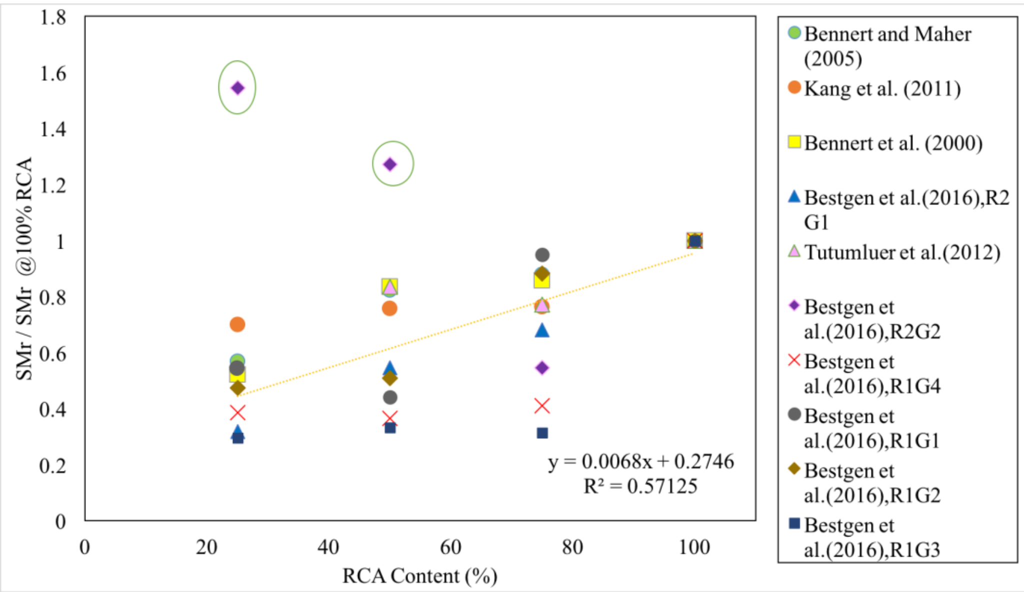

FIGURE 66. NORMALIZED SM_R AND RCA CONTENT

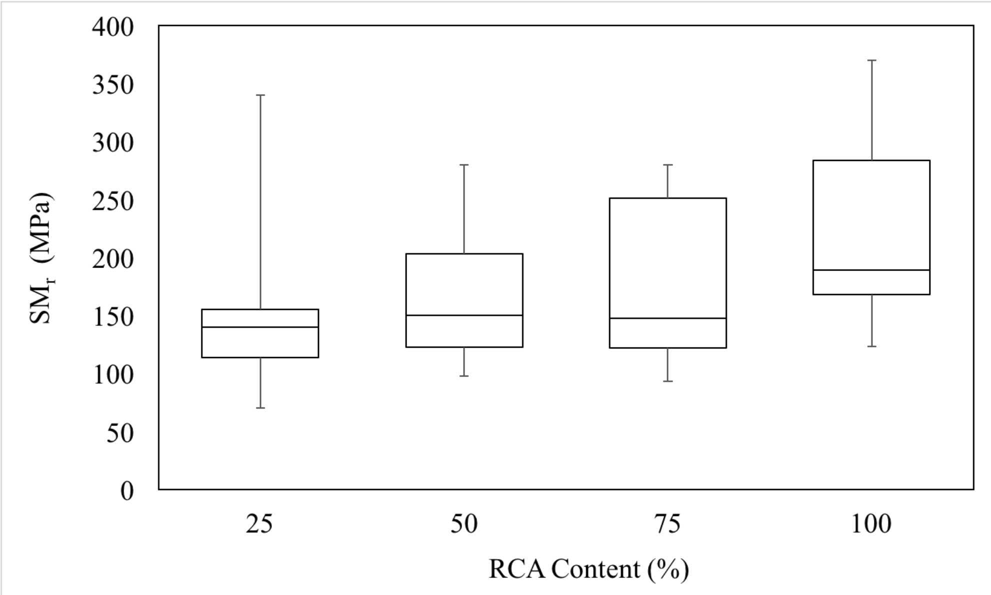

FIGURE 67. SM_R VERSUS RCA CONTENT (WHISKER PLOT)

3.4. PERMANENT DEFORMATION

The permanent deformation failure is attributed to the vertical compressive strains of geomaterials under repeated loading conditions which lead to failure mechanisms in the flexible pavement systems (Bennert et al. 2000, Thompson and Smith 1990). Permanent deformation is determined by performing a cyclic triaxial test in which the confining pressure, deviatoric stress and the number of cycles are predetermined.

Increasing the number of loading cycles leads to an increase in the permanent deformation of pavement foundation materials regardless of the aggregate type. A relatively higher permanent deformations were observed with an increase in the RAP content of the RAP-natural aggregate mixtures (Kim and Labuz 2007, Thakur and Han 2015). On the other hand, an increase in the RCA content of the RCA-natural aggregate mixtures caused a relatively lower permanent deformation (Bennert et al. 2000). In general, RCA showed the lowest permanent deformation among RCA, RAP and natural aggregate while RAP showed the highest permanent deformation (Bennert et al. 2000; Edil et al. 2012a). Having the highest permanent deformation in RAP may have been the progressive breakdown of its asphalt binder (Bennert et al. 2000). Moreover, viscous creep behavior of asphalt material could be one of the reasons for the high plastic deformation of RAP (Edil et al. 2012a). The permanent deformation of 100% RAPs ranged from 1.05% (Attia 2010) to 5.63% (Bennert and Maher 2005) while these values were between 0.1% (Bestgen et al. 2016) and 0.83% for RCAs (Edil et al. 2012a).

Different trends have been observed between RAP, RCA, and natural aggregate due to their different gradation characteristics (e.g. fines contents). Virgin aggregate could show lower permanent deformation than RCA due to its lower fines content (Bestgen et al. 2016). Fines content can significantly affect the permanent deformation while it has no considerable effect on the resilient moduli of aggregates. A relatively higher fines content leads to a higher permanent deformation of aggregates (Mishra and Tutumluer 2012). Moreover, repetitive load may break hydrated cement particles thus reduce the angularity of RCA which finally leads to a higher permanent deformation in RCA than those observed for natural aggregates (Bestgen et al. 2016).

According to Thompson and Smith (1990), permanent deformation plays an important role in determining the pavement performance. Bennert et al. (2000), Attia (2010), Garg and Thompson (1996), Kim and Labuz (2007) and Wen and Wu (2011) showed that permanent deformation of RAP-natural aggregate mixtures increased with an increase in the RAP content (Figure 68).

Particle sizes of the RCAs and RAPs are important since the presence of larger aggregates in the material matrix tend to lead to higher strength and the resistance against deformation (Gray 1962, Kazmee et al. 2016). Moreover, the thicker base layers result in the lower permanent deformation due to the improved stress distribution (Cetin et al. 2010, Schaertl 2010).

It was also observed that temperature is very crucial for RAPs permanent deformation performances. An increase in temperature yields an increase in the permanent deformation or RAP materials because of the temperature-sensitivity of RAP (Edil et al. 2012a; Soleimanbeigi et al. 2015). On the other hand, the temperature has little to no effect on the permanent deformation performances of RCA and natural aggregates (Edil et al. 2012a).

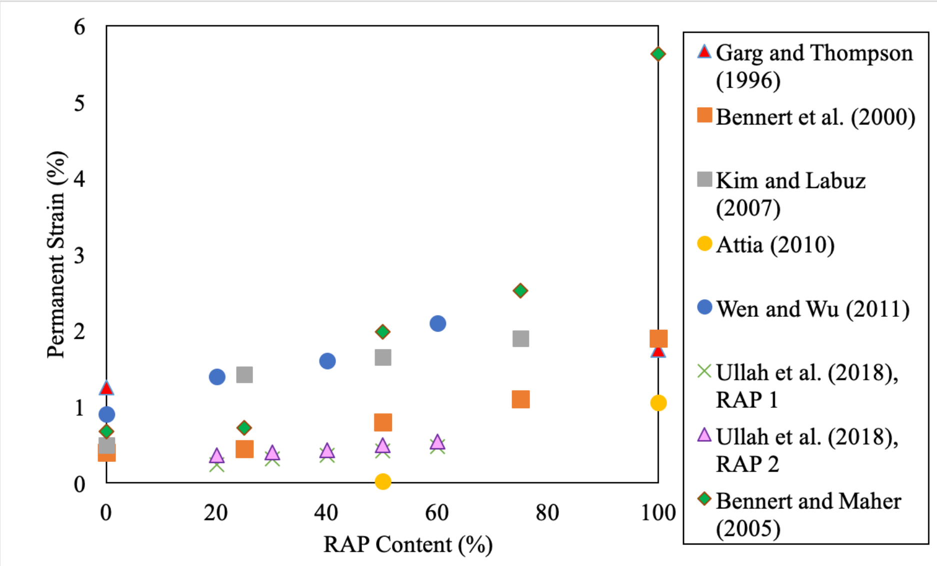

FIGURE 68. PERMANENT STRAIN VERSUS RAP CONTENT

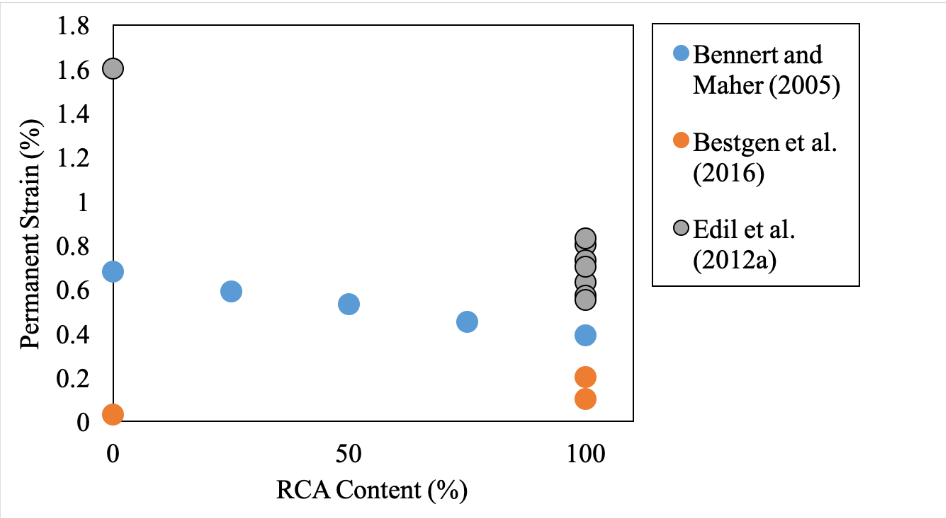

FIGURE 69. PERMANENT STRAIN VERSUS RCA CONTENT

3.5. SHEAR STRENGTH

Shear strength is the maximum shear stress that a soil can sustain. Attia (2010) identified shear strength as an important property for unbound materials when used under a thin HMA layer that is subjected to high shear stresses. Shear strength is a function of normal or confining stress, friction angle, and cohesion for a particular material. Cosentino et al. (2003), Bennert and Maher (2005), Attia (2010), Bejarano (2001), Garg and Thompson (1996), and Kim and Labuz (2007) evaluated shear strength parameters (friction angle and cohesion) of the RAP-blended natural aggregate materials. Results of this study showed that the friction angle (φ) and the cohesion (c) of 100 % RAP specimen varied from 44° to 52° and 0 kPa (0 psi) to 131 kPa (19 psi), respectively. The large variation in the cohesion of RAP may resulted from the variation in the asphalt binder content of the RAP used by different researchers. No correlations or trends were observed between the φ and the c parameters of RAP-natural aggregate mixtures and the corresponding RAP content (Figures 70 and 71). There were less available data regarding shear strength of RCAs. The “c” of RCAs ranged from 24.13 kPa (3.5 psi) to 191 kPa (27.7 psi) and the φ of RCAs ranged from 19° to 52.7° (Figures 72 and 73).

The typical ranges for angle of friction of granular soil materials for GW, GP, SW, SP are 33-40°, 32-44°, 33-43°, 30-39°, respectively (Swiss Standard SN 670 010b and Koloski et al. 1989) while they are between 35° and 51° for muddy shale and stone Mt. granite rocks (Goodman 1980).

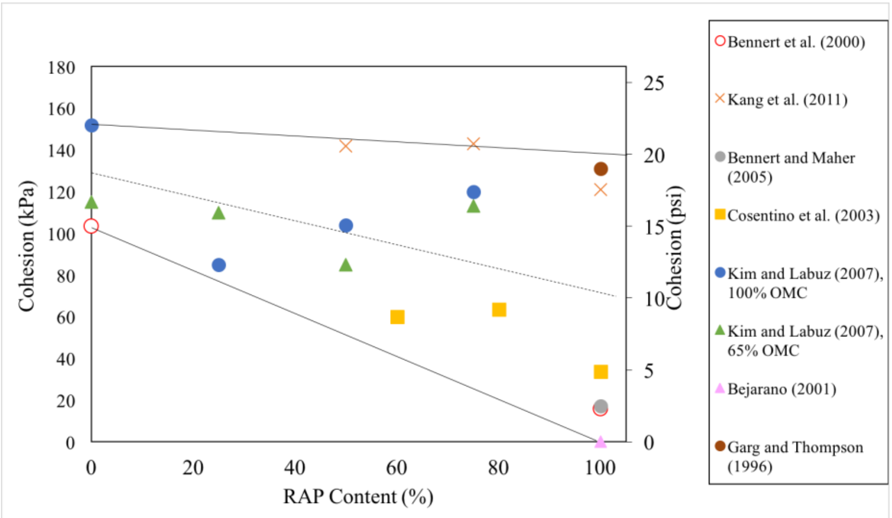

FIGURE 70. COHESION VERSUS RAP CONTENT

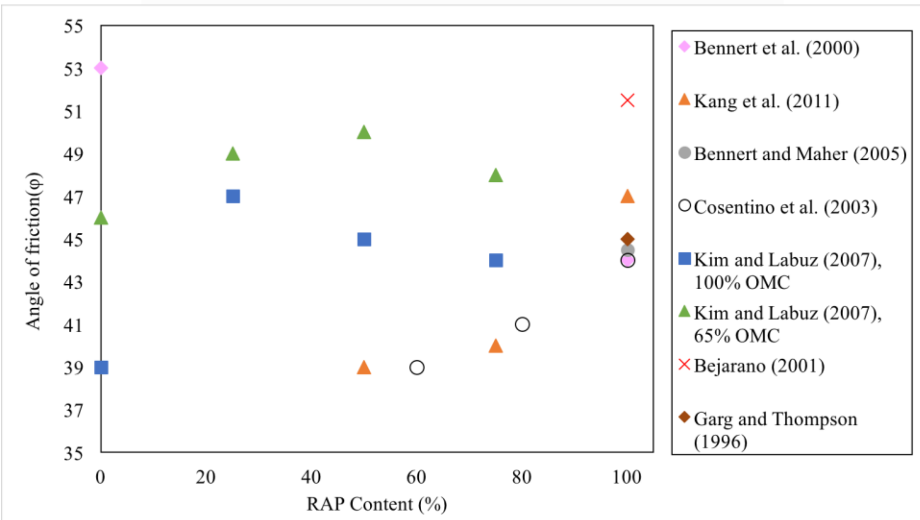

FIGURE 71. FRICTION ANGLE VERSUS RAP CONTENT

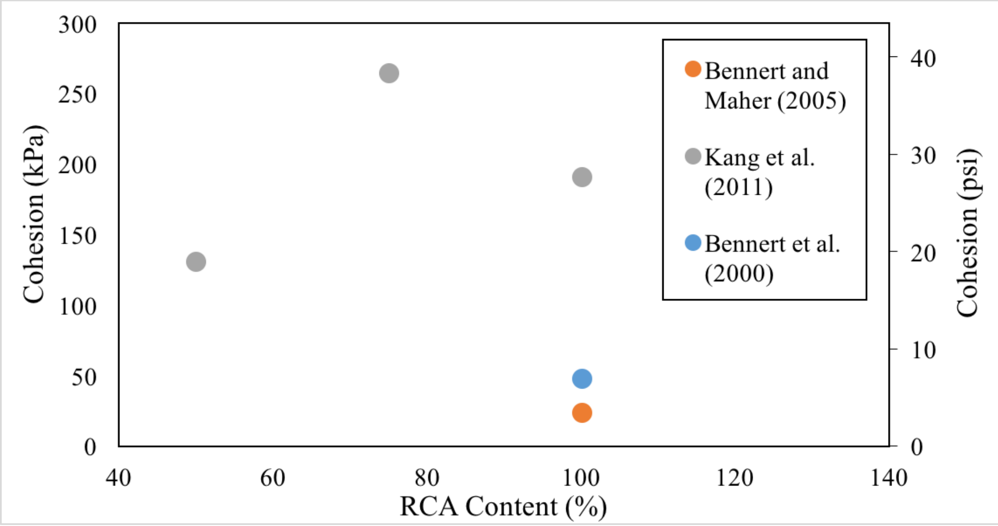

FIGURE 72. COHESION VERSUS RCA CONTENT

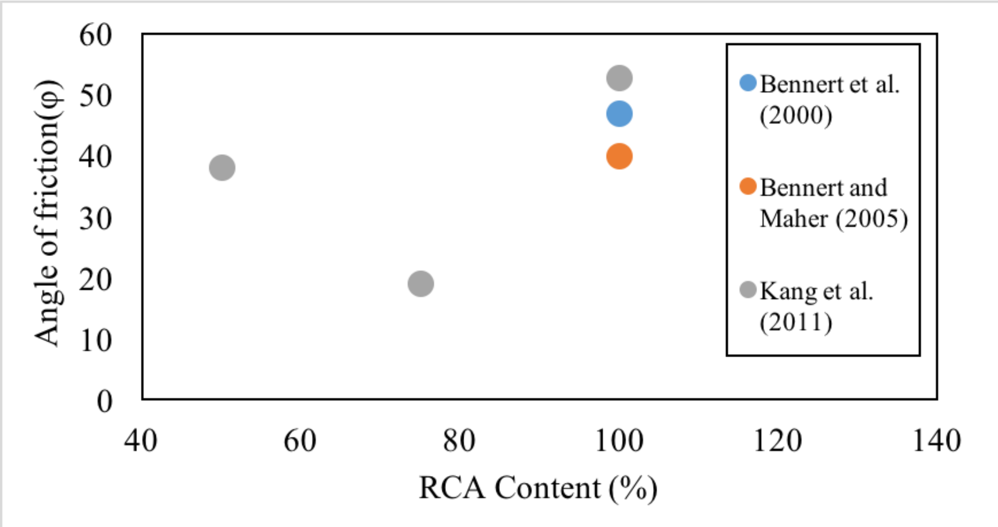

FIGURE 73. FRICTION ANGLE VERSUS RCA CONTENT

4. DESIGN METHODS

One of the most important steps for constructing high-quality and long-lasting pavement systems is the determination of surface, aggregate base, and subbase layers' thickness. While there are methods and assumptions for using natural aggregates as an aggregate base or subbase layer, designing pavement systems with recycled (RAP and RCA) can be challenging (Edil 2011). The engineering properties of RAP and RCA should be well understood as they play an important role in design. AASHTO (1993) and Mechanistic-Empirical Pavement Design Guide (MEPDG) are the most commonly used design methods for flexible and rigid pavements (Edil 2011). The focus of this research is to improve the inputs for MEPDG design method which is now called Pavement ME design.

4.1. PAVEMENT MECHANISTIC EMPIRICAL DESIGN

Plastic deformation is taken into account in the Pavement ME, which is a mechanistic-empirical approach in contrast to the AASHTO (1993) design method which is an empirical approach. There are several parameters such as the modulus values of layers, climate zone, traffic conditions, the designed service life of the pavement, and failure criteria to be considered to create the most suitable design. Resilient modulus values should be obtained from laboratory or field tests for conventional and recycled aggregates. Finally making iterations for specific materials along with other related conditions leads to determining the design thicknesses (Edil 2011). For performance evaluation of pavement systems, required parameters for the analysis can be obtained for RAP, RCA, natural aggregates, and the RAP-natural aggregate and RCA-natural aggregate mixtures.

5. SELECTED PRACTICES OF STATE DOTS

The materials which do not meet the specifications, which state DOTs have established, cannot be used due to high failure risk (NCHRP-838). As more DOTs understand the importance of RAPs and RCAs, they tend to develope guidelines for RAP and RCA usage in pavements as they can be more economical and readily available. This literature review illustrates the practical aspects of the use of RAP and RCA in pavement design by different state DOTs and how each guideline slightly differs from each other. Caltrans, MnDOT, MoDOT, WiDOT allow RAP and RCA to be used as a base course material in pavements if they meet the requirements for gradation and quality characteristics. MDOT and IDOT only allow RCA in base applications eventhough IDOT recently starts considering the use of RAP in such applications as well. More detailed information about DOT spesifications is discussed below.

5.1. CALIFORNIA DOT

In California, RAP and RCA base applications are allowed up to 100% since 2006 but before then their usage was limited to 50%. Recycled aggregates must meet the grading and quality specifications stated for natural aggregate in the Caltrans Standard Specifications (CalRecycle 2014).

Aggregate base and subbase applications of the recycled aggregates are discussed in Sections 25 and 26 of the Caltrans Standard Specifications published in 2015 (Caltrans 2015). Clean broken stone, crushed gravel, natural rough surfaced gravel, sand, and reclaimed processed Portland cement concrete (PCC) can be used as subbases and aggregate bases. The subbase aggregates must meet the gradation ranges of Class 1, Class 2, or Class 3 as shown in Table 4 (section 25 of Caltrans 2015). In addition, the aggregates must have adequate quality characteristics presented in Table 5 depending on its class. The aggregates used as base materials should meet the requirements of gradations and quality characteristics of Class 2 or Class 3 aggregates shown in Tables 6, 7, 8, and 9.

Contract compliance is a larger range than the Operating Range and is used to adjust fort not having to shut the job down or pay a fine. If the gradation is outside of the Operating Range but within the Contract Compliance requirements, this material can continue to be used for the remainder of the day. It should be noted, that even if within the Contract Compliance requirements, changes still need to be made by the next day to ensure the material is within Operating Range, or construction will be stopped until requirements are met. If a test results indicate the material is still outside the Contract Compliance requirements, Caltrans generally has the right to ask for removal or a payment deduction.

TABLE 4. AGGREGATE GRADATION FOR SUBBASE APPLICATIONS (CALTRANS 2015)

Sieve size	Percentage passing					
	Class 1		Class 2		Class 3	
	Operating range	Contract compliance	Operating range	Contract compliance	Operating range	Contract compliance
3"	100	100	100	100	100	100
2 1/2"	90–100	87–100	90–100	87–100	90–100	87–100
No. 4	35–70	30–75	40–90	35–95	50–100	45–100
No. 200	0–20	0–23	0–25	0–29	0–30	0–34

TABLE 5. AGGREGATE QUALITY CHARACTERISTICS FOR SUBBASE APPLICATIONS (CALTRANS 2015)

Quality characteristic	Requirement					
	Class 1		Class 2		Class 3	
	Operating range	Contract compliance	Operating range	Contract compliance	Operating range	Contract compliance
Sand equivalent, (min)	21	18	21	18	21	18
Resistance, (R-value, min)	--	60	--	50	--	40

TABLE 6. CLASS 2 AGGREGATE GRADATION FOR AGGREGATE BASE APPLICATIONS (CALTRANS 2015)

Sieve size	Percentage passing			
	1-1/2 inch maximum		3/4 inch maximum	
	Operating range	Contract compliance	Operating range	Contract compliance
2"	100	100	--	--
1-1/2"	90–100	87–100	--	--
1"	--	--	100	100
3/4"	50–85	45–90	90–100	87–100
No. 4	25–45	20–50	35–60	30–65
No. 30	10–25	6–29	10–30	5–35
No. 200	2–9	0–12	2–9	0–12

TABLE 7. CLASS 2 AGGREGATE QUALITY CHARACTERISTICS FOR AGGREGATE BASE APPLICATIONS (CALTRANS 2015)

Quality characteristic	Requirement	
	Operating range	Contract compliance
Resistance (R-value, min)	--	78
Sand equivalent (min)	25	22
Durability index (min)	--	35

TABLE 8. CLASS 3 AGGREGATE GRADATION FOR AGGREGATE BASE APPLICATIONS (CALTRANS 2015)

Sieve size	Percentage passing			
	1-1/2 inch maximum		3/4 inch maximum	
	Operating range	Contract compliance	Operating range	Contract compliance
2"	100	100	--	--
1-1/2"	90–100	87–100	--	--
1"	--	--	100	100
3/4"	50–90	45–95	90–100	87–100
No. 4	25–60	20–65	40–70	35–75
No. 30	10–35	6–39	12–40	7–45
No. 200	3–15	0–19	3–15	0–19

TABLE 9. CLASS 3 AGGREGATE QUALITY CHARACTERISTICS FOR AGGREGATE BASE APPLICATIONS (CALTRANS 2015)

Quality characteristic	Requirement	
	Operating range	Contract compliance
Resistance (R-value) (min)	--	50
Sand equivalent (min)	21	18

5.2. ILLINOIS DOT

Sections 311 and 351 of the IDOT Standard Specifications for Road and Bridge Construction published in 2016 allows crushed concrete produced from Portland cement concrete, crushed gravel and crushed stone for the aggregate base and subbase courses (IDOT 2016). According to section 1004, 20 different aggregate classes are defined for different applications (Table 10). Crushed concrete must have adequate gradation requirements of CA6 or CA10 aggregates for aggregate base applications (Table 11) (IDOT 2016).

As stated in Section 1004, coarse aggregate quality control specifications are established by Illinois DOT (Table 12). Crushed concrete should be evaluated as class D for checking its quality in terms of Illinois Test Procedure (ITP) 96 (LA abrasion test) and must be evaluated as a class C for Illinois Test Procedure (ITP) 203 which is used for the determination of deleterious particles in coarse aggregate. According to the Los Angeles (LA) abrasion limit, abrasion loss should be less than 45% and instead of the given limit for deleterious materials (2%), the content of other deleterious should be limited to 7% with no more than 5% RAP (IDOT - Bureau of Materials and Physical Research). The California bearing ratio should be 80 for the aggregate base applications of typical materials but there is no requirement for crushed concrete (IDOT 2016).

Per Section 303, IDOT allows RAP usage in constructing an aggregate subgrade improvement which can contain coarse aggregate or reclaimed asphalt pavement. Crushed RAP , from either full depth or single lift removal, may be mechanically blended with aggregate gradations CS 01, CS 02 and RR 01 but the total product must contain RAP at 40% or less. The size of RAP particles must be less than 4 inches and well graded. RAP with 100% passing 1-1/2 inch sieve and being well graded, may be used as a capping aggregate on the top 3 inches when aggregate gradations CS 01, CS 02 or RR 01 are used in lower lifts. The RAP used for aggregate subgrade improvement shall be selected according to the current Bureau of Materials and Physical Research Policy Memorandum, "Reclaimed asphalt pavement (RAP) for aggregate applications.

TABLE 10. GRADATION RANGES OF DIFFERENT AGGREGATES (IDOT 2016)

	COARSE AGGREGATE GRADATIONS												
	Sieve Size and Percent Passing												
Grad No.	3 in.	2 1/2 in.	2 in.	1 1/2 in.	1 in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No. 16	No. 50	No. 200 [1/]
	75 mm	63 mm	50 mm	37.5 mm	25 mm	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	300 μm	75 μm [1/]
CA 1	100	95±5	60±15	15±15	3±3								
CA 2		100	95±5		75±15		50±15		30±10		20±15		8±4
CA 3		100	93±7	55±20	8±8		3±3						
CA 4			100	95±5	85±10		60±15		40±10		20±15		8±4
CA 5				97±3 [2/]	40±25		5±5		3±3				
CA 6				100	95±5		75±15		43±13		25±15		8±4
CA 7				100	95±5		45±15 [7/]		5±5				
CA 8				100	97±3	85±10	55±10		10±5		3±3 [3/]		
CA 9				100	97±3		60±15		30±15		10±10		6±6
CA 10					100	95±5	80±15		50±10		30±15		9±4
CA 11					100	92±8	45±15 [4/7/]		6±6		3±3 [3/ 5/]		
CA 12						100	95±5	85±10	60±10		35±10		9±4
CA 13						100	97±3	80±10	30±15		3±3 [3/]		
CA 14							90±10 [6/]	45±20	3±3				
CA 15							100	75±15	7±7		2±2		
CA 16							100	97±3	30±15		2±2 [3/]		
CA 17	100								65±20		45±20	20±10	10±5
CA 18	100				95±5				75±25		55±25	10±10	2±2
CA 19	100				95±5				60±15		40±15	20±10	10±5
CA 20							100	92±8	20±10	5±5	3±3		

TABLE 11. TYPICAL AGGREGATES FOR VARIOUS APPLICATIONS (IDOT 2016)

Use	Gradation
Granular Embankment, Special	CA 6 or CA 10 1/
Granular Subbase:	
Subbase Granular Material, Ty. A	CA 6 or CA 10 2/
Subbase Granular Material, Ty. B	CA 6, CA 10, CA 12, or CA 19 2/
Subbase Granular Material, Ty. C	CA 7, CA 11, or CA 5 & CA 7 3/
Stabilized Subbase	CA 6 or CA 10 4/
Aggregate Base Course	CA 6 or CA 10 2/
Aggregate Surface Course:	
Type A	CA 6 or CA 10 1/
Type B	CA 6, CA 9, or CA 10 5/
Aggregate Shoulders	CA 6 or CA 10 2/

TABLE 12. COARSE AGGREGATE QUALITY CONTROL SPECIFICATIONS (IDOT 2016)

COARSE AGGREGATE QUALITY				
QUALITY TEST	CLASS			
	A	B	C	D
Na_2SO_4 Soundness 5 Cycle, ITP 104 1/, % Loss max.	15	15	20	25 2/
Los Angeles Abrasion, ITP 96, % Loss max.	40 3/	40 4/	40 5/	45
Minus No. 200 (75 µm) Sieve Material, ITP 11	1.0 6/	---	2.5 7/	---
Deleterious Materials 10/				
Shale, % max.	1.0	2.0	4.0 8/	---
Clay Lumps, % max.	0.25	0.5	0.5 8/	---
Coal & Lignite, % max.	0.25	---	---	---
Soft & Unsound Fragments, % max.	4.0	6.0	8.0 8/	---
Other Deleterious, % max.	4.0 9/	2.0	2.0 8/	---
Total Deleterious, % max.	5.0	6.0	10.0 8/	---

5.3. MINNESOTA DOT

RAP and RCA are both allowed in Section 2211 of the MnDOT Standard Specifications for construction published in 2018 to be used as aggregate base course (MnDOT 2018). In Section 3138, aggregates are classified based on their quality characteristics and they should meet the quality requirements of one of those classes (Table 13). In addition, RAP and RCA should meet the quality requirements, which are the same for all aggregate classes (Table 14) (MnDOT 2018). When the RAP content is more than 10% of the blend by volume, the gradation of RAP and aggregate blend must meet the specified gradation for the aggregate class (McGarrah 2007). RAP and natural aggregate must be blended at the crushing site, not at the job site with stockpiles aggregates (McGarrah 2007).

Almost all concrete pavements in Minnesota are recycled as dense-graded base aggregate material (Gonzalez and Moo-Young 2004). Fine-grained (< #4 sieve) RCA particles must be removed to avoid the drainage issues. Moreover, open-graded RCA can be mixed with natural aggregates to reduce the heavy metal leaching (Snyder 1995, as cited in Gonzalez and Moo-Young 2004).

Per Section 3138, depending on the project, the blends of natural aggregates and recycled aggregates with less than 25% recycled aggregates used as a pavement aggregate base material should meet the gradations specified for different aggregate classes (Table 15) (MnDOT 2018). If 25% or more up to 75% recycled aggregates are used in the blends, the mixture should meet the gradation criteria provided in Table 16. In addition, if 75% or more recycled concrete is used, the mixture should meet the gradation criteria shown in Table 17 (MnDOT 2018).

TABLE 13. QUALITY REQUIREMENTS FOR VIRGIN AGGREGATES (MNDOT 2018)

Requirement	Class			
	1 and 2	3 and 4	5 and 5Q	6
Max Shale, if No. 200 ≤ 7% by mass	NA	10.0%	10.0%	7.0%
Max Shale, if No. 200 > 7% by mass	NA	7.0%	7.0%	7.0%
Minimum Crushing Requirements *	NA	NA	10%	15%
Maximum Los Angeles Rattler (LAR) loss from carbonate quarry rock	40%	40%	40%	35%
Maximum Insoluble residue for the portion of quarried carbonate aggregates passing the No. 200 sieve	10%	10%	10%	10%
* Material crushed from quarries is considered crushed material.				

TABLE 14. QUALITY REQUIREMENTS FOR RECYCLED AGGREGATES (MNDOT 2018)

Requirement	Classes 1, 3, 4, 5, 5Q, and 6
Maximum Bitumen Content of Composite	3.5%
Maximum Masonry block %	10%
Maximum percentage of glass *	10%
Maximum size of glass *	¾ in
Crushing (Class 1, 5, 5Q, and 6) ‖	10% for Class 1 & 5 †, 60% for Class 5Q †, and 15% for Class 6 †
Maximum amount of Brick	1.0% #
Maximum amount of other objectionable materials including but not limited to: wood, plant matter, plastic, plaster, and fabric	0.3% #

* Glass must meet certification requirements on the Grading and Base website. Combine glass with other aggregates during the crushing operation.
† If material ≥ 20% RAP and/or Concrete, Class 5 crushing requirement is met.
† If material ≥ 60% RAP and/or Concrete, Class 5Q crushing requirement is met.
† If material ≥ 30% RAP and/or Concrete, Class 6 crushing requirement is met.
‖ Material crushed from quarries is considered crushed material.
\# The Contractor/Supplier may not knowingly allow brick and other objectionable material and must employ a QC process to screen it out, before it becomes incorporated into the final product.

TABLE 15. GRADATION OF BASE AGGREGATE CONTAINING LESS THAN 25% RECYCLED AGGREGATES (MNDOT 2018)

Sieve Size	Class 1 (Surfacing £)	Class 2 (Surfacing β)	Class 3 (Subbase)	Class 4 (Subbase)	Class 5 (Base)	Class 5Q (Base)	Class 6 (Base)
2 in	—	—	100	100	—	100	—
1½ in	—	—	—	—	100	—	100
1 in	—	—	—	—	—	65 - 95	—
¾ in	100	100	—	—	70 - 100	45 - 85	70 - 100
⅜ in	65 - 95	65 - 90	—	—	45 - 90	35 - 70	45 - 85
No. 4	40 - 85	35 - 70	35 - 100	35 - 100	35 - 80	15 - 45	35 - 70
No. 10	25 - 70	25 - 45	20 - 100	20 - 100	20 - 65	10 - 30	20 - 55
No. 40	10 - 45	12 - 35	5 - 50	5 - 35	10 - 35	5 - 25	10 - 30
No. 200	8.0 - 15.0	5.0 - 16.0	5.0 - 10.0	4.0 - 10.0	3.0 - 10.0	0.0 - 10.0	3.0 - 7.0

***** If product contains recycled aggregate, add letters in parentheses for each aggregate blend designating the type of recycled products included in the mixture.
(B) = Bituminous, (C) = Concrete, (G) = Glass
(BC) = Bituminous and Concrete, (BG) = Bituminous and Glass
(CG) = Concrete and Glass, (BCG) = Bituminous, Concrete, and Glass
£ Recycled concrete when used for surfacing is only allowed for shoulders
β Class 2 must be composed of 100% crushed quarry rock per 3138.2.B.2.

TABLE 16. GRADATION OF BASE AGGREGATE CONTAINING 25% OR MORE RECYCLED AGGREGATES and 75% OR LESS RECYCLED CONCRETE (MNDOT 2018)

Sieve Size	Class 1 (Surfacing £)	Class 3 (Subbase)	Class 4 (Subbase)	Class 5 (Base)	Class 5Q (Base)	Class 6 (Base)
2 in	—	100	100	—	100	—
1½ in	—	—	—	100	—	100
1 in	—	—	—		65 - 95	
¾ in	100	—	—	70 - 100	45 - 85	70 - 100
⅜ in	65 - 95	—	—	45 - 90	35 - 70	45 - 85
No. 4	40 - 85	35 - 100	35 - 100	35 - 80	15 - 45	35 - 70
No. 10	25 - 70	20 - 100	20 - 100	20 - 65	10 - 30	20 - 55
No. 40	10 - 45 † 5 - 45	5 - 50	5 - 35	10 - 35	5 - 25	10 - 30
No. 200	5.0 - 15.0 † 0 - 15.0	0 - 10.0	0 - 10.0	0 - 10.0	0 - 10.0	0 - 7.0

* Add letters in parentheses for each aggregate blend designating the type of recycled products included in the mixture.
(B) = Bituminous, (C) = Concrete, (G) = Glass
(BC) = Bituminous and Concrete, (BG) = Bituminous and Glass
(CG) = Concrete and Glass, (BCG) = Bituminous, Concrete, and Glass
† Note: For Class 1, if the bitumen content is ≥ 1.5%, the gradation requirement is modified to 5 – 45% for the #40 sieve and 0 – 15.0% for the #200 sieve.
£ Recycled concrete is only allowed for shoulders

TABLE 17. GRADATION OF BASE AGGREGATE CONTAINING MORE THAN 75% RECYCLED CONCRETE (MNDOT 2018)

Sieve Size	Class 1 (Surfacing £)	Class 3 (Subbase)	Class 4 (Subbase)	Class 5 (Base)	Class 5Q (Base)	Class 6 (Base)
2 in	—	100	100	100	100	100
1½ in	—	—	—	—		—
1 in	—	—	—	—	65 - 95	—
¾ in	100	—	—	45 - 100	45 - 85	45 - 100
⅜ in	65 - 95	—	—	25 - 90	35 - 70	25 - 85
No. 4	40 - 85	35 - 100	35 - 100	15 - 65	15 - 45	15 - 65
No. 10	25 - 70	20 - 100	20 - 100	10 - 45	10 - 30	10 - 45
No. 40	10 - 45	0 - 20	0 - 20	0 - 20	0 - 20	0 - 20
No. 200	5.0 - 15.0	0 - 6.0	0 - 6.0	0 - 6.0	0 - 6.0	0 - 6.0

* Add letters in parentheses for each aggregate blend designating the type of recycled products included in the mixture.
(B) = Bituminous, (C) = Concrete, (G) = Glass, (BC) = Bituminous and Concrete,
(BG) = Bituminous and Glass, (CG) = Concrete and Glass, (BCG) = Bituminous, Concrete, and Glass
£ Recycled concrete is only allowed for shoulders

5.4. MISSOURI DOT

The use of reclaimed asphalt and concrete aggregates as base aggregates are allowed in Sections 304 and 1007 of the MoDOT Standard Specifications for Highway Construction published in 2018 if they meet the gradation specifications of Type 1 (Table 18), Type 5 (Table 19), and Type 7 (Table 20) (MoDOT 2018). Section 1007 limits deleterious materials of Type 1, Type 5, and Type 7 aggregates to be less than 15%. Deleterious materials should be distributed uniformly along with sand, silt, and clay contents. Plasticity index (PI) of particles passing No. 40 sieve should not be more than 6 (MoDOT 2018). In addition to Types 1, 5, and 7 aggregates, durable stones containing no more than 10% (by weight) of earth, sand, shale, and non-durable rock are allowed for aggregate base applications according to Section 303. The maximum size depends on the layer thickness. For example, the maximum size should be about 12 and 9 inches for 18-inch and 12-inch rock base respectively (MoDOT 2018).

TABLE 18. GRADATION CRITERIA OF TYPE 1 AGGREGATE (MODOT 2018)

Sieve	Percent by Weight
Passing 1-inch	100
Passing 1/2-inch	60-90
Passing No. 4	35-60
Passing No. 30	10-35

TABLE 19. GRADATION CRITERIA OF TYPE 5 AGGREGATE (MODOT 2018)

Sieve	Percent by Weight
Passing 1-inch	100
Passing 1/2-inch	60-90
Passing No. 4	35-60
Passing No. 30	10-35
Passing No. 200	0-15

TABLE 20. GRADATION CRITERIA OF TYPE 7 AGGREGATE (MODOT 2018)

Sieve	Percent by Weight
Passing 1 1/2-inch	100
Passing 1-inch	70-100
Passing No. 8	15-50
Passing No. 200	0-12

5.5. WISCONSIN DOT

Aggregates, breaker run, crushed gravel, crushed stone, pit run, reclaimed asphalt, and crushed concrete can be used for different aggregate base applications according to Section 301 of the WisDOT Standard Specifications published in 2018 (Table 21). Reclaimed asphalt is only suitable for dense 1 ¼-inch aggregate base type while crushed concrete is suitable for dense ¾-inch, dense 1 1/4 -inch, and dense 3-inch aggregate base types (WisDOT 2018). Base course materials cannot contain any deleterious materials such as shale, soft or porous rock fragments, coal, and organic particles.

Per section 301, reclaimed asphalt aggregates should contain at least 75% of reclaimed asphaltic pavement or surfacing. Crushed concrete aggregate should contain at least 90% crushed concrete without any steel reinforcements or any other impurities. In addition, asphaltic pavement and surfacing material content should be lower than 10% in crushed concrete aggregate.

Crushed natural aggregates and recycled aggregates can be mixed at various percentages to create reprocessed materials or blended materials. Every single aggregate of blended materials must satisfy the specified aggregate base physical properties criteria (Table 22), and final blend must meet the specified gradation (WisDOT 2018). Per section 305, dense graded aggregates such as crushed stone, crushed gravel and crushed concrete (except reclaimed asphalt) should meet the gradations provided in Table 23. For reclaimed asphalt, gradation is primarily assessed visually, e.g., reclaimed asphalt 100% passing 1 ¼-inch sieve may be used for 1 ¼-inch aggregate base application (WisDOT 2018).
Per section 301, crushed concrete can contain up to 12% of glass, 7% of foundry slag, 75% of steel mill slag, 8% of bottom ash, and 7% of pottery cull (by weight). However, all of the by-products should not have any deleterious materials (WisDOT 2018).

TABLE 21. SUITABILITY OF VARIOUS AGGREGATE BASE MATERIALS (WISDOT 2018)

BASE TYPE	CRUSHED STONE	CRUSHED GRAVEL	CRUSHED CONCRETE	RECLAIMED ASPHALT	REPROCESSED MATERIAL	BLENDED MATERIAL
Dense 3/4-inch	Yes	Yes	Yes	No	Yes[1]	Yes[1]
Dense 1 1/4-inch	Yes	Yes	Yes	Yes	Yes	Yes
Dense 3-inch	Yes	Yes	Yes	No	Yes[2]	Yes[2]
Open-graded	Yes	Yes	No	No	No	No

[1] The contractor may provide reprocessed material or blended material as 3/4-inch base only if the material contains 50 percent or less reclaimed asphalt, by weight.

[2] Ensure that material is substantially free of reclaimed asphalt.

TABLE 22. AGGREGATE BASE PHYSICAL PROPERTIES (WISDOT 2018)

PROPERTY	CRUSHED STONE	CRUSHED GRAVEL	CRUSHED CONCRETE	RECLAIMED ASPHALT	REPROCESSED MATERIAL	BLENDED MATERIAL
Gradation AASHTO T27						
dense	305.2.2.1	305.2.2.1	305.2.2.1	305.2.2.2	305.2.2.1	305.2.2.1[1]
open-graded	310.2	310.2	not allowed	not allowed	not allowed	not allowed
Wear AASHTO T96 loss by weight	≤50%	≤50%	note[2]	___	note[2]	note[3]
Sodium sulfate soundness AASHTO T104 loss by weight						
dense	≤18%	≤18%	___	___	___	note[3]
open-graded	≤12%	≤12%	not allowed	not allowed	not allowed	not allowed
Freeze/thaw soundness AASHTO T103 loss by weight						
dense	≤18%	≤18%	___	___	___	note[3]
open-graded	≤18%	≤18%	not allowed	not allowed	not allowed	not allowed
Liquid limit AASHTO T89	≤25	≤25	≤25	___	___	note[3]
Plasticity AASHTO T90	≤6[4]	≤6[4]	≤6[4]	___	___	note[3]
Fracture ASTM D5821[6] min one face by count						
dense	58%	58%	58%	___	note[5]	note[3]
open-graded	90%	90%	not allowed	not allowed	not allowed	not allowed

[1] The final aggregate blend must conform to the specified gradation.

[2] No requirement for material taken from within the project limits. Maximum of 50 percent loss, by weight, for material supplied from a source outside the project limits.

[3] Required as specified for the individual component materials defined in columns 2 - 6 of the table before blending.

[4] For base placed between old and new pavements, use crushed stone, crushed gravel, or crushed concrete with a plasticity index of 3 or less.

[5] ≥75 percent by count of non-asphalt coated particles.

[6] as modified in CMM 8-60.

TABLE 23. GRADATION REQUIREMENTS OF DENSE-GRADED AGGREGATE BASE MATERIALS EXCEPT FOR RECLAIMED ASPHALT (WISDOT 2018)

	PERCENT PASSING BY WEIGHT		
SIEVE	3-INCH	1 1/4-INCH	3/4-INCH
3-inch	90 - 100	___	___
1 1/2-inch	60 - 85	___	___
1 1/4-inch	___	95 - 100	___
1-inch	___	___	100
3/4-inch	40 - 65	70 - 93	95 - 100
3/8-inch	___	42 - 80	50 - 90
No. 4	15 - 40	25 - 63	35 - 70
No. 10	10 - 30	16 - 48	15 - 55
No. 40	5 - 20	8 - 28	10 - 35
No. 200	2.0 - 12.0	2.0 - 12.0[1][3]	5.0 - 15.0[2]

5.6. MICHIGAN DOT

Sections 302 and 902 of the MDOT Standard Specifications for Construction published in 2012 allows the crushed concrete along with natural aggregate and iron blast furnace slag as base materials if they meet the gradation (Table 24) and quality (Table 25) specifications for Class 21AA, 21A, 22A, and 23A dense-graded aggregates. Dense-graded aggregates can be mixed with fine-grained aggregates to meet the specifications. Crushed concrete should not contain more than 5% of brick, wood, plaster or asphalt by particle count but steel reinforcement pieces are allowed as long as they meet the specified gradation of stated dense-graded aggregate Classes.

Crushed concrete can be used as long as there is an additional granular layer of at least 12 inches (with class I, II, IIA, or IIAA aggregates – Table 26) between the dense-graded aggregate base and an underdrain, which the dense-graded aggregate base drains into. In addition, a geotextile liner or geomembrane can be used as an alternative to granular layer between the dense-graded aggregate base and the underdrain (MDOT 2012).

TABLE 24. GRADING REQUIREMENTS FOR DENSE-GRADED AGGREGATES (MDOT 2012)

Series/Class	Sieve Analysis (MTM 109) Total Percent Passing								Loss by Washing (MTM 108) % Passing
	1½ in	1 in	¾ in	½ in	⅜ in	No. 4	No. 8	No. 30	No. 200
21 AA	100	85-100	-	50-75	-	-	20-45	-	4-8
21 AA	100	85-100	-	50-75	-	-	20-45	-	4-8
22 A	-	100	90-100	-	65-85	-	30-50	-	4-8
23 A	-	100	-	-	60-85	-	25-60	-	9-16

TABLE 25. PHYSICAL REQUIREMENTS FOR DENSE-GRADED AGGREGATES (MDOT 2012)

Series/Class	Crushed Material, % min (MTM 117)	Loss, % max, Los Angeles Abrasion (MTM 102)
21 AA	95	50
21 AA	25	50
22 A	25	50
23 A	25	50

TABLE 26. GRADING REQUIREMENTS FOR GRANULAR MATERIALS (MDOT 2012)

Material	Sieve Analysis (MTM 109), Total % Passing (a)									Loss by Washing % Passing No. 200 (a), (b)
	6 in	3 in	2 in	1 in	½ in	⅜ in	No. 4	No. 30	No. 100	
Class I	—	—	100	—	45–85	—	20–85	5–30		0–5
Class II (c)	—	100	—	60–100	—	—	50–100	—	0–30	0–7
Class IIA (c)	—	100	—	60–100	—	—	50–100	—	0–35	0–10
Class IIAA	—	100	—	60–100	—	—	50–100	—	0–20	0–5
Class III	100	95–100	—	—	—	—	50–100	—	—	0–15
Class IIIA	—	—	—	—	—	100	50–100	—	0–30	0–15

a. Test results based on dry weights.
b. Use test method MTM 108 for Loss by Washing.
c. Except for use in granular blankets, Class IIA granular material may be substituted for Class II granular material for projects located in the following counties: Arenac, Bay, Genesee, Gladwin, Huron, Lapeer, Macomb, Midland, Monroe, Oakland, Saginaw, Sanilac, Shiawassee, St. Clair, Tuscola, and Wayne counties.

6. CONCLUSIONS/RECOMMENDATIONS

Extensive literature review was conducted on RAP and RCA used as base or subbase materials. In addition, data for the RAP and RCA mixtures with natural aggregates was collected. The relationships between summary resilient modulus (SM_r), California Bearing Ratio (CBR), hydraulic conductivity, permanent deformation and index characteristics of these materials were investigated. Based on the analyses of dataset, the following conclusions can be drawn:

- Gravel contents of RAPs range from 3% to 68% with the median of 45% while the gravel contents of RCA are between 32 % and 94 % with the median to be 51%. Thus, RCA tends to be slightly coarser than RAP.
- Sand contents of RAP are between 28% and 97% with the median to be 54%. The lower limit of sand content is 4.9% and the upper limit of sand content is 65% in RCA with the median value of 46%.
- Fines contents in most of the RAP and RCA contents are below 12%. Fines content of RAP ranged between 0% and 11% with the median of 1% while it ranged from 0.1% to 13% with the median of 2.8% for RCA.
- Specific gravities of RAPs fall between 2.19 to 2.87 with the median of 2.395 while these values are between 2.12 and 2.7 with the median of 2.39 for the RCAs.
- Maximum dry unit weight (MDU) of RAPs ranges from 17.2 kN/m^3 (110 pcf) to 24.1 kN/m^3 (155 pcf) with the median of 19.6 kN/m^3 (126 pcf). MDU of RCAs falls between 18.3 kN/m^3 (118 pcf) and 21.7 kN/m^3 (139 pcf) with the median value to be 19.7 kN/m^3 (127 pcf).
- Optimum moisture content (OMC) of RAP and RCAs ranges between 4-10.7% and 6.1-14.8%, respectively.
- Summary resilient modulus (SM_r) of RAPs ranges from 168 MPa (24366 psi) to 400 MPa (58015 psi) with the median value of 262 MPa (37927 psi). The SM_r of RCA is between 123 MPa (17897 psi) and 370 MPa (53664 psi) with the median value of 183 MPa (26542 psi).
- The permanent deformation of 100% RAPs ranges from 1.05% to 5.63%. The permanent deformation of 100% RCAs is between 0.1% and 0.83%. RCA shows the lowest permanent deformation among RCA, RAP and natural aggregates while RAP shows the highest permanent deformation.
- CBR of RAP is between 18 and 68 with the median of 28 while CBR of RCA ranges between 58 and 169 with the median to be 146.

- Angle of friction (φ) and the cohesion (c) of 100 % RAP specimen vary from 44° to 52º and 0 kPa to 131 kPa, respectively.
- The cohesion (c) of RCAs range from 24 kPa to 191 kPa and angle of friction (φ) of RCAs range from 19° to 52.7°.
- No trend was observed between CBR and gravel-to-sand ratio (G/S) or fines content in both RCA and RAP.
- Hydraulic conductivity of RAPs falls between 1.8×10^{-7} m/s (2.12×10^{-3} ft/hr) and 1.14×10^{-3} m/s (13.46 ft/hr) with the median value to be 6.89×10^{-5} m/s (8.14×10^{-1} ft/hr). Hydraulic conductivity of RCA ranges from 1.05×10^{-6} m/s (1.24×10^{-2} ft/hr) to 1.2×10^{-3} m/s (14.17 ft/hr) with the median value to be 1.7×10^{-5} m/s (2.00×10^{-1} ft/hr).
- It is observed that higher D_{10} values results in higher hydraulic conductivity and higher fines contents yield smaller hydraulic conductivity for RAP and RCA materials.
- SM_r of RAPs and RCAs increases with higher G/S ratio while fines contents have no effect on SM_r of RAPs and RCAs.
- There is an increasing trend in SM_r of RAPs with higher D_{30} and D_{60} values.
- RAPs with higher values of C_c and C_u will have higher SM_r.
- RCAs with higher C_u tends to have higher SM_r.
- As temperature increases SM_r of RAPs decreases except when thermal preloading is applied. On the other hand, SM_r of RCA is independent from both compaction and testing temperature conditions.
- SM_r of RAPs decrease as optimum moisture content (OMC) of RAPs increases.
- Higher permanent deformation of natural aggregates is observed with addition of RAP which needs to be considered when designing a pavement with RAP.
- As RCA content increases in RCA-natural aggregate blends, OMC increases as well while MDU of the blends decreases.

The main part of the project was to collect engineering and index properties data from RAP and RCA and the whole database is summarized in the Table 27.

TABLE 27. SUMMARY OF DATABASE

Characteristics	RAP			RCA		
	Lower Limit	**Median**	**Upper Limit**	**Lower Limit**	**Median**	**Upper Limit**
% Gravel	3 (52)	45 (52)	68.1 (52)	31.8 (34)	51 (34)	94.1 (34)
% Sand	28.1 (52)	54 (52)	97 (52)	4.9 (34)	46.3 (34)	64.9 (34)
% Fines	0 (52)	1 (52)	11 (52)	0.1 (34)	2.8 (34)	12.8 (34)
D_{10} (mm/in)	10^{-1}/ $3.9\text{x}10^{-3}$ (30)	$5\text{x}10^{-1}$/ $1.96\text{x}10^{-2}$ (30)	1/ $3.93\text{x}10^{-2}$ (30)	10^{-1}/ $3.9\text{x}10^{-3}$ (19)	$2.3\text{x}10^{-1}$/ $9\text{x}10^{-3}$ (19)	$4.3\text{x}10^{-1}$/ $1.7\text{x}10^{-2}$ (19)
D_{30} (mm/in)	$8\text{x}10^{-2}$/ $3.1\text{x}10^{-3}$ (27)	1.5/ $6\text{x}10^{-2}$ (27)	4.9/ $1.9\text{x}10^{-1}$ (27)	$2\text{x}10^{-1}$/ $7.9\text{x}10^{-3}$ (17)	1.2/ $4.72\text{x}10^{-2}$ (17)	6.5/ $2.56\text{x}10^{-1}$ (17)
D_{60} (mm/in)	$1.5\text{x}10^{-1}$/ $5.9\text{x}10^{-3}$ (27)	4.82/ $1.89\text{x}10^{-1}$ (27)	10.4/ $4.09\text{x}10^{-1}$ (27)	$6\text{x}10^{-1}$/ $2.36\text{x}10^{-2}$ (17)	6.8/ $2.67\text{x}10^{-1}$ (17)	16.3/ $6.42\text{x}10^{-1}$ (17)
C_u	5 (35)	10.65 (35)	40 (35)	2.1 (29)	32 (29)	66 (29)
C_c	0.21 (37)	1.2 (37)	8 (37)	0.14 (29)	1.4 (29)	6 (29)
G_s	2.19 (38)	2.395 (38)	2.87 (38)	2.12 (32)	2.39 (32)	2.7 (32)
MDU (kN/m^3/pcf)	17.2/ 110 (46)	19.61/ 126 (46)	24.12/ 155 (46)	18.3/ 118 (35)	19.7/ 127 (35)	21.7/ 140 (35)
OMC(%)	4 (46)	6.05 (46)	10.7 (46)	6.1 (35)	10.8 (35)	14.8 (35)
SM_r (MPa/psi)	168/ 24366.3 (32)	261.5/ 37927.368 (32)	400/ 58015.1 (32)	123.4/ 17897.657 (18)	183/ 26541.9 (18)	370/ 53664 (18)
CBR (%)	18 (12)	28 (12)	68 (12)	58 (4)	146 (4)	169 (4)
Hydraulic conductivity (m/s/ft/hr)	$1.8\text{x}10^{-7}$/ $2.12\text{x}10^{-3}$ (23)	$6.89\text{x}10^{-5}$/ $8.14\text{x}10^{-1}$ (23)	$1.14\text{x}10^{-3}$/ 1.35x10 (23)	$1.05\text{x}10^{-6}$/ $1.24\text{x}10^{-2}$ (12)	$1.7\text{x}10^{-5}$/ $2.01\text{x}10^{-1}$ (12)	$1.2\text{x}10^{-3}$/ 1.42x10 (12)

Notes: The main part of the project was to collect engineering and index properties data for RAP and RCA and the whole database is summarized in the table 27. Numbers provided in parantheses for each data represent the corresponding sample size.

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APPENDIX-A

APPENDIX A. GRADATION CHARACTERISTICS, CLASSIFICATION AND SPECIFIC GRAVITY OF RCA-RAP DATABASE

Ref	Loc	Type of Material	Gravel (%)	Sand (%)	Fine (%)	Classification - USCS	Classification - AASHTO	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c	G_s
Edil et al. (2012a)	MN	Aggregate Class 5	22.9	67.6	9.5	GW-GM	A-1-b	0.1	0.4	1.7	21	1.4	2.57
		Blend	32.7	63.8	3.4	SP	A-1-b	0.2	0.6	2.8	13	0.5	
		RAP	26.3	71.2	2.5	SP	A-1-a	0.3	0.7	2.3	7	0.7	2.41
		RCA	31.8	64.9	3.3	SW	A-1-a	0.1	0.4	1.7	21	1.4	2.39
	MI	RCA	68.5	28.3	3.2	GP	A-1-a	0.4	4.1	12.3	35	3.9	2.37
		RPM	49.3	50.4	0.4	SW	A-1-b	0.4	1.7	6.5	17	1.1	2.39
	CO	RCA	40.9	46.3	12.8	SC	A-1-b	0.1	0.6	4.9	66	1.1	2.28
		RAP	31.7	67.7	0.7	SP	A-1-a	0.4	0.9	3.3	9	0.7	2.23
	CA	RCA	50.6	47.1	2.3	GW	A-1-a	0.3	1.7	6.8	22	1.4	2.32
		RAP	36.8	61.4	1.8	SW	A-1-a	0.3	1.3	4.2	13	1.2	2.56
	TX	RCA	76.3	21.6	2.1	GW	A-1-a	0.4	6.5	16.3	38	6	2.27
		RAP	41	44.9	1	SW	A-1-a	0.7	2.5	7.9	11	1.1	2.34
	OH	RCA	43.2	49.5	7.3	SW-SM	A-1-a	0.2	1.2	5.3	34	1.7	2.24
		RAP	32.1	66.2	1.7	SW	A-1-a	0.5	1.6	3.8	7	1.3	2.43
	NJ	RCA	41.2	54.6	4.3	SP	A-1-b	0.2	0.5	5.1	28	0.3	2.31
		RAP	50.9	48.4	0.7	GW	A-1-a	1	2.8	5.9	6	1.3	2.37
		RMP	55.7	43.6	0.6	GW	A-1-b	0.5	2.1	8.7	18	1	2.35
	WI	RAP	30.9	68.5	0.5	SP	A-1-b	0.6	1.4	3.6	6	0.9	2.37
Edil et al. (2012b)	WI	RPM	46	43	11	GW-GM	A-1-a						
Edil et al. (2012c)	MN	RPM	40	52	8	SW-SM	A-1-a						
Tutumluer et al. (2015)	IL	blend	73	25	2	GW		1.2	4.9	20	16.6	1	
		RAP	49	50	1	SW		0.9	2.8	5.5	6.1	1.5	
Locander (2009)	CO	RAP	55	43.6	1.4	GW-GP							2.25
			64	35.1	0.9	GW-GP							2.36
			54	43.6	2.4	GW-GP							2.3
			59	40.1	0.9	GW-GP							2.33
			45	54.4	0.6	SW-SP							2.39

			56	43	1	GW-GP							2.39
			59	40.2	0.8	GW-GP							2.37
			59	40	1	GW-GP							2.34
			67	32.2	0.8	GW-GP							2.36
			67	31.8	1.2	GW-GP							2.26
			75	24.1	0.9	GW-GP							2.29
Mokwa and Peebles (2005)	MT	CBC#1 unmixed	52.46	41.58	5.96	GW-GP	A-1-a (6A)						2.67
		CBC#1 20%RAP	54.98	42.39	1.82	GW-GP	A-1-a(5A)						2.67
		CBC#1 50%RAP	49.28	49.01	1.71	SW-SP	A-1-a(5A)						2.59
		CBC#2 unmixed	55.8	41.59	2.61	GW-GP	A-1-a (6A)						2.7
		CBC#2 20%RAP	54.35	43.55	2.1	GW-GP	A-1-a (6A)						2.66
		CBC#2 50%RAP	53.74	42.37	1.7	GW-GP	A-1-a(5A)						2.59
		CBC#3 unmixed	55.5	39.35	5.15	GW-GP	A-1-a(5A)						2.68
		CBC#3 20%RAP	52.31	45.68	2.01	GW-GP	A-1-a(5A)						2.66
		CBC#3 50%RAP	58.48	40.09	1.43	GW-GP	A-1-a(5A)						2.59
		Pitrun unmixed	41.79	40.74	1.05	SP	Spec. Borrow	0.4	1.6	17	42.5	0.37	2.72
		Pitrun 20%RAP	57.66	38.23	1.62	GP	Spec. Borrow	0.4	2	15	37.5	0.66	2.63
		Pitrun 50%RAP	53.08	38.04	1	GW	Spec. Borrow	0.53	2.5	12	22.6	0.98	2.61
Saeed (2008)	FL	FL RAP unprocessed				GW/SW	A-1-a	0.28-0.32	1.3-2	5.1-6	17.1	1.2-2.2	
		FL RAP Hammermill				SW	A-1-a	0.35	1.9	3.75-5	10-14.3	1.5-2.1	
		FL RAP Tubgrinder				SP	A-1-a	0.35	0.9	5	14-14.3	0.5	
Ullah and Tanyu (2019)	VA	Virgin aggregate	45	43	12	SM-SC			0.7	7			2.95
		RAP1 (Plagioclase and Pyroxene)	46	53	1	SW		0.5	2	5.1	10.2	1.5	2.85
		20%RAP1	45	45.6	9.4	SW-SP							
		30%RAP1	44	47.8	8.2	SW-SP							

		40%RAP1	45	47.8	7.2	SW-SP							
		50%RAP1	46	47.8	6.2	SW-SP							
		60%RAP1	46	48.8	5.2	SW-SP							
		RAP2 (Plagioclase and Pyroxene)	39	60	1	SW		0.5	1.5	4.5	9	1	2.82
		RAP5 (Plagioclase and Pyroxene)	26	73	1	SW		0.32	1.1	3	9.3	1.26	2.87
		RAP11 (Muscovite, Quartz, Biotite and Amphibo)	42	57	1	SW		0.5	1.7	5	10	1.1	2.6
Bennert et al. (2000)	NJ	DGABC	60	33	7	GW		0.18	2.1	9	50	2.7	
		RAP	60	59	1	GW		1	3.1	8	8	1.2	
		RCA	60	56	4	GW		0.18	1.5	11	61	1.1	
Kim et al. (2005)	MN	100% aggregate CR 3	17	74.5	8.5	SW-SP		0.14	0.42	2.6	18.5		
		25% RAP from CR 3	27	67	6	SW-SP		0.19	0.85	3.5	18.4		
		50% RAP from CR 3	35	61.5	3.5	SW		0.36	2.3	4.3	11.9		
		75% RAP from CR 3	40	58	2	SW		0.7	2.7	4.9	7		
Huang and Dong (2014)	TN	RAP	41	58	1	SW-SP							
Mijic et al. (2019)	MD	RAP 1	46.3	51.8	1.83	SW	A-1-a				14	1.79	2.25
		RAP2	37.8	61.3	0.93	SW	A-1-a				10.6	1.26	2.36

		RAP3	45.7	54.1	0.13	SP	A-1-a				5.6	1.03	2.25
		RAP4	40.7	59	0.33	SW	A-1-a				8.28	1.58	2.44
		RAP5	44	54.8	1.19	SW	A-1-a				11.7	1.36	2.29
		RAP6	45.3	54.2	0.47	SW	A-1-a				11.2	1.32	2.48
		RAP7	47.6	52	0.39	SW	A-1-a				6.87	1.26	2.4
Ullah et al. (2018)	VA	RAP 1 as is	45	53.5	1.5	SW	A-1-a				10.65	1.43	2.43
		RAP 2 as is	40	57.8	2.2	SW	A-1-a				9	1.36	2.6
		Virgin aggregate as is	46	42	12	SW-SM	A-1-a				93	1.1	2.85
		Virgin aggregate Eng.	48	45.7	6.5	SW-SM	A-1-a				31	2.6	2.81
Edil et al. (2017)	MN	Natural aggregate	22.9	67.6	9.5	GW-GM	A-1-b				21	1.4	2.57
		RCA	31.8	64.9	3.3	SW	A-1-a				21	1.4	2.39
		RCA blend	32.7	63.8	3.4	SP	A-1-b				13	0.5	
		RAP	26.3	71.2	2.5	SP	A-1-a				7	0.7	2.41

Hasan et al. (2018)	NM	Subgrade soil	4	91.5	4.5	SW	A-2-6	0.2	0.8	1.8	9	1.7	
		RAP	48	51.7	0.3	SP		0.5	0.98	9	18	0.2	
		30% RAP	44.8	50.7	4.50	SP		0.4	0.9	9	22.5	0.2	
Puppala et al. (2012)	TX	RAP	48	48	4	GP					5	0.98	
Soleimanbeigi and Edil (2015a)	WI	RAP	20	78	2	SW							2.39
Camargo et al. (2013)	WI	RPM	46	43	11	GW-GM							
Soleimanbeigi et al.(2015)	CA	RCA			2.3		A-1-a	0.31			22	1.4	2.32
	TX				2.1		A-1-a	0.43			38	6	2.27
	NJ				4.3		A-1-b	0.18			28	0.3	2.31
	MI				3.2		A-1-a	0.4			35	3.9	2.37
	CO	RAP			0.7		A-1-a	0.35			9	0.7	2.23

	TX				1		A-1-a	0.72			11	1.1	2.34
	NJ				0.7		A-1-a	1			6	1.3	2.37
	MN				2.5		A-1-a	0.3			7	0.7	2.41
Kang et al (2011)	MN	25%RCM	40	59	1	SP		0.6	1	5	8.3	0.3	
		50% RCM	41	58	1	SP		0.5	0.9	5	10	0.3	
		75% RCM	42	57	1	SP		0.42	0.9	5	11	0.3	
		100% RCM	48	51	1	SP		0.4	0.8	7	17.5	0.22	
Attia and Abdelrahman (2010a)	MN	RAP Trunk highway 10	51	48.6	0.4	GP	A-1-b	0.6	2	7	11.7	0.95	
		RAP TH 19-MM 101 field 50-50	22	76.6	1.4	SP	A-1-b	0.32	0.6	1.8	5.6	0.6	
		RAP TH 19-MM 104 field 50-50	24	73.9	2.1	SP	A-1-b	0.25	0.6	2	8	0.72	
		RAP TH 22 field 50-50	41	57.7	1.3	SP	A-1-b	0.42	1.3	5	11.9	0.8	
		50% RAP TH 10 +50% Class 5 lab	41.5	56.85	1.65	SP	A-1-b	0.32	0.95	5	15.6	0.56	

		75% RAP TH 10+25% Class 5 lab	46.25	52.72	1.03	SP	A-1-b	0.4	1.3	6.5	16.2	0.065	
Guthrie et al. (2007)	UT	RAP 1	45	46.5	8.5	SW-SM	A-1-a	0.127	0.889	5.08			2.47
		RAP 2	45	54	1	SW	A-1-a	0.508	1.651	4.826			2.47
		Base1	55	35.5	9.5	GWGM	A-1-a	0.08382	1.016	9.652			2.64
		Base2	44	46.5	9.5	SP-SM	A-1-a	0.08382	1.27	4.826			2.68
Bradshaw et al (2016)	RI	RAP1, 23%	3	97	0	SW-SP	A-1-a						
		RAP2, 14%	3	97	0	SW-SP	A-1-a						
		RAP3, 23%	9	91	0	SW-SP	A-1-a						
		RAP FDR no treat	7	93	0	SW-SP	A-1-a						
		RAP4, 26%	5	95	0	SW-SP	A-1-a						
		Rap 5, 19%	15	85	0	SW-SP	A-1-a						

		RAP 6 , 39%	8	92	0	SW-SP	A-1-a						
Bennert and Maher (2005)	NJ	RAP	49	50.9	0.1	SW		0.516	0.08	0.15	10.85	1.22	
		RCA	71	26.2	2.8	GW		0.29	0.2	0.6	52.95	4.71	
Bestgen et al. (2016)	Eastern USA	G1					A-1-a	0.1	1.8	10			
		G2					A-1-a(0)	0.05	0.3	5			
		G3					A-1-a(0)	0.08	1	10			
		G4					A-1-a(0)	0.1	0.3	6.8			
		RCA 1	45	45	10	SP	A-1-a(0)	0.11	0.6	6.5	59	0.5	
		RCA 2	40	55	5	SP	A-1-a(0)	0.11	0.28	5	45	0.14	
Tutumluer et al. (2012)	IL	RCA	55	37	8	GP		0.23	2.5	7.5	32	3.6	2.41
		75% RCA	55	36	9	GP		0.1	2.5	7.5	75	8.3	
		50% RCA	55	35	10	GP		0.075	2.5	7.5		11	
Natarajan et al. (2019)	MN	RCA				GW							2.7
		RCA Passing lane	55	43	2	GW		0.4	1.9	8			2.26
		RCA Center line	37	61	2	GW		0.35	0.8	4			2.13
		RCA Driving lane	52	46	2	GW		0.32	1.4	8			2.5
Mahedi and Cetin (2020)	TX	RCA1	93.4	5.8	0.8	GP	A-1-a				2.1	1.1	2.44
		RCA2	68.8	31.1	0.1	GP	A-1-a				32	3.6	2.41
	IA	RCA1	48.8	51.1	0.1	SP	A-1-a				7.9	0.6	2.33
		RCA 2	82	17.8	0.2	GW	A-1-a				7.6	1.8	2.36
	MN	RCA	94.1	4.9	1	GP	A-1-a				2.1	1.4	2.12
Chen et al. (2013)	CA	RCA				SP							2.6
	CO	RCA				SM							2.6
	MI	RCA				GP							2.7
	MN	RCA				SP							2.7
	TX	RCA				GP-GM							2.6

	WI Fresh	RCA				GP							2.7
	WI Stock Pile	RCA				SP							2.6
Diagne et al. (2015)	WI	RCA	51	47.2	1.8	GW		0.17	1.2	7	41.67	1.25	2.41
Cetin et al. (2020)	MN	Coarse RCA	61.7	34.9	3.4	GW	A-1-a				34.49	1.75	2.64
		Fine RCA	38.3	54.6	7.1	SW-SM	A-1-a				33.93	1.12	2.64
		RCA+ RAP	41	50.4	8.6	SP-SM	A-1-a				49.41	0.98	2.52
Wu et al. (2012)	WA	RAP	67	32	1	GP		0.45	4.9	10.4	23	5.13	
Alam et al. (2010)	MN	RAP 100%	4	96	0	SP-SW							
Cosentino et al. (2012)	FL	APAC Melbourne Crushed	24.2	75.2	0.6	SP	A-1-a	0.3	0.91	3.1	10.7	0.9	2.508
		APAC Melbourne Milled	41.9	57.6	0.5	SW	A-1-a	0.5	2	5	9.6	1.9	2.524
		Whitehurst Gainesville Milled	54	45.6	0.4	SP	A-1-a	0.4	1.5	4.8	11.2	0.8	2.576
		APAC Jacksonville Crushed	26.6	66.6	6.8	SP	A-1-b	0.1	0.3	3	26.2	0.4	2.604

		75% milled mel and LR	43	56	1			0.39	2	5			
		50% milled Melbourne and 50% LimeRock	45	53	2			0.3	1.8	6			
		25% milled Melbourne and 75% LimeRock	50	47	3			0.2	1.3	7.1			
Cosentino et al. (2003)	FL	100% RAP modified	40		0.9	SP	A-1-a	0.27	0.65	4.7	17	0.3	2.19
		80% RAP-20% fine sand			3.1		A-1-b	0.17	0.35	3.3	19	0.2	2.25
		60% RAP-40% fine sand			4			0.15	0.25	0.62	4.1	0.7	2.37
Kim and Labuz (2007)	MN	25% RAP from CR 3	28	66	6			0.2	0.85	3.5			
		50% RAP from CR 3	36	60	4			0.35	2.3	4.3			
		75% RAP from CR 3	40	58	2			0.7	2.7	4.9			
Bejarano (2001)	CA	RAP	54	45	1			0.46	2.1	7			

Garg and Thompson (1996)	IL	RAP	68.1	28.1	3.8								
Ba et al. 2013	CO, TX	TX RAP	54	45.01	0.99	SW		0.8	2.5	8			2.34
		CO RAP	31	68.31	0.69	SP		0.4	0.9	3.1			2.23

Notes: CBC= Crushed base aggregate; DGABC= Dense graded aggregate base course; CR= County Road; RPM= Recycled pavement material; RCM= Recycled concrete material; RAP TH= RAP Trunk Highway; RAP FDR= Full-depth reclamation. Pyroxene is a group of important rock-forming silicate minerals of variable composition including calcium-, magnesium-, and iron-rich varieties predominate, while Plagioclase contains calcium and sodium and is a mixture of albite (Ab), or sodium aluminosilicate ($NaAlSi_3O_8$), and anorthite (An), or calcium aluminosilicate ($CaAl_2Si_2O_8$).

APPENDIX-B

APPENDIX B. RESILIENT MODULUS

Reference	Location	Type of Material	Method	SM_r (MPa)
Edil et al. (2012a)	MN	Aggregate calss 5	Power function	152
			NCHRP Model	144
		Agg at 0 F-T cycle	Power function	191
		Agg at 5 F-T cycle		186
		Agg at 10 F-T cycle		177
		Agg at 20 F-T cycle		153
		Blend	Power function	182
			NCHRP Model	191
		RAP	Power function	180
			NCHRP Model	174
		RAP at 0 F-T cycle	Power function	238
		RAP at 5 F-T cycle		220
		RAP at 10 F-T cycle		200
		RAP at 20 F-T cycle		180
		RCA	Power function	189
			NCHRP Model	190
	MI	RCA	Power function	171
			NCHRP Model	171
		RCA at 0 F-T cycle	Power function	199
		RCA at 5 F-T cycle		191
		RCA at 10 F-T cycle		257
		RCA at 20 F-T cycle		268
		RPM	Power function	168
			NCHRP Model	161
	CO	RCA	Power function	175
			NCHRP Model	162
		RAP	Power function	184

			NCHRP Model	177
	CA	RCA	Power function	178
			NCHRP Model	166
		RCA at 0 F-T cycle	Power function	262
		RCA at 5 F-T cycle		227
		RCA at 10 F-T cycle		282
		RAP	Power function	173
			NCHRP Model	166
		RAP at 0 F-T cycle	Power function	256
		RAP at 5F-T cycle		249
		RAP at 10 F-T cycle	NCHRP Model	223
		RAP at 20 F-T cycle		203
	TX	RCA	Power function	164
			NCHRP Model	151
		RCA at 0 F-T cycle	Power Model	258
		RCA at 5 cycle		211
		RCA at 10 F-T cycle		236
		RCA at 20 F-T cycle		289
		RAP	Power function	198
			NCHRP Model	188
		RAP at 2% dry	Power function	341
		RAP at OMC		334
		RAP at 2% wet		317
		RAP at 0 F-T cycle	Power function	334
		RAP at 5		287
		RAP at 10		272
		RAP at 20		254
	OH	RCA	Power function	163
			NCHRP Model	158
		RCA at 2% dry	Power function	239

		RCA at OMC		222
		RCA at 2% wet		148
		RAP	Power function	197
			NCHRP Model	192
		RAP 2% dry	Power function	297
		RAP at OMC		287
		RAP at 2% wet		243
	NJ	RCA	Power function	208
			NCHRP Model	203
		RAP	Power function	209
			NCHRP Model	207
		RPM	Power function	264
			NCHRP Model	264
	WI	RAP	Power function	266
			NCHRP Model	274
Tutumluer et. al(2015)	IL	Blend	Geoguage composite surface modulus	90
				137
			LWD	74.7
				80.4
				66.3
				79.6
		RAP	Geoguage composite surface modulus	115
				169
			LWD	99.9
				97.6
				64
				97.9

Locander (2009)	CO	Rap	MR AASHTO T274-82	239.64
				211.8
				181.13
Ullah and Tanyu (2019)	VA	VA		141.1
		20%RAP1 Plagioclase and Pyroxene with high binder content		144.2
		30%RAP1		176.5
		40%RAP1		199.1
		50%RAP1		211.9
		60%RAP1		212.3
		20%RAP2 Plagioclase and Pyroxene with low binder		152.1
		30%RAP2		159.7
		40%RAP2		173.6
		50%RAP2		176.5
		60%RAP2		179.1
		20%RAP5 Plagioclase and Pyroxene with medium binder		153.9
		30%RAP5		172.1

		40%RAP5		188.8
		50%RAP5		197.6
		60%RAP5		200.7
Bennert et al. (2000)	NJ	DGABC	AASHTO bulk stress model	139.2
		25% RAP		187.06
		50% RAP		215.09
		75% RAP		222
		100%RAP		300.3
		25% RCA		155.06
		50% RCA		248.4
		75% RCA		255.03
		100%RCA		297.6

Kim et al. (2005)	MN	100% CR 3 at OMC		170
		100% CR 3 at 65% OMC		225
		25% RAP at OMC		175
		25% RAP at 65% OMC		235
		50% RAP at OMC		175
		50% RAP at 65% OMC		225
		75% RAP at OMC		215
		75% RAP at 65% OMC		260
Huang and Dong (2014)	TN	RAP	Universal model power law	286.5
		Limestone		185.122
		gravel		153.36

Edil et al.(2017)	MN	Natural aggregate at 15 cm depth 7 F-T cycle	FWD Modulus	127
		Natural aggregate at 30 cm depth 7 F-T cycle		125
		RCA at 15 cm depth 7 F-T cycle	FWD	160
		RCA at 30 cm depth 7 F-T cycle		160
		RCA blend at 15 cm depth 7 F-T cycle	FWD	160
		RCA blend at 30 cm depth 7 F-T cycle		150
		RAP at 15 cm depth 7 F-T cycle		208
		RAP at 30 cm depth 7 F-T cycle	FWD	200
Hasan et al.(2018)	NM	30% RAP with 6.3 MC		160
		30% RAP with 7.1 MC		170
		30% RAP with 5.7 MC		175
		30% RAP with 7.6 MC		155
		75% RAP at 7.1		290
Abdelrahman and Noureldin (2014)	MN	Class 5		137
		100% RAP		330

		75% RAP		262
		50% RAP		289
Wu et al.(2012)	WA	0% RAP	high cyclic stress (cyclic stress/sigma 3 = 7)	177
		20% RAP		195
		40% RAP		197

		60% RAP		205
		80% RAP		550
Puppala et al. (2012)	TX	RAP		251
Soleimanbeigi and Edil (2015b)	WI	RAP at 5 C without thermal preloading		410
		RAP at 22 without thermal preloading		390
		RAP at 35 without thermal preloading		285
		RAP at 50 without thermal preloading		280
		RAP at 5C with thermal preloading		305
		RAP at 35 with thermal preloading		410
		RAP at 50 with thermal preloading		490

Camargo et al. (2013)	WI	RPM	Moosazedh and Witczak	309
Edil et al. (2012c)	MN	RPM	NCHRP 1-28A	257
Edil et al.(2012b)	WI	RPM	Moosazedh and Witczak	310
Soleimanbeigi et al.(2015)	NJ	RCA	RCA at 7 °C	167
			RCA at 23 °C	160
			RCA at 35 °C	157
			RCA at 50 °C	190
	TX	RCA	RCA at 7 °C	210
			RCA at 23 °C	188
			RCA at 35 °C	180
			RCA at 50 °C	190
	CO	RCA	RCA at 7 °C	199
			RCA at 23 °C	229
			RCA at 35 °C	219
			RCA at 50 °C	190
	CO	RAP	RAP at 7 °C	225
			RAP at 23 °C	255
			RAP at 35 °C	170
			RAP at 50 °C	200
	TX	RAP	RAP at 7 °C	355
			RAP at 23 °C	345
			RAP at 35 °C	220
			RAP at 50 °C	190
	NJ	RAP	RAP at 7 °C	240
			RAP at 23 °C	280
			RAP at 35 °C	260
			RAP at 50 °C	270
Kang et al. (2011)	MN	25%RAP		90.16302929

		50% RAP		137.1396913
		75%RAP		162.563205
		100%RAP		192.7881852
		25%RCM		224.178598
		50%RCM		313.8744445
		75%RCM		260.759109
		100%RCM		119.5822602
Attia and Abdelrahman (2010a)	MN	RAP Trunk highway 10	OMC	380
			OMC + 1%	239
			OMC – 1%	482
			OMC – 3%	750
		RAP TH 19-MM 104 field 50-50	OMC	227
			OMC + 2%	182
			OMC – 2%	460
		50% RAP TH 10 +50% Class 5 lab	OMC	275.8

			OMC + 1%	224
			OMC – 1%	441.2
			OMC – 3%	572
Bradshaw et al. (2016)	RI	RAP1, 23%		220
		RAP2, 14%		200
		RAP3, 23%		210
		RAP 3R, 25%		260
		RAP4, 26%		186
		Rap 5, 19%		240
		RAP 6 , 39%		230
Attia and Abdelrahman (2010b)	MN	50% RAP sample 1 Ref case, 50% class 5	Witczak model	247.79

			MEPDG model	247
		50% RAP sample 2, 50% class 5	Witczak model	302.67
			MEPDG model	310.26
		75% RAP sample 1 Ref case, 25% class 5	Witczak model	217.87
			MEPDG model	227.5
		75% RAP sample 2, 25% Class 5	Witczak model	259.93
			MEPDG model	265
		100% RAP sample 1r ef case	Witczak model	334.39
			MEPDG model	340
		100% RAP sample 2	Witczak model	414.37
			MEPDG model	420
Alam et al. (2010)	MN	Class 6		135.58
		RAP 30%		154.88
		RAP 50%		192.14
		RAP 70%		221.9
		RAP 100%		271.3
Attia and Abdelrahman (2011)	MN	RAP TH 10 (100%)		400
		50% RAP TH10 50% class 5		265
		75% RAP TH10 25% Class 5		210

		RAP cell 18 100% RAP		
		RAP TH 19 - MM 104 50% RAP 50% field agg		240
		RAP TH 22 50% RAP 50% field agg		
		RAP TH 19 - MM 101 50% RAP 50% field agg		
Bennert and Maher (2005)	NJ	100% RAP		268
		75% RAP		213.8
		50% RAP		233.7
		25% RAP		201.5
		100% RCA		272.9
		75% RCA		239.5

		50% RCA		224.4
		25% RCA		155.1
Bestgen et al. (2016)	Eastern USA	G1	power model	210
		G2		114
		G3		91
		G4		123
		RCA 1		295
		RCA 2		220
		25R175G1		160
		50R150G1		130
		75R125G1		280
		25R175G2		140
		50R150G2		150
		75R125G2		260
		25R275G1		70
		50R250G1		120
		75R225G1		150
		25R275G2		340
		50R250G2		280
		75R225G2		120
		25R175G3		87
		50R150G3		98
		75R125G3		93
		25R175G4		114
		50R150G4		108
		75R125G4		121
Tutumluer et al. (2012)	IL	RCA	power	188
		75% RCA		145

		50% RCA		157
Diagne et al. (2015)	WI	RCA 0 F-T cycle		370
		RCA 5 F-T cycle		297
		RCA 10 F-T cycle		288
Cetin et al. (2020)	MN	Coarse RCA	MEPDG model	127.3770752
				122.6131468
		Fine RCA		123.3858925
				121.5127776
		RCA+RAP		114.8798754
				112.4405639
Cosentino et al. (2003)	FL	100% RAP modified	mixed with processed organic soil	291.39
				261.56
		80%- fine sand		
		60%		176.45
Kim and Labuz (2007)	MN	25% RAP from CR 3	100% OMC=8.7%	175
		50% RAP from CR 3	100% OMC= 8%	190
		75% RAP from CR 3	OMC= 7.2%	230
Bejarano (2001)	CA	RAP	95% maximum wet density	310
			100% maximum wet density	450
Garg and Thompson (1996)	IL	RAP		218.58