

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

Principal Investigator:

Bora Cetin, Ph.D.

Co-Principal Investigator:

Tuncer Edil, Ph.D.

Research Team:

Ida Gheibi

Mustafa Hatipoglu

Department of Civil and Environmental Engineering

Michigan State University

May 20, 2020

Pavement ME

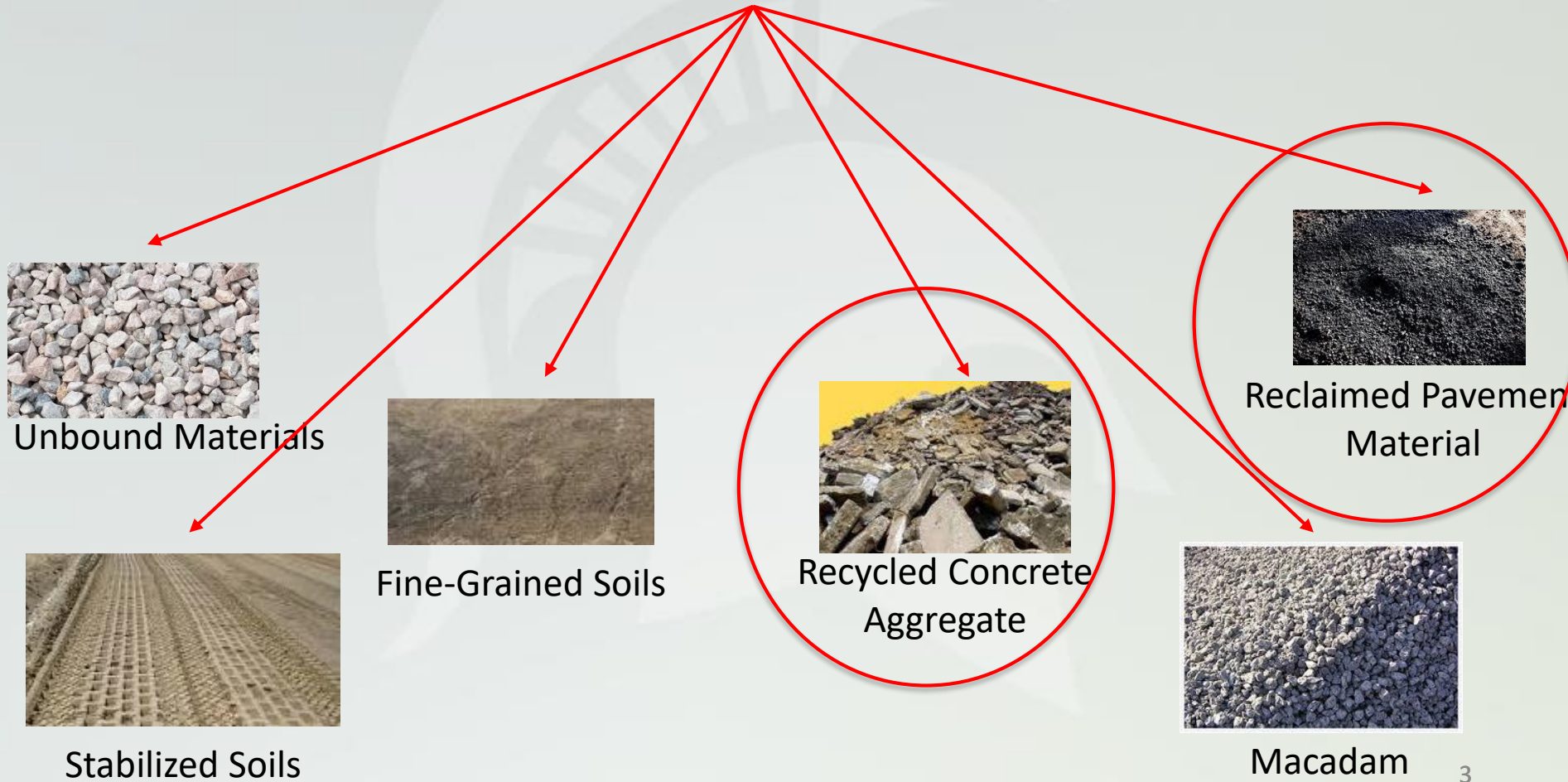
- Requires several inputs
 - Hourly climate data, materials, location, pavement structure, traffic
- Calculates pavement performance parameters
 - Asphalt – IRI, Rutting, and Longitudinal, Thermal, and Alligator Cracking
 - Concrete – IRI, Transverse Cracking, Joint Faulting



Figures from:
<http://www.aashtoware.org/Pages/default.aspx>
<http://www.pavementinteractive.org/article/Rutting/>
<http://brc-amps.wikidot.com/brc-road-condition-assessment-manual>
<http://blackdiamondpaving.com/terms-you-should-know/>

MATERIALS INPUT

Range of Materials



MATERIALS INPUT FOR PAVEMENT ME

Strength/Stiffness Parameters:

- Resilient Modulus (M_R)
- California Bearing Ratio (CBR)
- Unconfined Compressive Strength (UCS)

Index Parameters:

- Gradation Characteristics
- Absorption Content
- Binder Content
- Density
- Angularity
- Void Ratio

Overview of Research Plan

- **Task 1** – Initial Memorandum on Expected Research Benefits and Potential Implementation Steps
- **Task 2** – Data Collection
- **Task 3** – Sensitivity Analyses
- **Task 4** – Final Report

TASK 2 – DATA COLLECTION

List of data that will be collected:

- Index Properties
 - Gradation characteristics
 - Atterberg limits
 - Absorption
 - Binder content
 - Density
 - Void ratio
- Strength/Stiffness Properties
 - CBR
 - UCS
 - M_R
- Construction Specifications



#	Locations	Type of material	Grain Size Distribution	Atterberg Limits	Compaction	Hydraulic Conductivity	Shear Strength	Resilient Modulus	R Value	CBR
1	OH	RAP	1		1	1		5		
		RCA	1		1	1		5		
2	CA	RAP	1		1	1		6		
		RCA	2		2	1		5		
3	IL	RAP	2		2		6	12		
		RCA	3		3			3		3
4	CO	RAP	13	11	13	12		53	11	
		RCA	1		1	1		4		
5	MT	RAP	12		12	12	48		96	
6	MI	RAP	1		1	1		2		
		RCA	2		2	1		6		
7	VA	RAP	8	9	4			21 + PD=11		16
8	FL	RAP	3		12		3	PD=3		12
9	NJ	RAP	1			8	4	28		8
		RCA	1			8	1	48		8
10	MN	RAP	16	6	26	7	4	64 + PD= 6		1
		RCA	6		2	4	4	4		
11	TN	RAP	1		3			9		
12	MD	RAP	7		7	7				
13	NM	RAP	3		1			16		
14	WA	RAP			5	5		20		
15	TX	RAP	2		2	1		14 +8		
		RCA	1		1	1		8 +8		
16	WI	RAP	4	1	5	1		11		1
		RCA	1		1	1		2		
17	UT	RAP	4	4	4					
18	RI	RAP	7		7			7		
19	Eastern USA	RCA	2		2			24		13
Total			109	31	122	76	70	448	107	59

No	Ref.	Location	Type of material	Gravel (%)	Sand (%)	Fine (%)	Classification - USCS	Classification - ASHTO	D ₁₀ (mm)	D ₃₀ (mm)	D ₆₀ (mm)	C _u	C _c	G _s			
1	Edil et al. (2012)	MN	Aggregate class5	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					
2	Tutumluer et al. (2015)	IL	blend	73	25	2			1.2	4.9	20						
			RAP	49	50	1			0.9	2.8	5.5						
3	Locander et al. (2009)	CO	RAP	55	43.6	1.4									2.25		
				64	35.1	0.9										2.36	
				54	43.6	2.4										2.3	
				59	40.1	0.9											2.33
				45	54.4	0.6											2.39
				56	43	1											2.39
				59	40.2	0.8											2.37
				59	40	1											2.34
				67	32.2	0.8											2.36
				67	31.8	1.2											2.26
		75	24.1	0.9										2.29			
4	Mokwa et al. (2005)	MT	CBC#1 unmixed	52.46	41.58	5.96		A-1-a (6A)							2.67		
			CBC#1 20%RAP	54.98	42.39	1.82		A-1-a(5A)							2.67		
			CBC#1 50%RAP	49.28	46.31	1.71		A-1-a(5A)							2.59		
			CBC#2 unmixed	55.8	41.59	2.61		A-1-a (6A)								2.7	
			CBC#2 20%RAP	54.35	43.55	2.1		A-1-a (6A)								2.66	
			CBC#2 50%RAP	53.74	42.37	1.7		A-1-a(5A)								2.59	
			CBC#3 unmixed	55.5	39.35	5.15		A-1-a(5A)								2.68	
			CBC#3 20%RAP	52.31	45.68	2.01		A-1-a(5A)								2.66	
			CBC#3 50%RAP	58.48	40.09	1.43		A-1-a(5A)								2.59	
			Pitrun unmixed	41.79	40.74	1.05		Spec. Borrow		0.4	1.6	17				2.72	
			Pitrun 20%RAP	57.66	38.23	1.62		Spec. Borrow		0.4	2	15				2.63	
Pitrun 50%RAP	53.08	38.04	1		Spec. Borrow		0.53	2.5	12				2.61				
5	NCHRP Report 598	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				
6	Ullah and Tanyu (2019)	VA	VA	45	43	12					0.7	7			2.95		
			RAP1	46	53	1			0.5	2	5.1				2.85		
			20%RAP1	45		9.4											
			30%RAP1	44		8.2											
			40%RAP1	45		7.2											
			50%RAP1	46		6.2											
			60%RAP1	46		5.2											
			RAP2	39	60	1			0.5	1.5	4.5					2.82	
			RAP5	26	73	1			0.32	1.1	3					2.87	
RAP11	42	57	1			0.5	1.7	5					2.60				

No	Ref	Location	Sample	Max dry density (kN/m ³)	Optimum moisture content (%)	Void ratio		Relative compaction (%)
						e _{max}	e _{min}	
1	Edil et al. (2012)	MN	Aggregate class 5	20.1	8.9			
			Blend	21.3	8			
			RAP	20.8	6.7			
			RCA	19.5	11.2			
		MI	RCA	20.8	8.7			
			RPM	21.5	5.2			
		CO	RCA	18.9	11.9			
			RAP	20.7	5.7			
		CA	RCA	19.9	10.4			
			RAP	20.7	6.1			
		TX	RCA	19.7	9.2			
			RAP	20.3	8			
		OH	RCA	19.4	11.8			
			RAP	19.8	8.8			
NJ	RCA	19.8	9.5					
	RAP	20.4	6.5					
		RPM	20.6	6.3				
		WI	RAP	20	7.3			
2	Tutumluer et al. (2015)	IL	RAP	18.9	6.2			
3	Locander et al. (2009)	CO	RAP	19.35	8.5			
				19.35	7.2			
				19.35	6.5			
				19	10.7			
				19	10.1			
				18.9	5.7			
				18.8	6.4			
				18.8	8.8			
				18.4	7.7			
				17.8	7.5			
			17.3	4.4				
4	Mokwa et al. (2005)	MT	CBC#1 unmixed	22.3	4.85	0.65	0.36	97.1
			CBC#1 20%RAP	22.3	5	0.64	0.32	92.6
			CBC#1 50%RAP	21.1	6.2	0.86	0.34	96.5
			CBC#2 unmixed	22.4	5.59	0.59	0.28	93
			CBC#2 20%RAP	22.3	5.91	0.63	0.33	95.3
			CBC#2 50%RAP	21.8	5.2	0.66	0.3	92.4
			CBC#3 unmixed	22.4	5.9	0.74	0.33	96.4
			CBC#3 20%RAP	22	5.75	0.7	0.32	92.8
			CBC#3 50%RAP	21.4	6.1	0.66	0.34	92.6
			Pitrun unmixed	22.7	4.95	0.81	0.41	92.1
			Pitrun 20%RAP	22.6	5.04	0.68	0.34	93.1
Pitrun 50%RAP	22.1	5.2	0.79	0.33	92.1			

No	Ref	Location	Sample No.	K_s (m/s)
1	Edil et al. (2012)	MN	Aggregate class 5	4.62x10 ⁻⁷
			Blend	
		MI	RAP	1.10x10 ⁻⁶
			RCA	1.78x10 ⁻⁵
		CO	RCA	2.62x10 ⁻⁵
			RPM	2.31x10 ⁻⁴
		CA	RCA	1.57x10 ⁻⁵
			RAP	3.82x10 ⁻⁵
		TX	RCA	1.93x10 ⁻⁵
			RAP	
		OH	RCA	7.56x10 ⁻⁶
			RAP	3.18x10 ⁻⁵
		NJ	RCA	
			RAP	2.38x10 ⁻⁶
WI	RAP	3.69x10 ⁻⁴		
	RPM	1.03x10 ⁻⁴		
2	Mokwa et al. (2005)	MT	RAP	5.19x10 ⁻⁵
			CBC#1 unmixed	3x10 ⁻⁵
			CBC#1 20%RAP	8.5x10 ⁻⁵
			CBC#1 50%RAP	1.8x10 ⁻⁴
			CBC#2 unmixed	4.4x10 ⁻⁵
			CBC#2 20%RAP	9.8x10 ⁻⁵
			CBC#2 50%RAP	5.5x10 ⁻⁴
			CBC#3 unmixed	2.8x10 ⁻⁵
			CBC#3 20%RAP	1.1x10 ⁻⁴
			CBC#3 50%RAP	1.4x10 ⁻³
			Pitrun unmixed	2.1x10 ⁻⁵
			Pitrun 20%RAP	5x10 ⁻⁶
			Pitrun 50%RAP	9x10 ⁻⁵
			3	Wu et al. (2012)
20% RAP	0.00087			
40% RAP	0.0079			
60% RAP	0.0039			
80% RAP	0.0001			
4	Bennert and Maher (2005)	NJ	100% RAP	0.00004865
				0.00005915
			75% RAP	0.00000735
				0.00000595
			50% RAP	0.0001365
				0.00039795
			25% RAP	0.0000973
				0.0004249
			100% RCA	0.00000105
			75% RCA	0.00022925
				0.00022925
			50% RCA	0.00022925
	0.000231			
25% RCA	0.0002786			
	0.00026775			

Characteristics	RAP		RCA	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit
SM _r (MPa)	168	390	119.6	297.6
CBR (%)	12.5	106.25	144	205
D ₁₀ (mm)	0.3	1	0.1	0.43
D ₃₀ (mm)	0.08	3.1	0.2	6.5
D ₆₀ (mm)	0.15	8.7	0.6	16.3
% Fines	0.1	11	1	12.8
% Sand	35.1	78	21.6	64.9
% Gravel	20	75	31.8	76.3
Hydraulic Conductivity (m/s)	$1.1 \cdot 10^{-6}$	$1.14 \cdot 10^{-3}$	$1.05 \cdot 10^{-6}$	$2.62 \cdot 10^{-5}$
Maximum dry unit weight (kN/m ³)	16.96	21.5	18.9	20.8
Optimum Moisture Content (%)	4	10.7	7.5	11.9

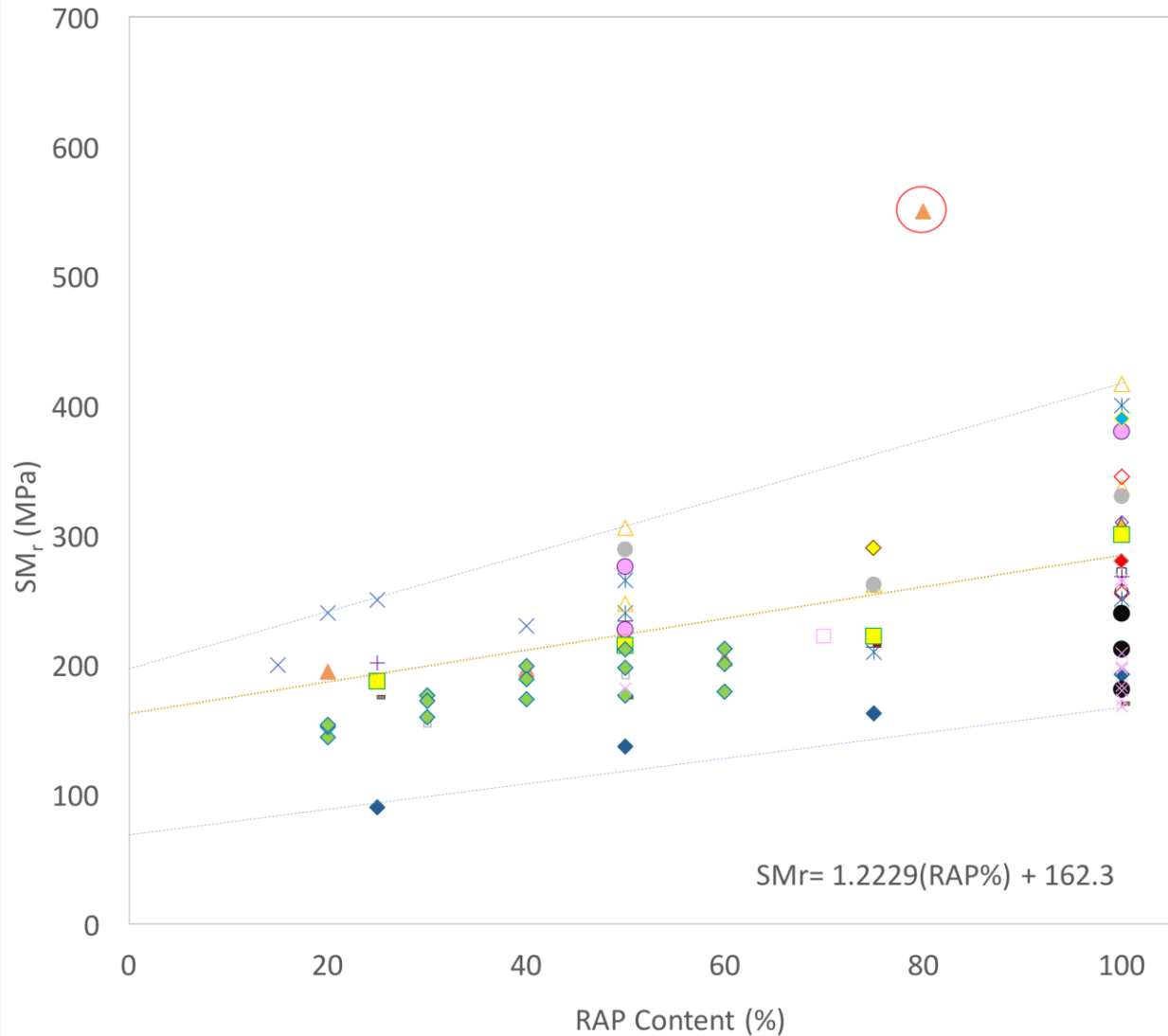
RAP

Characteristics		SM _r (MPa)		CBR (%)		Hydraulic conductivity (m/s)	
		Min – Max	Mean	Min – Max	Mean	Min – Max	Mean
D ₁₀	0.3-1	168-380	274	18-47	32.5	1.1*10 ⁻⁶ – 3.69*10 ⁻⁴	1.8505*10 ⁻⁴
% Gravel	20-50	168-390	279			1.1*10 ⁻⁶ – 1.14*10 ⁻³	5.705*10 ⁻⁴
	50-64	181-380	280.5			3.69*10 ⁻⁴ – 7.7 * 10 ⁻⁴	5.695*10 ⁻⁴
% Sand	35.1-50	181-380	280			3.18*10 ⁻⁵ – 7.7*10 ⁻⁴	4.009*10 ⁻⁴
	50-78	168-390	279			1.1*10 ⁻⁶ – 1.14*10 ⁻³	5.705*10 ⁻⁴
% Fine	0.1-5	168-390	279			1.1*10 ⁻⁶ – 7.7 * 10 ⁻⁴	3.855*10 ⁻⁴
	5-12	257-309	283				
C _u	5-9	180-300	240			1.1*10 ⁻⁶ – 1.14*10 ⁻³	5.705*10 ⁻⁴
	9-18	168-380	274			3.18*10 ⁻⁵ – 5.66 * 10 ⁻⁴	2.989*10 ⁻⁴
Gravel/Sand	0.25-1	168-390	279			1.1*10 ⁻⁶ – 1.14*10 ⁻³	5.705*10 ⁻⁴
	1-1.82	181-380	280.5			3.69*10 ⁻⁴ – 7.7 * 10 ⁻⁴	5.695*10 ⁻⁴

RCA

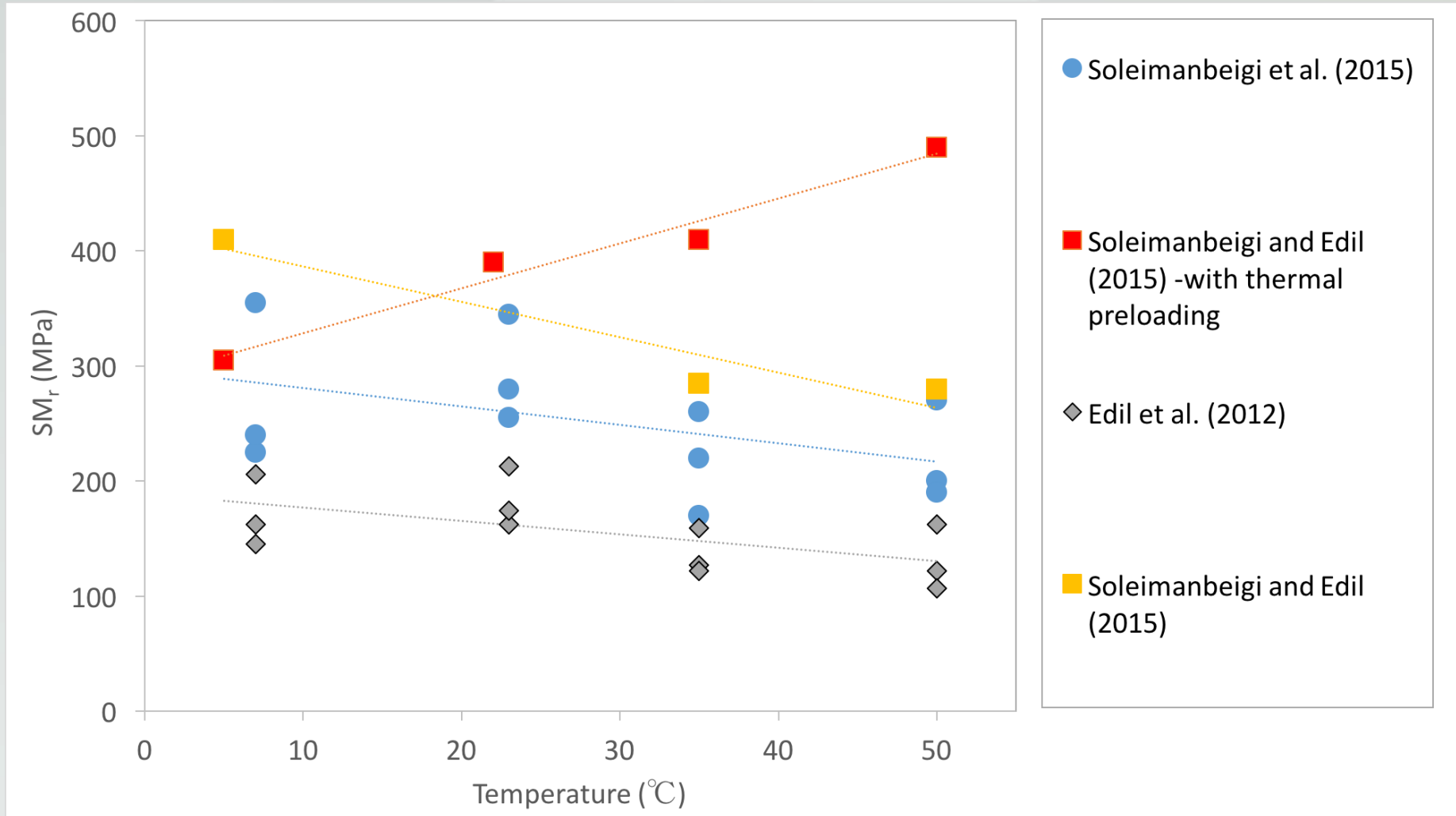
Characteristics		SM _r (MPa)		CBR (%)		Hydraulic conductivity (m/s)	
		Min – Max	Mean	Min – Max	Mean	Min – Max	Mean
D ₁₀	0.1-0.43	119-297	208	58-169	113.5	1.05*10 ⁻⁶ – 2.62*10 ⁻⁵	1.36*10 ⁻⁵
% Gravel	31.8-50	119-295	207			2.38*10 ⁻⁶ – 1.78*10 ⁻⁵	1.009*10 ⁻⁵
	50-76.3	164-188	176			7.56*10 ⁻⁶ – 2.62* 10 ⁻⁵	1.68*10 ⁻⁵
% Sand	21.6-50	163-295	229			7.56 *10 ⁻⁶ – 2.62 *10 ⁻³	1.68*10 ⁻⁵
	50-64.9	119-220	169.5			2.38*10 ⁻⁶ – 1.78 * 10 ⁻⁵	1.009*10 ⁻⁵
% Fine	1-5	119-297	208			1.05 *10 ⁻⁶ - 2.62* 10 ⁻⁵	1.36*10 ⁻⁵
	5-12.8	163-295	229			1.57* 10 ⁻⁵	1.57* 10 ⁻⁵
C _u	7.5-35	119-208	163.5			2.38*10 ⁻⁶ – 1.93*10 ⁻⁵	1.084*10 ⁻⁵
	35-66	164-297	230.5			1.05*10 ⁻⁶ – 2.62*10 ⁻⁵	1.36*10 ⁻⁵
Gravel/Sand	0.48-1	119-220	169.5			2.38*10 ⁻⁶ – 1.78 * 10 ⁻⁵	1.009*10 ⁻⁵
	1-3.53	164-295	229.5			7.56 *10 ⁻⁶ – 2.62* 10 ⁻⁵	1.68*10 ⁻⁵

SM_r – RAP Content

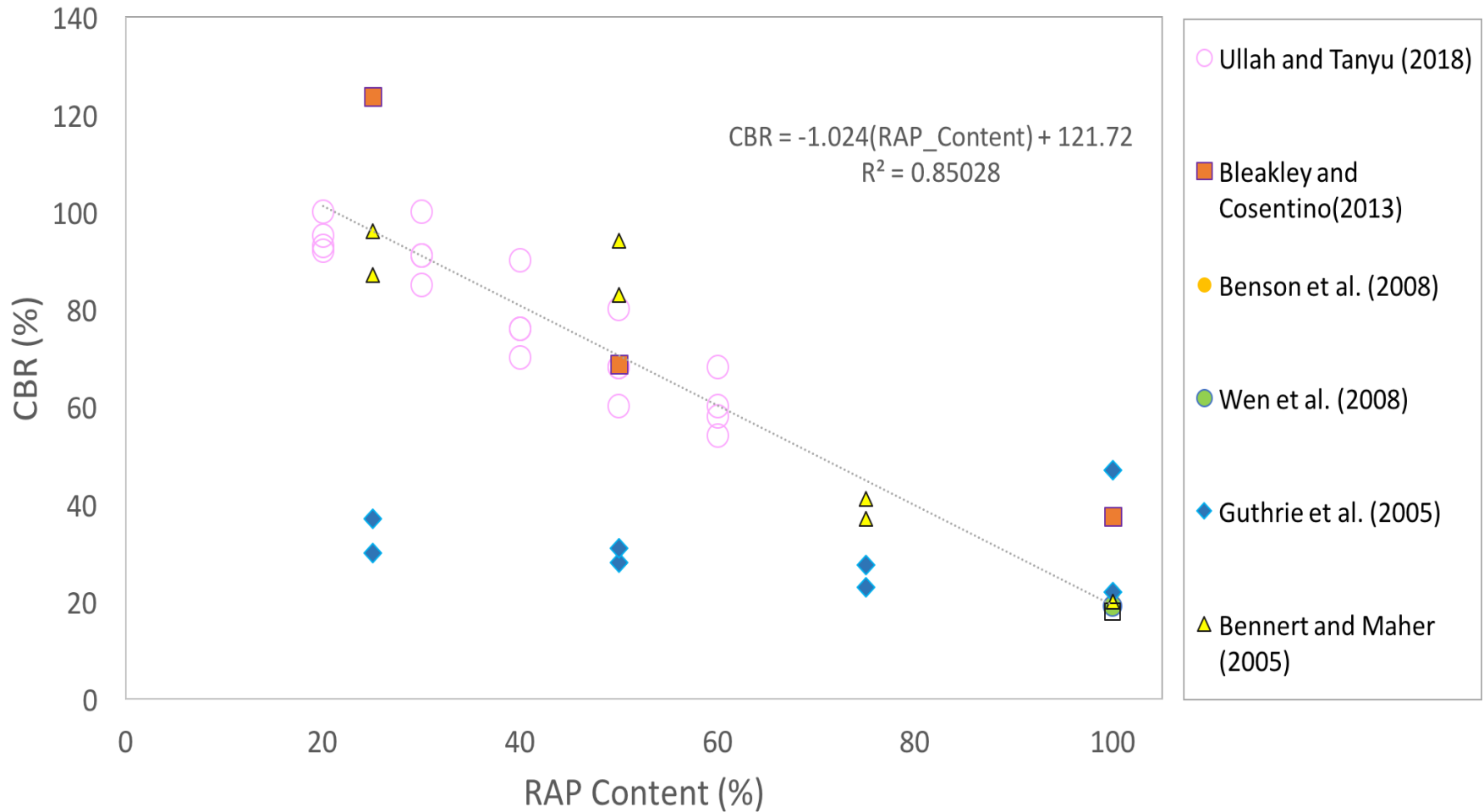


- + Bennert and Maher (2005)
- × Attia and abdelrahman (2011)
- Alam et al. (2010)
- △ Attia and Abdelrahman (2010)
- × Bradshaw et al. (2016)
- Attia and Abdelrahman et al. (2010)
- ◆ Kang et al. (2011)
- ◇ Soleimanbeigi et al. (2015)
- ◇ Ebrahimi et al. (2012)
- Wen et al. (2008)
- ▲ Benson et al. (2008)
- ◆ Soleimanbeigi and Edil (2015)
- × Puppala et al. (2012)
- ▲ Wu et al. (2012)
- Noureldin and Abdelrahman (2014)
- ◇ Hasan et al. (2018)
- Kim et al. (2005)
- Bennert et al. (2000)
- ◆ Ullah and Tanyu (2018)
- Locander et al. (2009)
- × Edil et al. (2012)

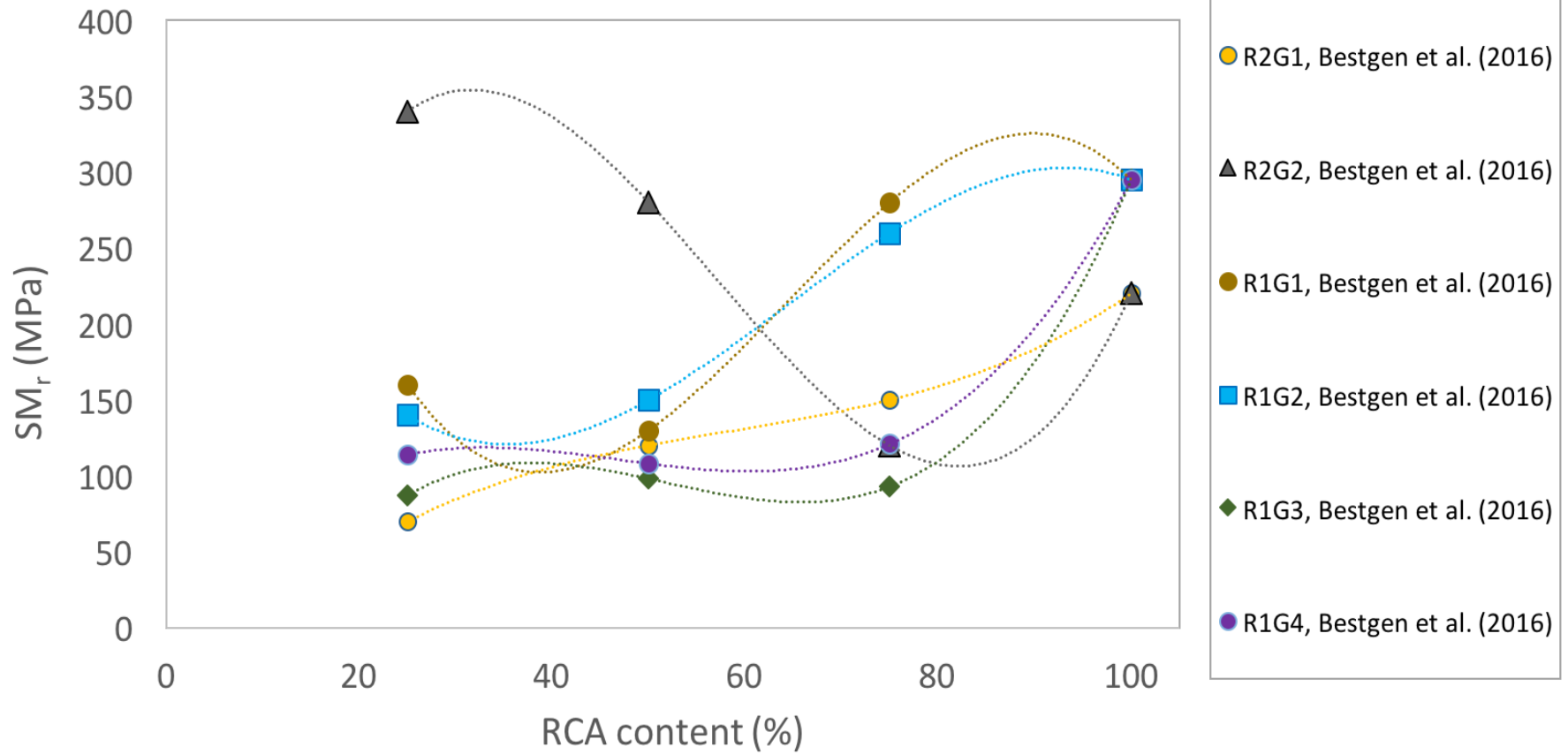
SM_r – Temperature (RAP)



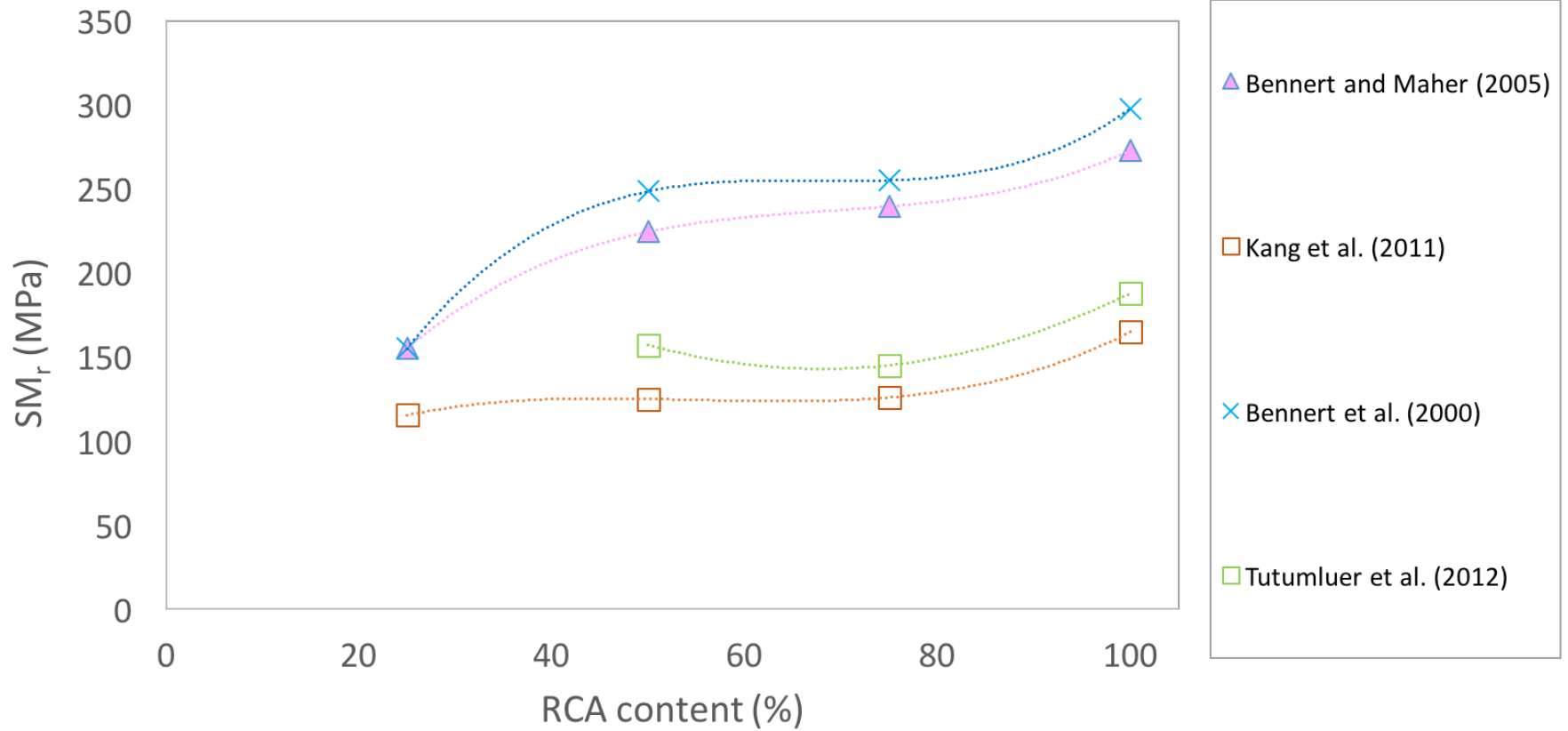
CBR – RAP Content



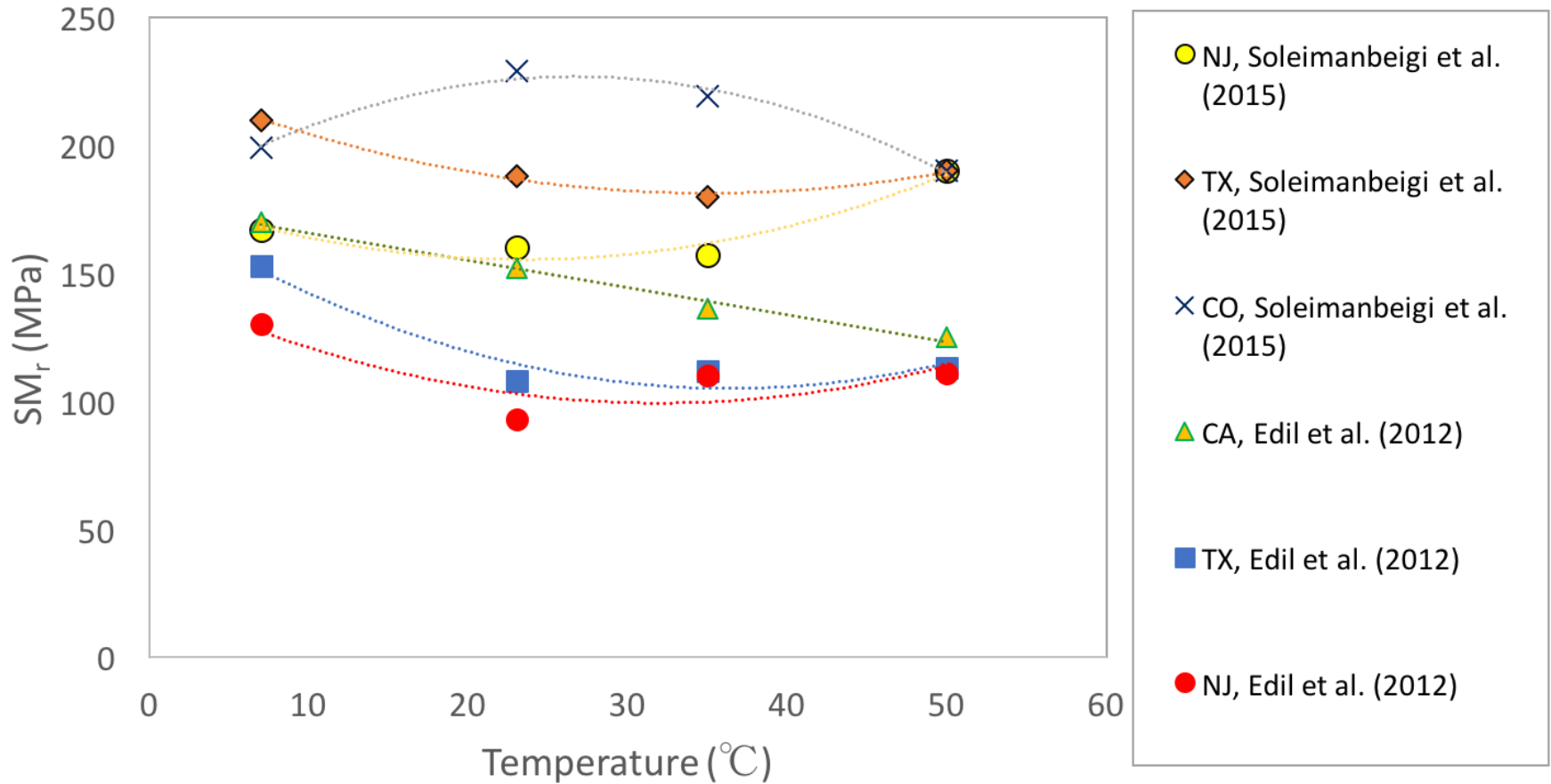
SM_r - RCA Content



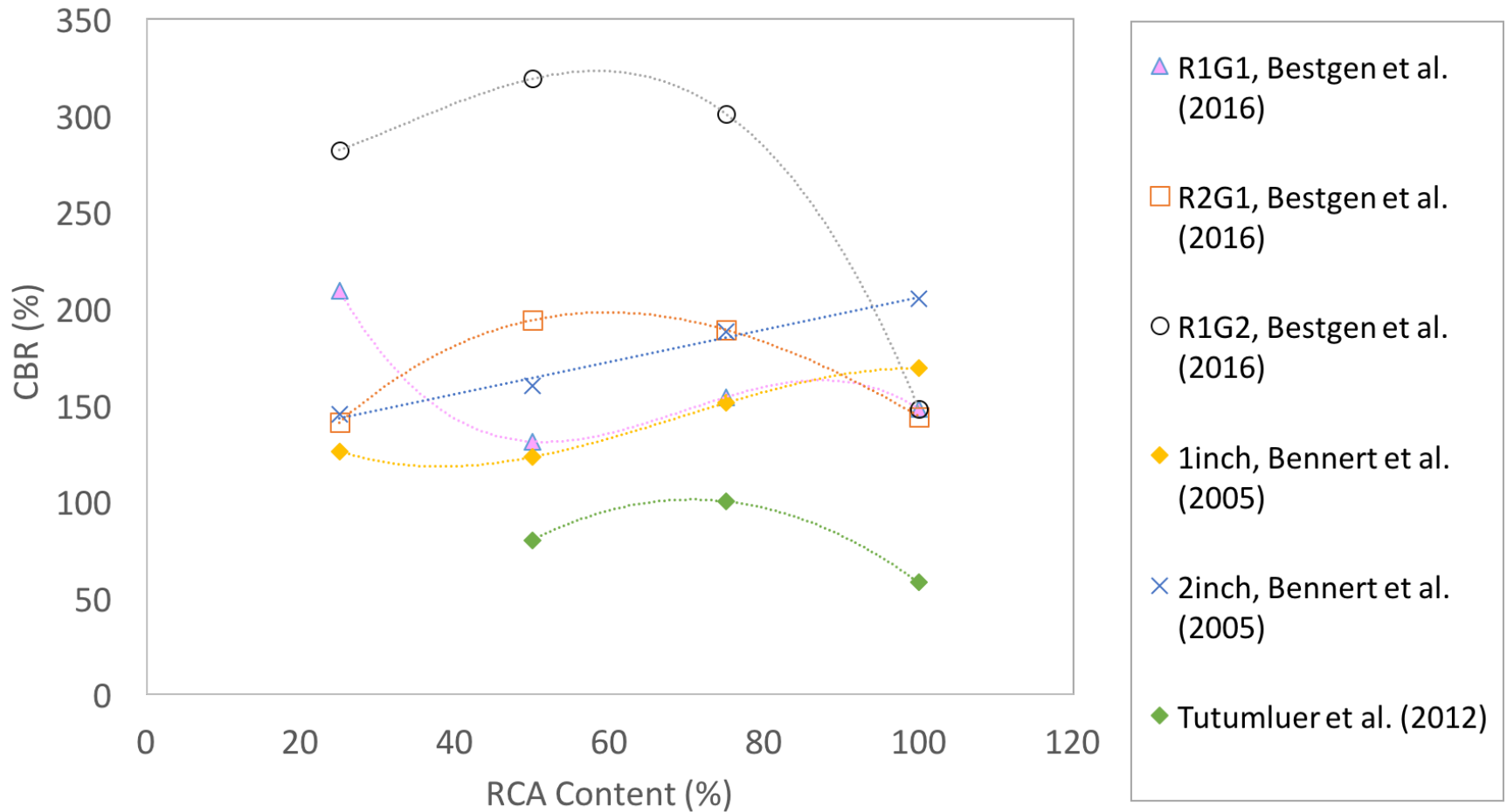
SM_r - RCA Content



SM_r – Temperature (RCA)



CBR – RCA Content



General Trends seen in our Data

- As the RAP content increases, the SM_r values increase
- Higher permanent strain obtained with the increase of RAP content.

Ongoing...

More relations are being investigated between RAP and RCA characteristics such as:

- Hydraulic conductivity with D_{10} or fine percent
- Optimum moisture content with SM_r
- Freeze and thaw cycles with SM_r