IOWA STATE UNIVERSITY | WISCONSIN UNIVERSITY OF WISCONSIN–MADISON | MICHIGAN STATE UNIVERSITY

Determining Pavement Design Criteria for Recycled Aggregate Base and Large Stone Subbase

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MnDOT Project TPF-5(341)

Monthly Meeting

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- Caltrans
- MDOT
- IDOT
- LRRB
- MoDOT
- WisDOT
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- Iowa DOT
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- MOBA Mobile Automation
- Geophysical Survey Systems
- Leica Geosystems
- University of St. Thomas
- Trimble

OUTLINE

- Follow-up
- Test cells & materials
- Task 7
  - Estimation of laboratory test results
  - Estimation of field test results
  - Pavement ME performance models
  - Conclusions & Recommendations
    - Material selection
    - Recycled aggregate base design
    - LSSB design

FOLLOW-UP

- **Task 1** – Literature review and recommendations
- **Task 2** – Tech transfer “state of practice”
- **Task 3** – Construction monitoring and reporting
- **Task 4** – Laboratory testing
- **Task 5** – Performance monitoring and reporting
- **Task 6** – Instrumentation
- **Task 7** – Pavement design criteria
- **Task 8 & 9** – Draft/final report

Green – Completed
Red – In Progress

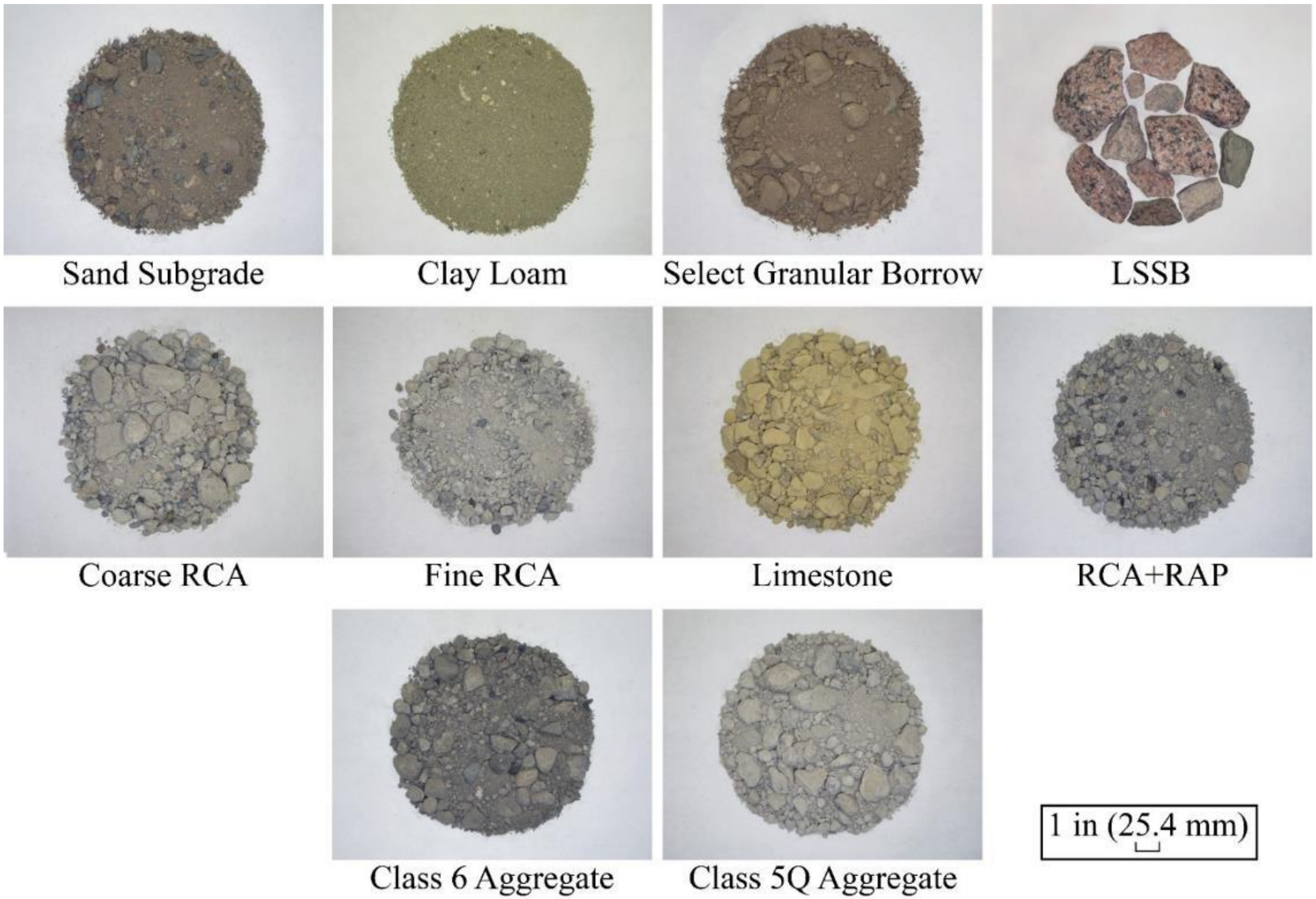
TEST CELLS

Section	Cell	Layer 1	Layer 2	Layer 3	Geosynthetic	Subgrade
Recycled Aggregate Base	185	3.5 in Superpave	12 in Coarse RCA	3.5 in S. Granular Borrow		Sand
Recycled Aggregate Base	186	3.5 in Superpave	12 in Fine RCA	3.5 in S. Granular Borrow		Sand
Recycled Aggregate Base	188	3.5 in Superpave	12 in Limestone	3.5 in S. Granular Borrow		Clay Loam
Recycled Aggregate Base	189	3.5 in Superpave	12 in RCA+RAP	3.5 in S. Granular Borrow		Clay Loam
Large Stone Subbase	127	3.5 in Superpave	6 in Class 6 Aggregate	18 in LSSB (1 lift)		Clay Loam
Large Stone Subbase	227	3.5 in Superpave	6 in Class 6 Aggregate	18 in LSSB (1 lift)		Clay Loam
Large Stone Subbase with Geosynthetics	328	3.5 in Superpave	6 in Class 5Q Aggregate	9 in LSSB	TX	Clay Loam
Large Stone Subbase with Geosynthetics	428	3.5 in Superpave	6 in Class 5Q Aggregate	9 in LSSB	TX+GT	Clay Loam
Large Stone Subbase with Geosynthetics	528	3.5 in Superpave	6 in Class 5Q Aggregate	9 in LSSB	BX+GT	Clay Loam
Large Stone Subbase with Geosynthetics	628	3.5 in Superpave	6 in Class 5Q Aggregate	9 in LSSB	BX	Clay Loam
Large Stone Subbase with Geosynthetics	728	3.5 in Superpave	6 in Class 5Q Aggregate	9 in LSSB		Clay Loam

S. Granular Borrow = Select Granular Borrow

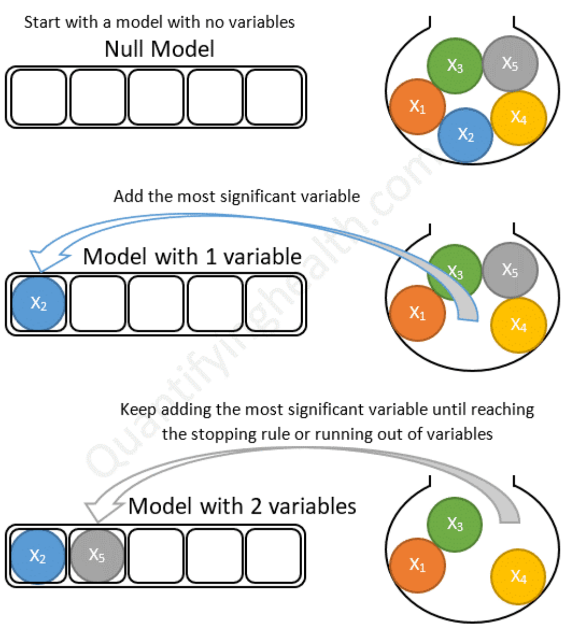
TX = Triaxial Geogrid
BX = Biaxial Geogrid
GT = Nonwoven Geotextile

MATERIALS


Sand Subgrade
Clay Loam
Select Granular Borrow
LSSB
Coarse RCA
Fine RCA
Limestone
RCA+RAP
Class 6 Aggregate
Class 5Q Aggregate
1 in (25.4 mm)

TASK 7

- Estimation of laboratory & field test results
  - Forward stepwise regression to find correlations
    - If p-value < 0.05 (alpha) - parameter is statistically significant
    - If significance F < 0.05 - correlation is statistically significant
    - When no correlation can be found → alpha = 0.1
    - No limitation for the p-value of the intercept



https://quantifyinghealth.com/stepwise-selection/

Corrected OMC (%)	Combined Absorption (%)	Fine Apparent G_s
9.48	6.97	2.61
11.07	8.65	2.60
6.28	1.72	2.80
9.97	4.34	2.42
8.26	3.86	2.55
9.63	6.32	2.59

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.981681406
R Square	0.964
Adjusted R Square	0.939497304
Standard Error	0.407546868
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	13.22791906	6.613959529	39.82047289	0.006916541
Residual	3	0.498283349	0.16609445		
Total	5	13.72620241			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	22.0333	4.224747406	5.215303304	0.013706983	8.588307332	35.478371	8.58830733	35.4783709
Combined Absorption (%)	0.5026	0.07687707	6.537889455	0.00727342	0.257956636	0.7472709	0.25795664	0.74727093
Fine Apparent Gs	-6.0058	1.572277974	-3.819824097	0.031577075	-11.00951552	-1.002135	-11.0095155	-1.00213506

TASK 7

- Estimation of laboratory test results
  - Corrected OMC (%)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.5026*Combined Absorption (%) - 6.0058*Fine Apparent G_s + 22.0333	0.964	0.939	0.4075	6	< 0.05	< 0.05
-9.1895*Combined OD G_s + 30.5418	0.924	0.905	0.5102	6	< 0.05	< 0.05
-8.1230*Fine SSD G_s + 28.2286	0.890	0.862	0.6149	6	< 0.05	< 0.05
-5.9208*Fine OD G_s + 22.1405	0.882	0.853	0.6359	6	< 0.05	< 0.05
-11.7635*Combined SSD G_s + 37.9200	0.880	0.850	0.6415	6	< 0.05	< 0.05
0.5912*Combined Absorption (%) + 5.9768	0.787	0.734	0.8547	6	< 0.05	< 0.05

OMC = optimum moisture content
OD G_s = oven-dry specific gravity
SSD G_s = saturated-surface-dry specific gravity

TASK 7

- Estimation of laboratory test results
  - Corrected MDD (kN/m^3)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
5.4563*Combined OD G_s - 0.4420*Asphalt Binder Content - Ignition (%) + 8.7018	0.994	0.990	0.1156	6	< 0.05	< 0.05
6.4234*Combined OD G_s + 0.0551*D_{60} (mm) + 4.8986	0.989	0.981	0.1561	6	< 0.05	< 0.05
3.2017*Fine OD G_s - 0.7433*Asphalt Binder Content - Ignition (%) + 15.1387	0.989	0.981	0.1585	6	< 0.05	< 0.05
4.2779*Fine OD G_s + 0.1074*D_{60} (mm) + 10.0510	0.977	0.961	0.2258	6	< 0.05	< 0.05
3.9122*Fine OD G_s + 0.6678*Gravel-to-Sand Ratio + 10.8568	0.970	0.950	0.2555	6	< 0.05	< 0.05
4.3220*Fine OD G_s + 0.1350*D_{50} (mm) + 10.0800	0.968	0.947	0.2634	6	< 0.05	< 0.05
8.5169*Combined SSD G_s - 0.5435	0.964	0.954	0.2448	6	< 0.05	< 0.05
6.4424*Combined OD G_s + 5.2901	0.949	0.936	0.2904	6	< 0.05	< 0.05
-0.6590*Corrected OMC (%) + 26.3182	0.907	0.884	0.3909	6	< 0.05	< 0.05
3.9711*Fine OD G_s + 11.5752	0.829	0.786	0.5303	6	< 0.05	< 0.05
12.4780*Coarse SSD G_s - 11.5034	0.664	0.580	0.7427	6	< 0.05	< 0.05

MDD = maximum dry density
OMC = optimum moisture content
OD G_s = oven-dry specific gravity
SSD G_s = saturated-surface-dry specific gravity

TASK 7

- Estimation of laboratory test results
  - K_{sat} (cm/sec)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.002991655*Void Ratio - Based on Apparent G_s - 0.000136146*Fine Apparent G_s - 0.000221884	0.999	0.998	7.16E-06	6	< 0.05	< 0.05
0.002534332*Void Ratio - Based on Apparent G_s + 1.77713E-05*Corrected OMC (%) - 0.000611369	0.998	0.996	8.98E-06	6	< 0.05	< 0.05
-0.000189822*Corrected MDD (kN/m^3) + 0.001357674*Combined Apparent G_s + 0.000522604	0.995	0.992	1.25E-05	6	< 0.05	< 0.05
0.00508301*Porosity - Based on Apparent G_s - 0.00084454	0.988	0.985	1.75E-05	6	< 0.05	< 0.05
0.003073*Void Ratio - Based on Apparent G_s - 0.000598	0.986	0.982	1.90E-05	6	< 0.05	< 0.05
-0.000182804*Corrected MDD (kN/m^3) + 0.000933374*Fine Apparent G_s + 0.001538639	0.975	0.958	2.95E-05	6	< 0.05	< 0.05
0.016696071*$e^3/(1+e)$ - 4.0528*E-05	0.956	0.945	3.36E-05	6	< 0.05	< 0.05
5.5193E-05*Combined Absorption (%) - 4.5053E-05	0.914	0.892	4.71E-05	6	< 0.05	< 0.05
7.80017E-05*Corrected OMC (%) - 0.000463028	0.810	0.763	6.99E-05	6	< 0.05	< 0.05
2.90566E-05*Fine Absorption (%) + 3.46191E-05	0.745	0.682	8.10E-05	6	< 0.05	< 0.05
-0.000106*Corrected MDD (kN/m^3) + 0.002409	0.722	0.653	8.46E-05	6	< 0.05	< 0.05

K_{sat} = saturated hydraulic conductivity
MDD = maximum dry density
OMC = optimum moisture content
OD G_s = oven-dry specific gravity
SSD G_s = saturated-surface-dry specific gravity
e = void ratio

TASK 7

- Estimation of laboratory test results
  - Residual VWC (SWCC)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
-0.0100*Corrected OMC (%) + 0.1127	0.554	0.442	0.0167	6	$0.05 < p < 0.1$	$0.05 < p < 0.1$

  - Saturated VWC (SWCC)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
-0.13823*Combined OD G_s + 0.021261*C_c + 0.567179	0.907	0.845	0.0106	6	< 0.05	< 0.05
0.027149*Coarse Absorption (%) + 0.184503	0.903	0.879	0.0094	6	< 0.05	< 0.05
0.001841*Residual Mortar Content (%) + 0.231506	0.766	0.707	0.0146	6	< 0.05	< 0.05
-0.24131*Coarse OD G_s + 0.871849	0.697	0.621	0.0166	6	< 0.05	< 0.05
-0.0848*Fine OD G_s + 0.463185	0.681	0.602	0.0170	6	< 0.05	< 0.05

VWC = volumetric water content
SWCC = soil-water characteristic curve
OMC = optimum moisture content
OD G_s = oven-dry specific gravity

TASK 7

- Estimation of laboratory test results
  - Air entry pressure (SWCC)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
48.5469*Void Ratio - Based on Apparent G_s - 2.2888*Coarse Absorption (%) - 0.1958*Fines (%) - 1.2909	0.997	0.991	0.149	6	< 0.05	< 0.05
78.8067*Porosity - Based on Apparent G_s - 1.4732*Coarse Absorption (%) - 9.0649	0.966	0.944	0.378	6	< 0.05	< 0.05
46.0499*Void Ratio - Based on Apparent G_s - 1.3624*Coarse Absorption (%) - 5.1737	0.960	0.934	0.409	6	< 0.05	< 0.05
31.5864*Void Ratio - Based on Apparent G_s - 0.6861*D_{30} (mm) - 4.7364	0.933	0.889	0.532	6	< 0.05	< 0.05
52.2180*Porosity - Based on Apparent G_s - 0.7107*D_{30} (mm) - 7.2297	0.925	0.875	0.564	6	< 0.05	< 0.05

VWC = volumetric water content
SWCC = soil-water characteristic curve

TASK 7

- Estimation of laboratory test results
  - M_R (MPa)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.9121*Residual Mortar Content (%) + 95.0309	0.999	0.998	0.5105	4	< 0.05	< 0.05
13.9035*Coarse Absorption (%) + 69.9919	0.993	0.990	1.3203	4	< 0.05	< 0.05
5.4794*OMC (%) + 61.4114	0.981	0.972	2.1925	4	< 0.05	< 0.05
-39.5364*Fine OD G_s + 201.5303	0.970	0.954	2.7988	4	< 0.05	< 0.05
-118.4860*Coarse OD G_s + 409.3854	0.946	0.919	3.7272	4	< 0.05	< 0.05
-8.4659*MDD (kN/m^3) + 284.6113	0.941	0.912	3.8926	4	< 0.05	< 0.05
-143.1262*Coarse SSD G_s + 482.0049	0.917	0.876	4.6148	4	< 0.05	< 0.05
2.4855*Fine Absorption (%) + 95.5617	0.917	0.876	4.6171	4	< 0.05	< 0.05
-56.4223*Combined OD G_s + 246.2814	0.907	0.861	4.8854	4	< 0.05	< 0.05

M_R = resilient modulus
MDD = maximum dry density
OMC = optimum moisture content
OD G_s = oven-dry specific gravity
SSD G_s = saturated-surface-dry specific gravity

TASK 7

- Estimation of laboratory test results

$$M_R = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

  - k_1

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
11.6644*Fine Absorption (%) + 16.1631*D_{30} (mm) + 731.5558	1.000	1.000	0.7345	4	< 0.05	< 0.05
83.7374*Coarse Absorption (%) + 153.4469*Fine Apparent G_s + 173.1523	1.000	1.000	0.2597	4	< 0.05	< 0.05
86.6269*Coarse Absorption (%) + 227.7959*Combined Apparent G_s - 39.0482	1.000	1.000	0.2963	4	< 0.05	< 0.05
13.4873*Fine Absorption (%) + 738.4029	0.962	0.944	16.5059	4	< 0.05	< 0.05
70.6962*Coarse Absorption (%) + 614.7812	0.915	0.872	24.8015	4	< 0.05	< 0.05

  - k_2

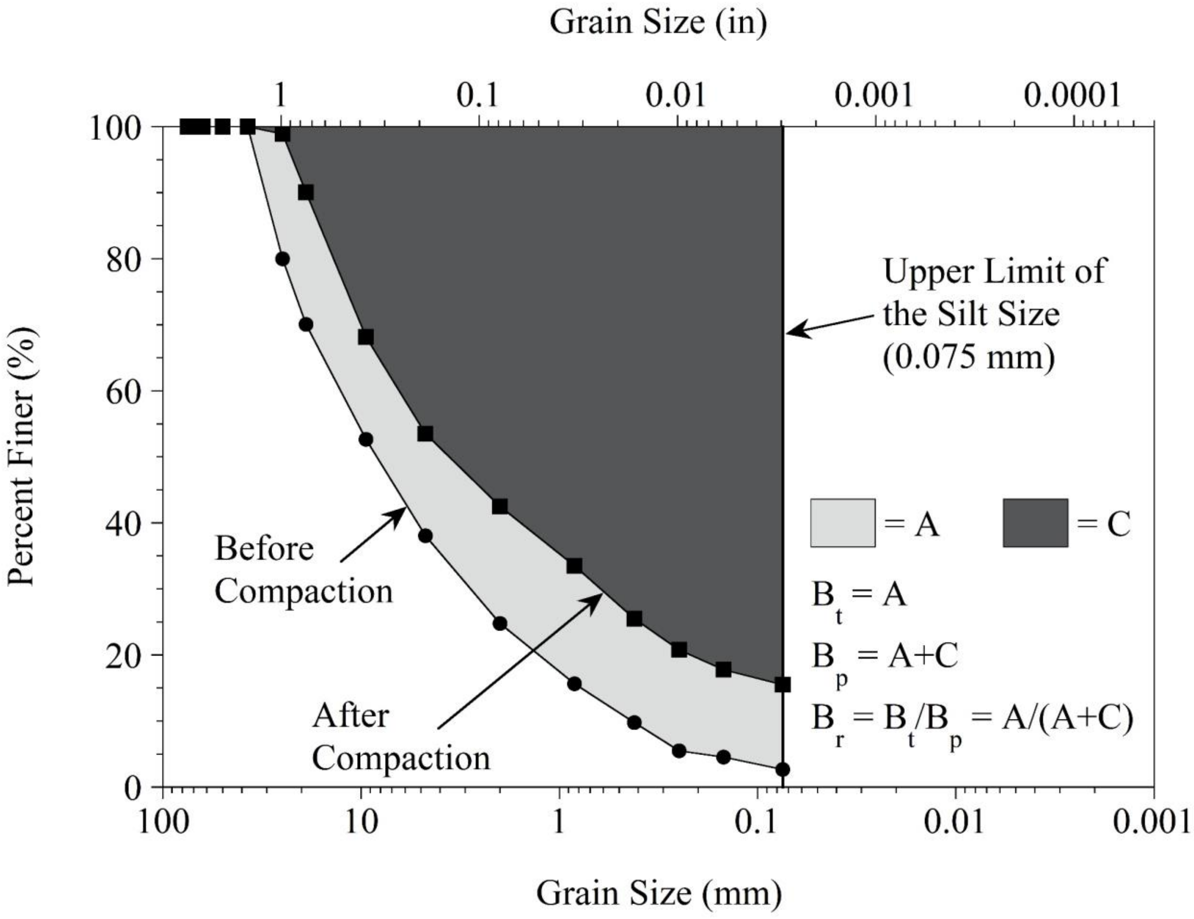
Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
-0.5822*Combined Apparent G_s - 0.0136*Corrected MDD (kN/m^3) + 2.250	1.000	1.000	0.0007	4	< 0.05	< 0.05
-0.5946*Combined Apparent G_s + 0.0092*Corrected OMC (%) + 1.9211	1.000	1.000	0.0007	4	< 0.05	< 0.05
-0.4716*Fine Apparent G_s + 0.0061*Combined Absorption (%) + 1.6280	1.000	1.000	0.0003	4	< 0.05	< 0.05
-0.7294*Combined Apparent G_s + 2.3626	0.980	0.969	0.0142	4	< 0.05	< 0.05
-0.5161*Fine Apparent G_s + 1.7773	0.955	0.933	0.0211	4	< 0.05	< 0.05

  - k_3

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.2190*Fine Apparent G_s + 0.0048*Combined Absorption (%) - 0.6708	1.000	1.000	0.0002	4	< 0.05	< 0.05
0.5910*Fine Apparent G_s + 0.7889*k_2 - 1.9552	1.000	1.000	0.0000	4	< 0.05	< 0.05

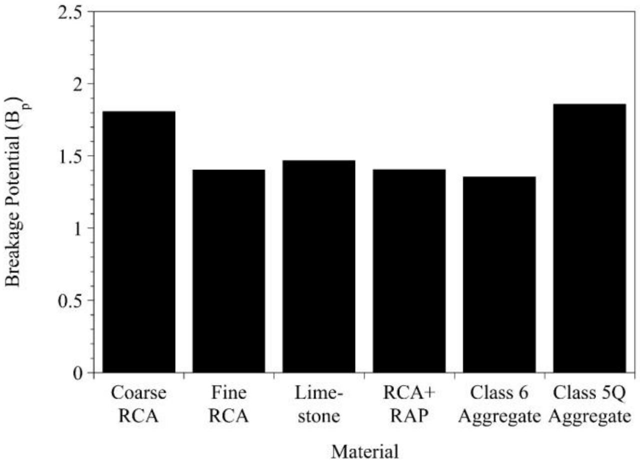
TASK 7

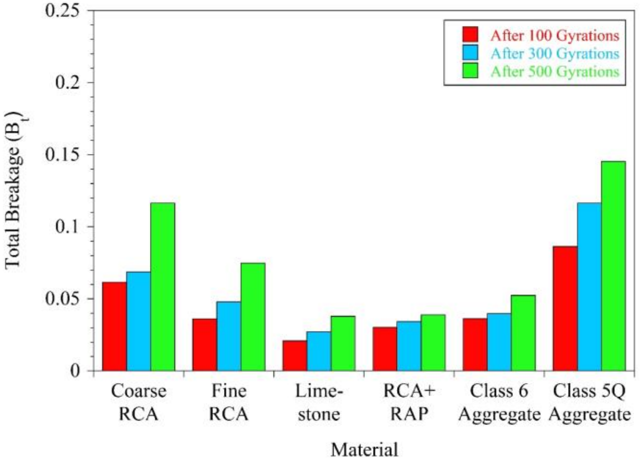
- Estimation of laboratory test results
  - Abrasion

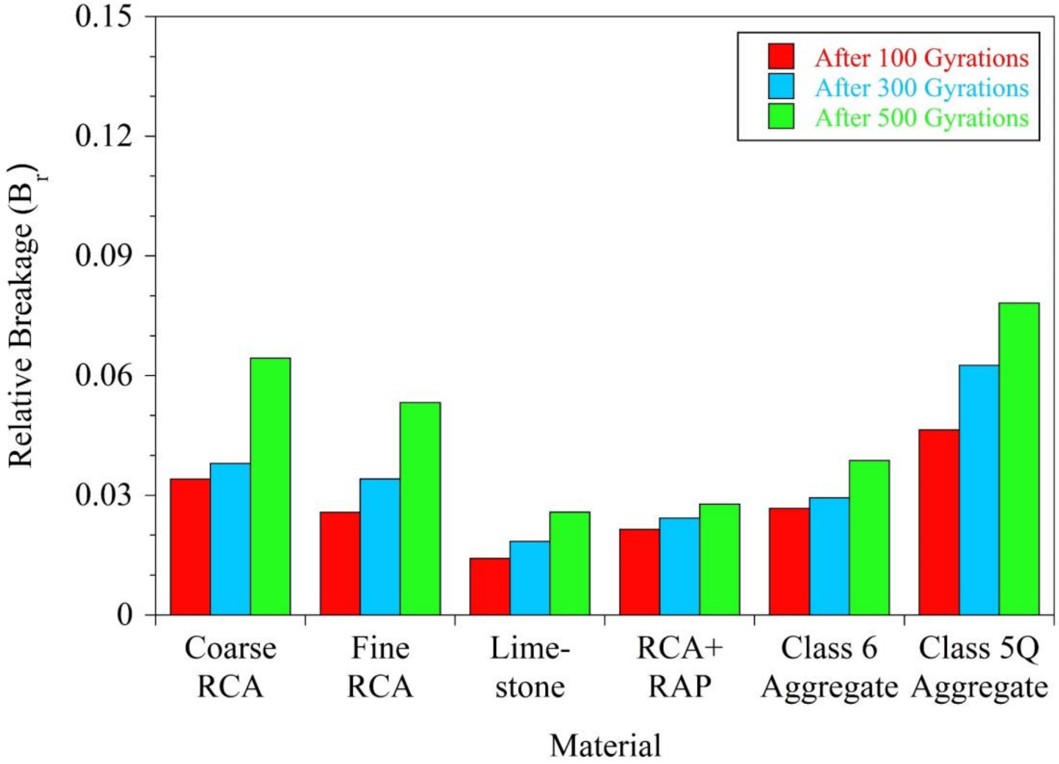


TASK 7

- Estimation of laboratory test results
  - Abrasion

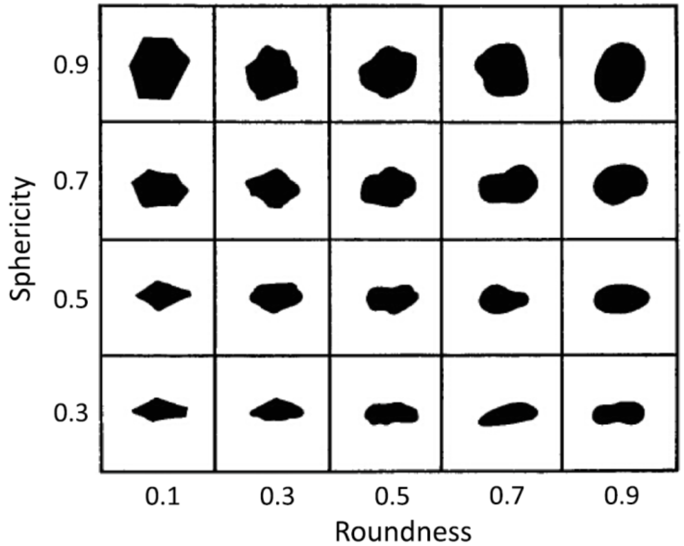






TASK 7

- Estimation of laboratory test results



(Krumbein and Sloss 1951; Hryciw et al. 2016)

  – Relative breakage (B_r) after 100 gyrations

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.0005*Residual Mortar Content (%) + 0.0042*Percent Less Rounded by Number (%) - 0.5 - 0.0281	0.964	0.940	0.0027	6	< 0.05	< 0.05
0.0007*Residual Mortar Content (%) - 0.5216*Median Roundness + 0.3519	0.939	0.898	0.0036	6	$0.05 < p < 0.1$	< 0.05
0.0008*Residual Mortar Content (%) + 0.0096	0.762	0.702	0.0061	6	< 0.05	< 0.05
0.0067*Percent Less Rounded by Number (%) - 0.5 - 0.0407	0.685	0.607	0.0070	6	< 0.05	< 0.05

TASK 7

- Estimation of laboratory test results
  - B_r after 300 gyrations

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.0009*Residual Mortar Content (%) - 0.9992*Median Roundness + 0.6665	0.980	0.967	0.0028	6	< 0.05	< 0.05
0.0009*Residual Mortar Content (%) + 0.0033*Percent Less Rounded by Number (%) - 0.7 - 0.2066	0.962	0.936	0.0039	6	< 0.05	< 0.05
0.0006*Residual Mortar Content (%) + 0.0066*Percent Less Rounded by Number (%) - 0.5 - 0.0485	0.904	0.840	0.0062	6	$0.05 < p < 0.1$	< 0.05
0.0095*Percent Less Rounded by Number (%) - 0.5 - 0.0630	0.714	0.643	0.0092	6	< 0.05	< 0.05
0.0010*Residual Mortar Content (%) + 0.0109	0.643	0.554	0.0103	6	$0.05 < p < 0.1$	$0.05 < p < 0.1$

  - B_r after 500 gyrations

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.0009*Residual Mortar Content (%) + 0.0083*Percent Less Rounded by Number (%) - 0.5 - 0.0601	0.945	0.908	0.0064	6	< 0.05	< 0.05
0.0014*Residual Mortar Content (%) - 1.0793*Median Roundness + 0.7221	0.938	0.897	0.0067	6	< 0.05	< 0.05
0.0014*Residual Mortar Content (%) + 0.0035*Percent Less Rounded by Number (%) - 0.7 - 0.2165	0.919	0.864	0.0077	6	$0.05 < p < 0.1$	< 0.05
0.0014*Residual Mortar Content (%) + 0.0139	0.726	0.657	0.0123	6	< 0.05	< 0.05
0.0128*Percent Less Rounded by Number (%) - 0.5 - 0.0827	0.694	0.618	0.0130	6	< 0.05	< 0.05

TASK 7

- Estimation of field test results
  - Base DCPI (mm/blow)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
-1.6462*Median NDG Dry Density (kN/m^3) + 11.3118*Combined OD G_s + 13.2990	0.634	0.542	0.9087	11	< 0.05	< 0.05
-0.2650*Median Relative MDD (%) + 33.2674	0.558	0.509	0.9406	11	< 0.05	< 0.05

  - Base CBR (%)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.8407*Median Relative MDD (%) - 51.3895	0.529	0.476	3.1683	11	< 0.05	< 0.05

DCPI = dynamic cone penetration index
NDG = nuclear density gauge
MDD = maximum dry density
OD G_s = oven-dry specific gravity

$$\text{CBR (\%)} = \frac{292}{\text{DCP}^{1.12}}$$ for DCP in mm/blow (ASTM D6951)

TASK 7

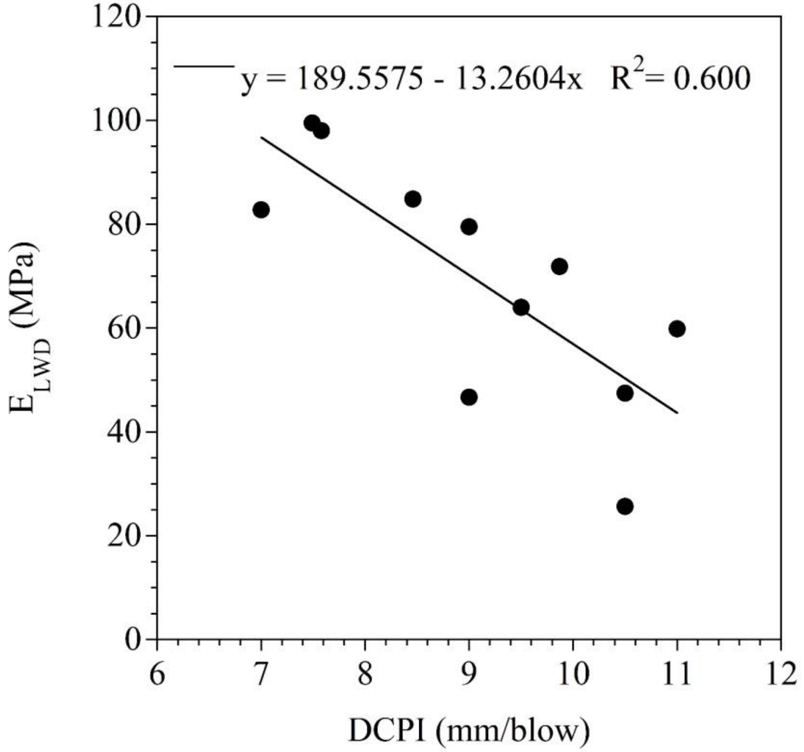
- Estimation of field test results
  - Base E_{LWD} (MPa)

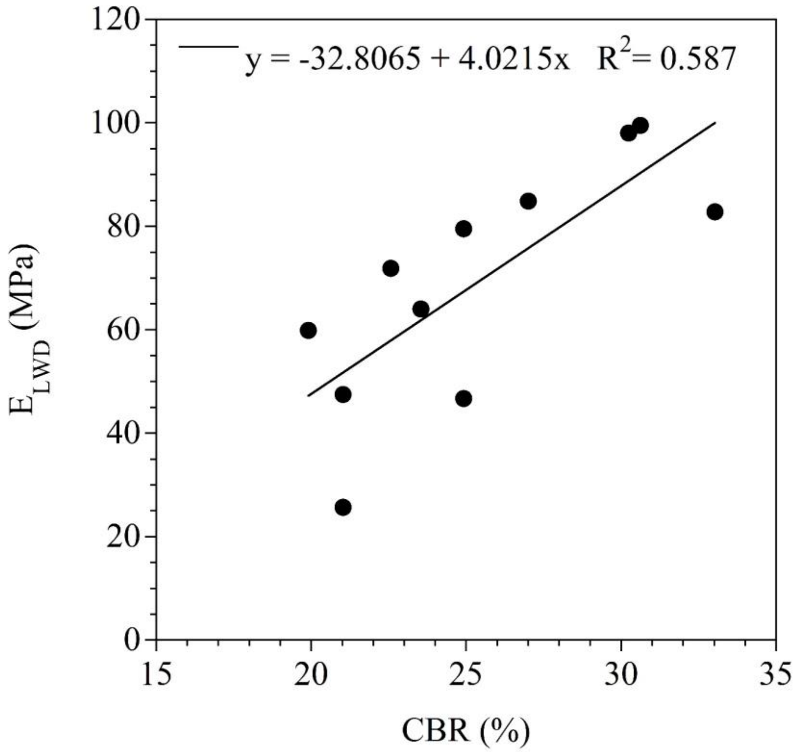
Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
31.7980*Median NDG Dry Density (kN/m^3) - 217.5777*Combined OD G_s - 14.4437	0.808	0.760	11.2475	11	< 0.05	< 0.05
27.6348*Median NDG Dry Density (kN/m^3) - 240.6255*Combined SDD G_s + 145.4250	0.734	0.667	13.2569	11	< 0.05	< 0.05
34.2796*Median NDG Dry Density (kN/m^3) - 144.5733*Fine OD G_s - 251.1844	0.731	0.663	13.3342	11	< 0.05	< 0.05
33.7399*Median NDG Dry Density (kN/m^3) - 198.3377*Fine SSD G_s - 92.1880	0.724	0.654	13.5074	11	< 0.05	< 0.05
5.1192*Median Relative MDD (%) - 398.1386	0.712	0.680	13.0063	11	< 0.05	< 0.05
24.4016*Median NDG Dry Density (kN/m^3) - 9.7645*Combined Absorption (%) - 435.6365	0.639	0.549	15.4377	11	< 0.05	< 0.05
-13.2604*Median DCPI (mm/blow) + 189.5575	0.600	0.556	15.3116	11	< 0.05	< 0.05
4.0215*Median CBR (%) - 32.8065	0.587	0.541	15.5645	11	< 0.05	< 0.05

E_{LWD} = elastic modulus obtained from light weight deflectometer
NDG = nuclear density gauge
DCPI = dynamic cone penetration index
MDD = maximum dry density
OD G_s = oven-dry specific gravity
SSD G_s = saturated-surface-dry specific gravity

TASK 7

- Estimation of field test results
  - Base E_{LWD} (MPa)





TASK 7

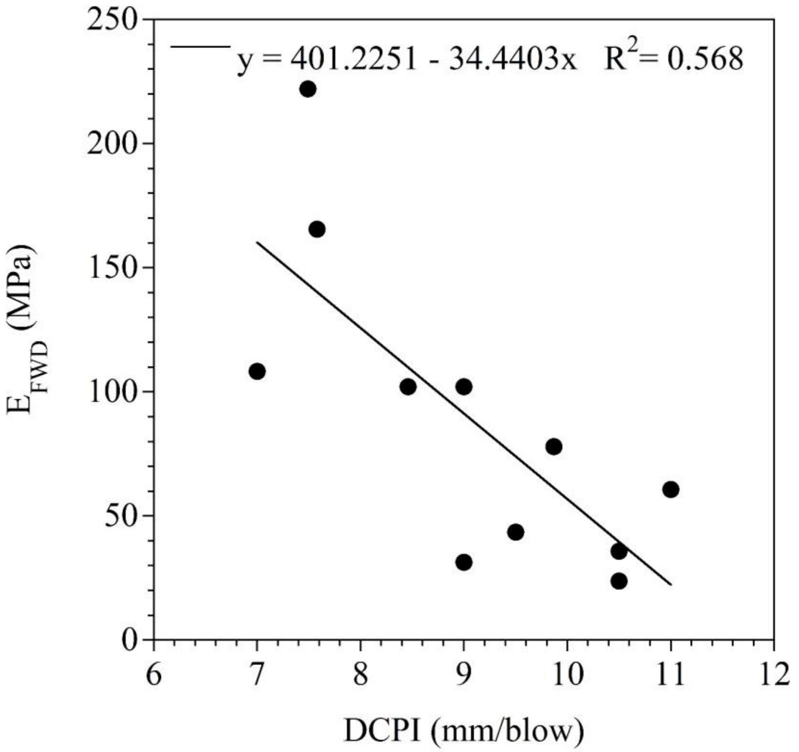
- Estimation of field test results
  - Base E_{FWD} (MPa)

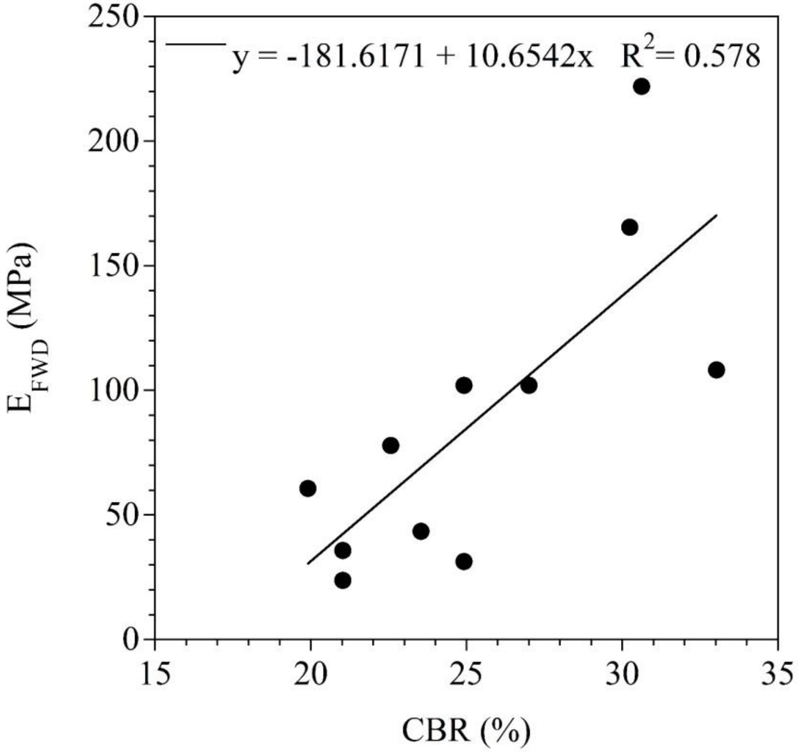
Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
-58.3327*D_{30} (mm) + 30.1898*Fine Absorption (%) - 37.5641*Corrected OMC (%) + 329.4163	0.971	0.958	12.5182	11	< 0.05	< 0.05
2.2010*Median E_{LWD} (MPa) + 20.8064*Combined Absorption (%) - 21.8024*Median NDG Moisture Content (%) - 30.8626	0.954	0.935	15.6985	11	< 0.05	< 0.05
-40.4818*D_{30} (mm) + 21.5511*Fine Absorption (%) + 31.0942*Median NDG Dry Density (kN/m^3) - 563.7491	0.946	0.923	17.0707	11	< 0.05	< 0.05
2.2769*Median E_{LWD} (MPa) + 11.8182*Combined Absorption (%) - 1.8902*Median Relative OMC (%) + 4.5147	0.944	0.920	17.3700	11	< 0.05	< 0.05
1.8589*Median E_{LWD} (MPa) + 16.4004*Combined Absorption (%) - 165.2143*D_{10} (mm) - 86.5880	0.939	0.913	18.1121	11	< 0.05	< 0.05
2.4732*Median E_{LWD} (MPa) + 9.7178*Combined Absorption (%) - 136.4322	0.889	0.861	22.8708	11	< 0.05	< 0.05
2.3858*Median E_{LWD} (MPa) - 76.4845	0.798	0.776	29.0421	11	< 0.05	< 0.05
16.1040*Median Relative MDD (%) + 10.1868*Fine Absorption (%) - 1461.9277	0.773	0.716	32.7063	11	< 0.05	< 0.05
10.6542*Median CBR (%) - 181.6171	0.578	0.531	42.0154	11	< 0.05	< 0.05
-34.4403*Median DCPI (mm/blow) + 401.2251	0.568	0.520	42.5059	11	< 0.05	< 0.05
11.7122*Median Relative MDD (%) - 980.6099	0.522	0.469	44.6924	11	< 0.05	< 0.05

E_{FWD} = elastic modulus obtained from falling weight deflectometer
E_{LWD} = elastic modulus obtained from light weight deflectometer
NDG = nuclear density gauge
DCPI = dynamic cone penetration index

TASK 7

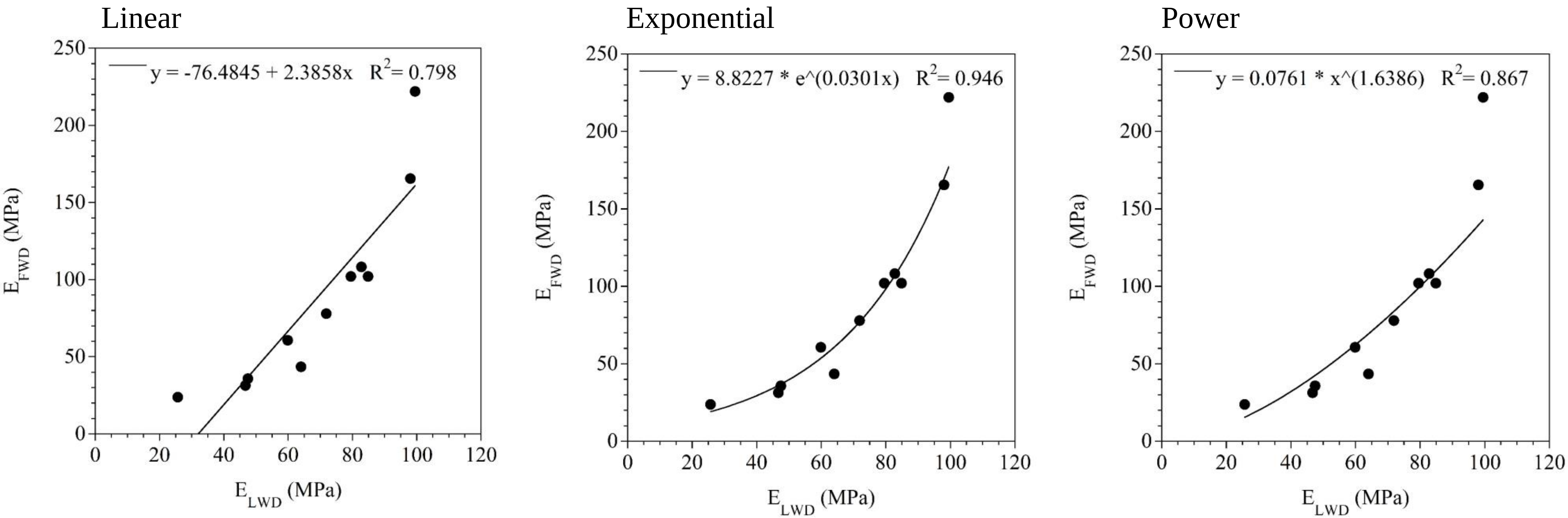
- Estimation of field test results
  - Base E_{FWD} (MPa)





TASK 7

- Estimation of field test results
  - Base E_{FWD} (MPa)



TASK 7

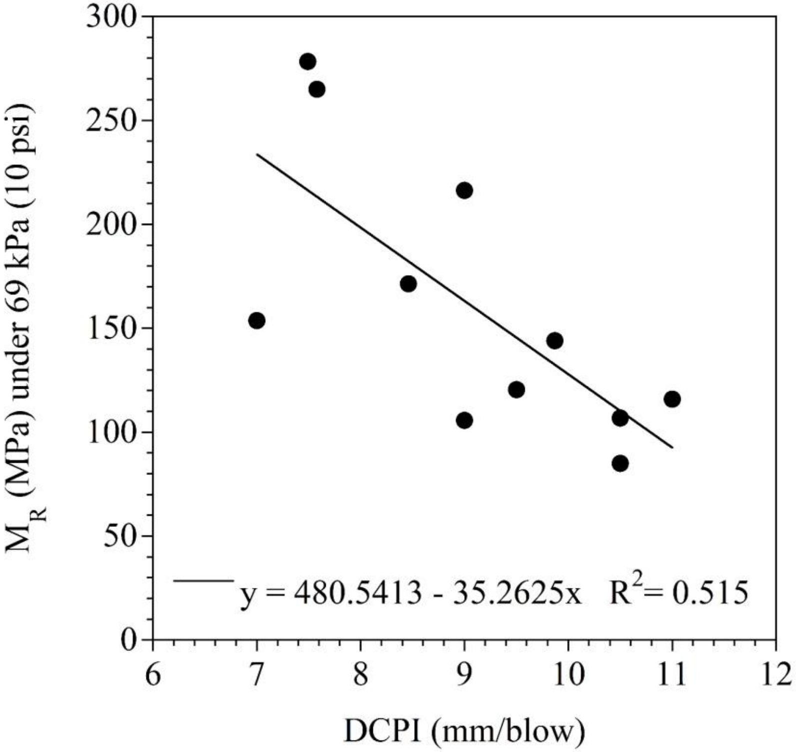
- Estimation of field test results
  - Base M_R (MPa) under 69 kPa (10 psi) loading

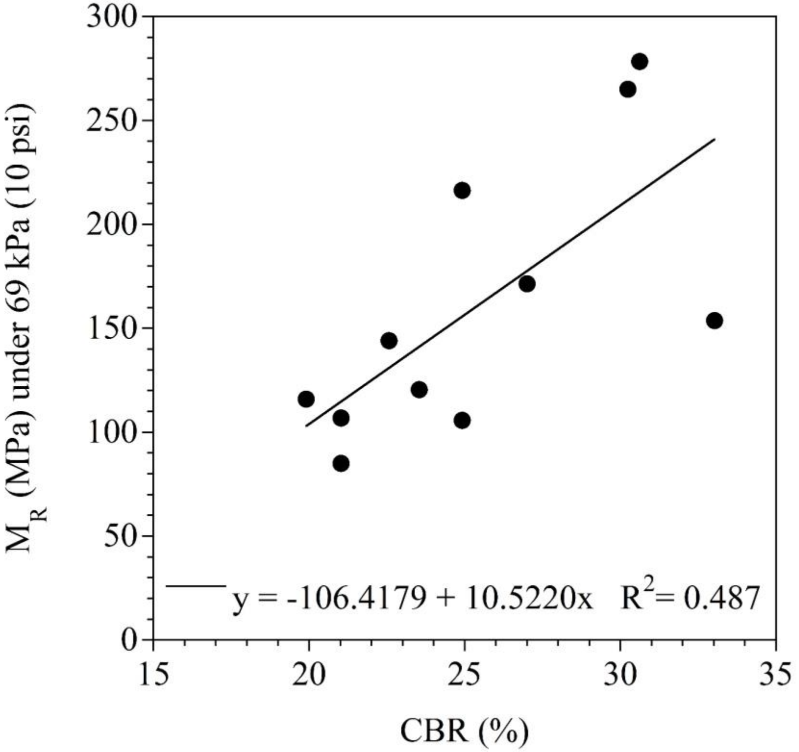
Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
1.0258*Median E_{FWD} (MPa) + 69.5686	0.909	0.899	20.9284	11	< 0.05	< 0.05
2.5583*Median E_{LWD} (MPa) - 16.5596	0.793	0.771	31.6165	11	< 0.05	< 0.05
16.8683*Median Relative MDD (%) + 10.4512*Fine Absorption (%) - 1461.9308	0.731	0.663	38.2853	11	< 0.05	< 0.05
-35.2625*Median DCPI (mm/blow) + 480.5413	0.515	0.461	48.4612	11	< 0.05	< 0.05
12.3625*Median Relative MDD (%) - 968.1201	0.503	0.448	49.0357	11	< 0.05	< 0.05
10.5220*Median CBR (%) - 106.4179	0.487	0.430	49.8141	11	< 0.05	< 0.05

M_R = field resilient modulus obtained from intelligent compaction
E_{FWD} = elastic modulus obtained from falling weight deflectometer
E_{LWD} = elastic modulus obtained from light weight deflectometer
DCPI = dynamic cone penetration index

TASK 7

- Estimation of field test results
  - Base M_R (MPa) under 69 kPa (10 psi) loading

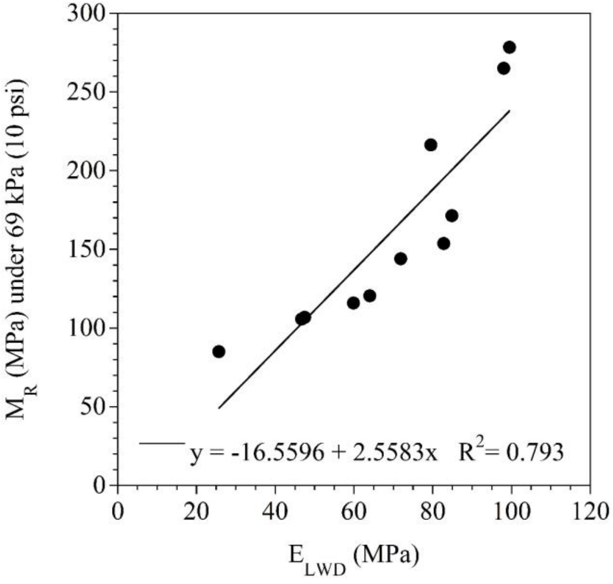




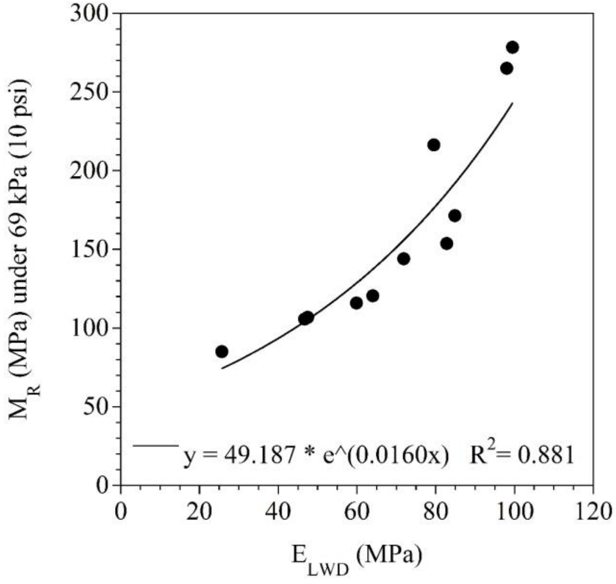
TASK 7

- Estimation of field test results
  - Base M_R (MPa) under 69 kPa (10 psi) loading

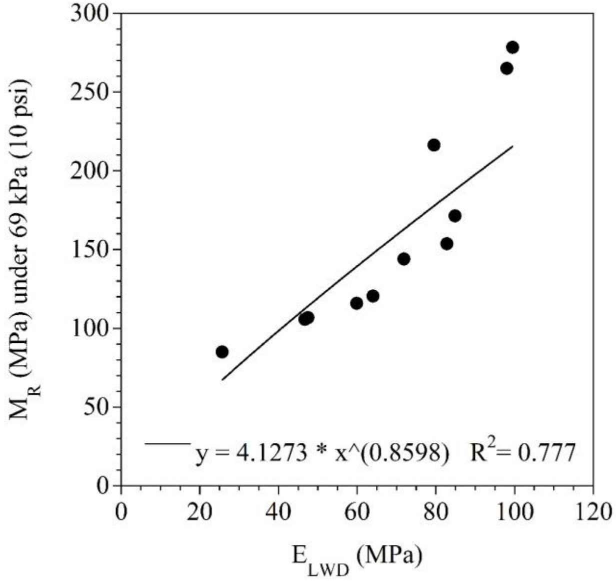
Linear



Exponential

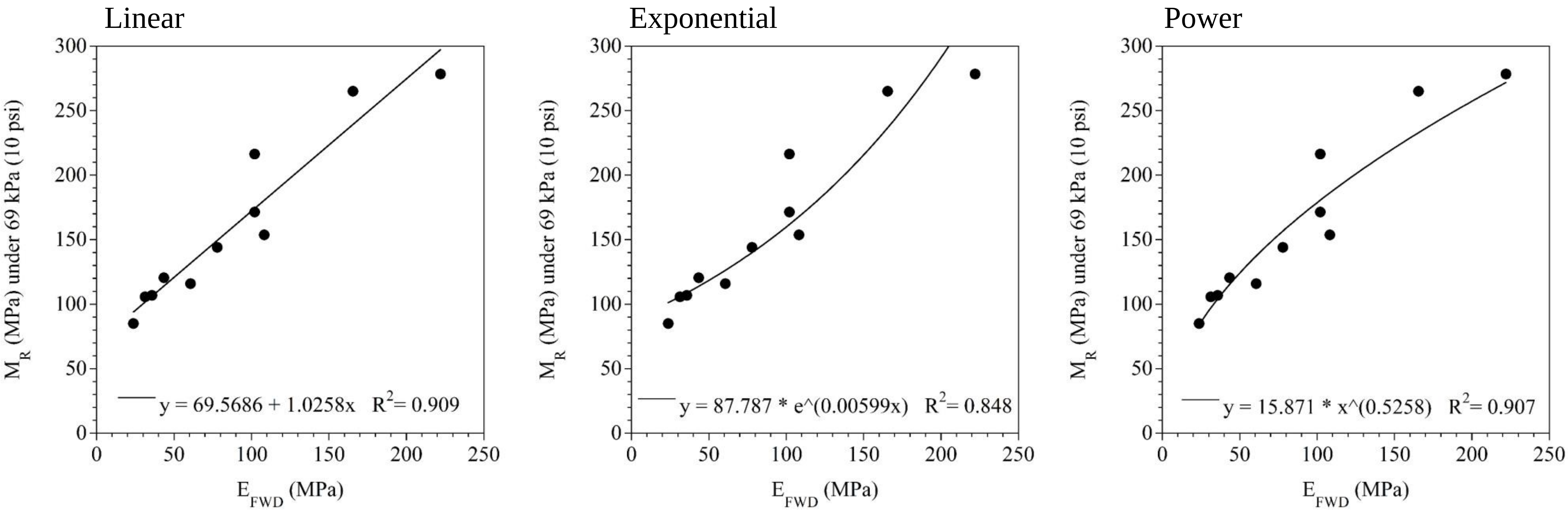


Power



TASK 7

- Estimation of field test results
  - Base M_R (MPa) under 69 kPa (10 psi) loading



TASK 7

- Pavement ME performance models
  - General information
    - Design life - 20 years
    - Construction/traffic open dates - actual dates (August 2017/September 2017)
    - Initial IRI - 63 in/mile
    - Terminal IRI - 170 in/mile
    - AC bottom-up fatigue cracking - 25% lane area
    - AC thermal cracking - 1000 ft/mile
    - AC top-down fatigue cracking - 2000 ft/mile
    - Permanent deformation - AC only - 0.25 in
    - Permanent deformation - total pavement - 0.75 in
    - 90% reliability
  - Climatic parameters and regional information
    - Location - MnROAD
    - Water table depth - 10 ft

TASK 7

- Pavement ME performance models
  - Traffic information
    - Operational speed - 50 mph
    - Growth factor - 3% (linear)
    - TTC4 Level 3 default vehicle distribution
  - Traffic levels
    - 100 AADTT
    - 500 AADTT
    - 1,000 AADTT
    - 7,500 AADTT
    - 25,000 AADTT

Parameter	Low Traffic			Medium Traffic	High Traffic
	100 AADTT	**500 AADTT**	**1,000 AADTT**	**7,500 AADTT**	**25,000 AADTT**
Number of Lanes in Design Direction	1	2	2	3	3
Percent of Trucks in Design Direction (%)	50	50	50	50	50
Percent of Trucks in Design Lane (%)	100	75	75	55	50
Operational Speed (mph)	50	50	50	50	50

(NCHRP 1-47)

TTC = truck traffic classification
AADTT = average annual daily truck traffic

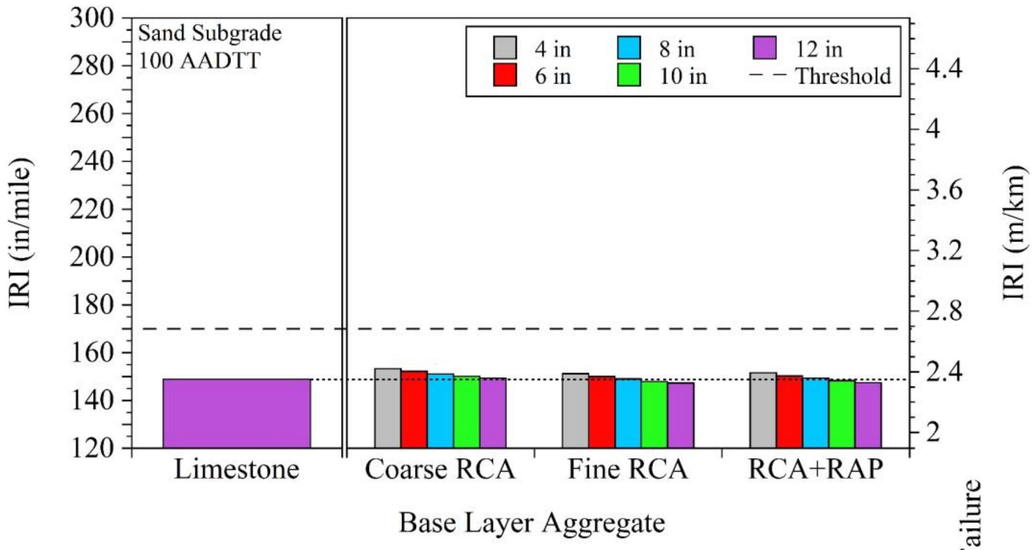
TASK 7

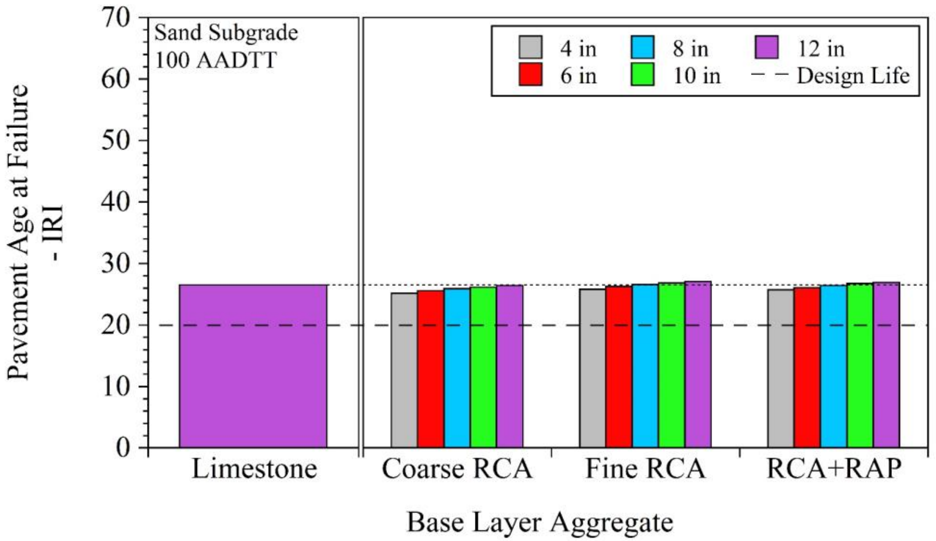
- Pavement ME performance models
  - Recycled aggregate base group
    - Base layer thickness
      - 12 in (original thickness)
      - 10 in
      - 8 in
      - 6 in
      - 4 in
    - Subgrade types
      - Sand subgrade
      - Clay loam subgrade

Recycled Aggregate Base			
185	186	188	189
3.5 in Asphalt	3.5 in Asphalt	3.5 in Asphalt	3.5 in Asphalt
12 in Coarse RCA	12 in Fine RCA	12 in Limestone	12 in RCA+RAP
3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow
Sand	Sand	Clay Loam	Clay Loam

TASK 7

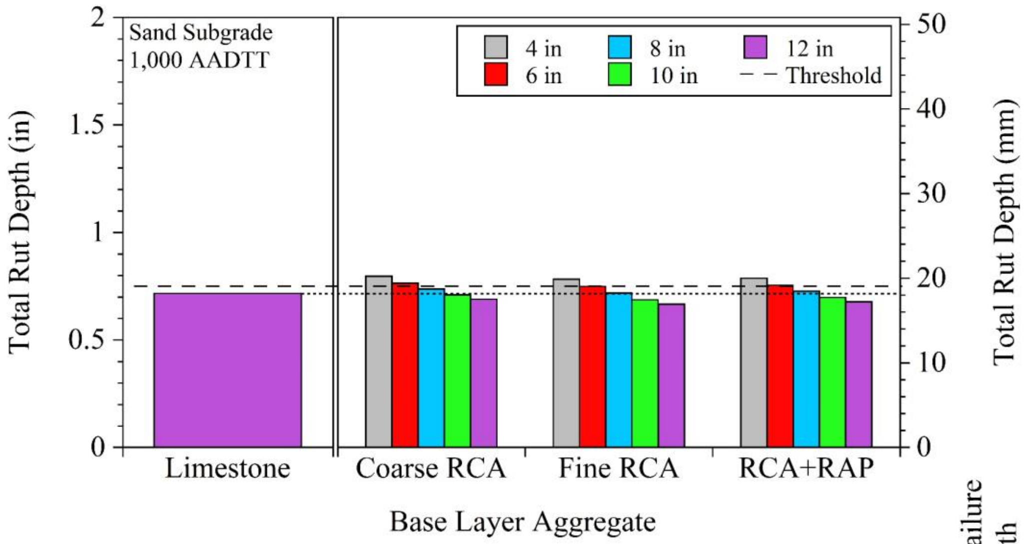
- Pavement ME performance models
  - Relative base layer thickness - IRI

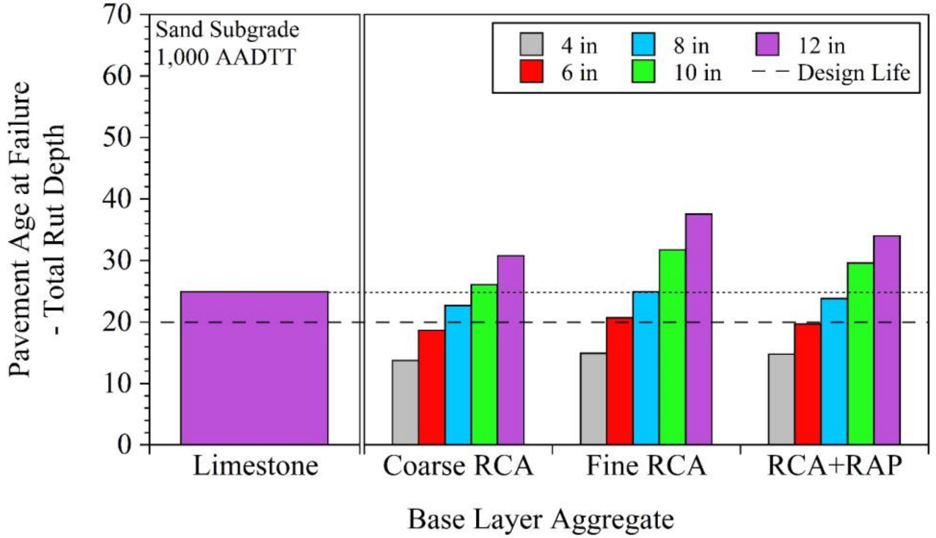




TASK 7

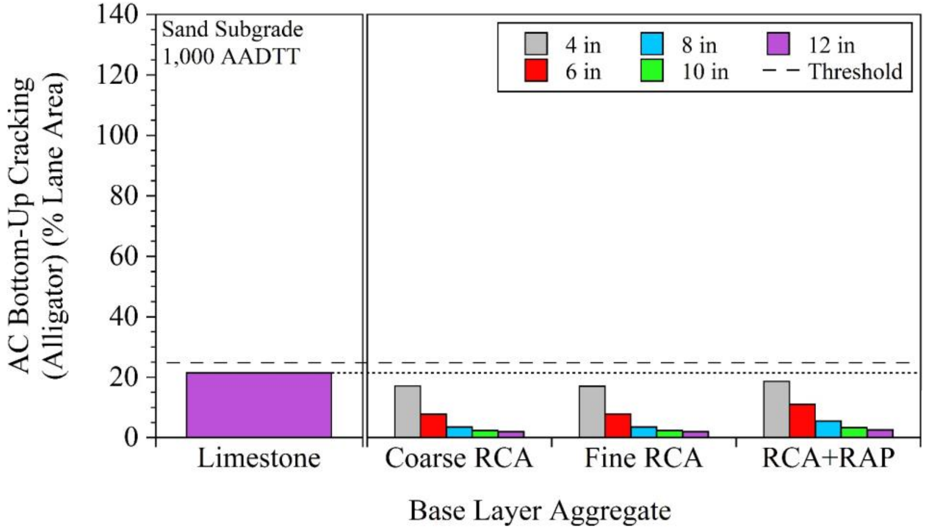
- Pavement ME performance models
  - Relative base layer thickness - rutting

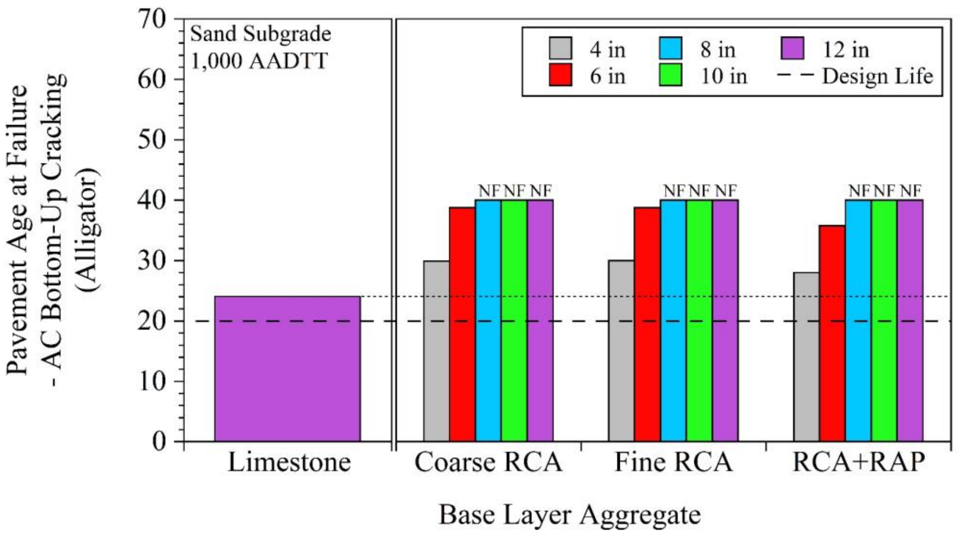




TASK 7

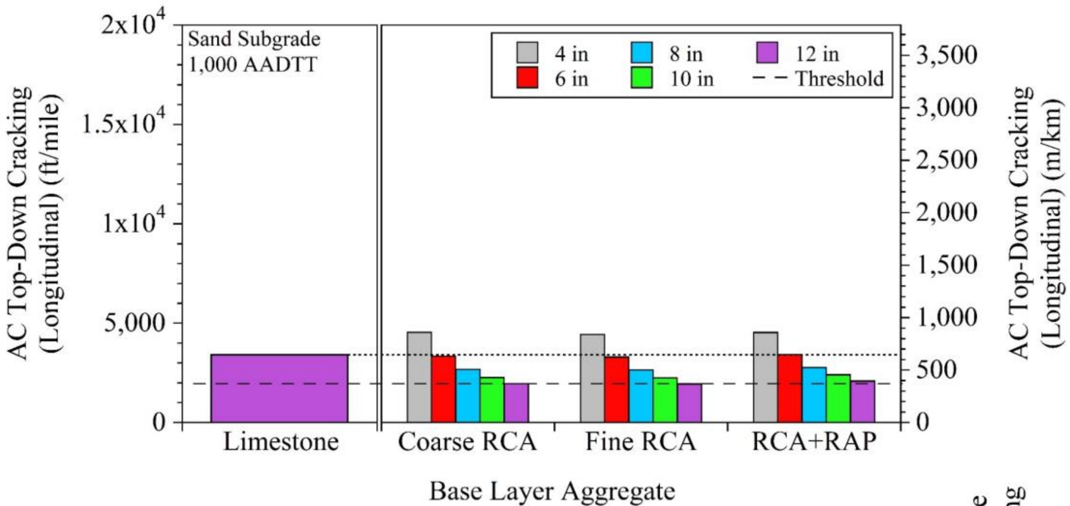
- Pavement ME performance models
  - Relative base layer thickness - alligator cracking

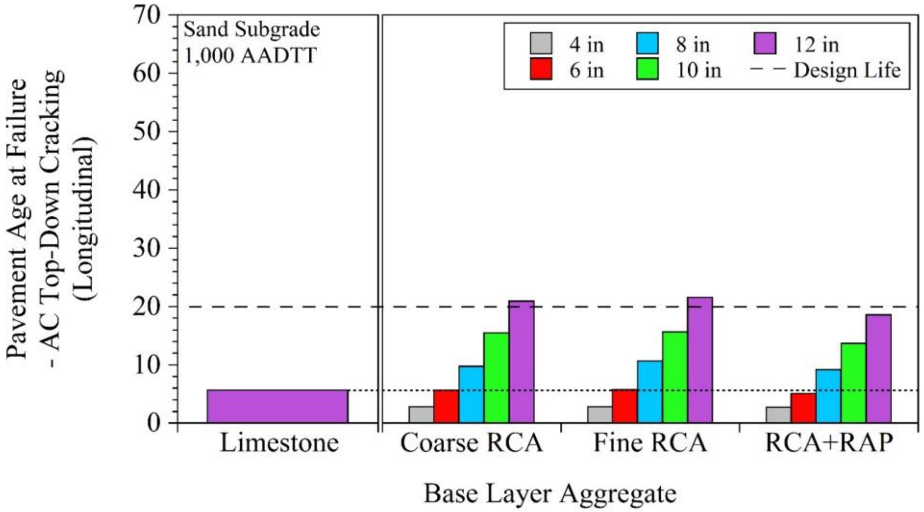




TASK 7

- Pavement ME performance models
  - Relative base layer thickness - longitudinal cracking





TASK 7

- Pavement ME performance models
  - Relative base layer thickness - summary

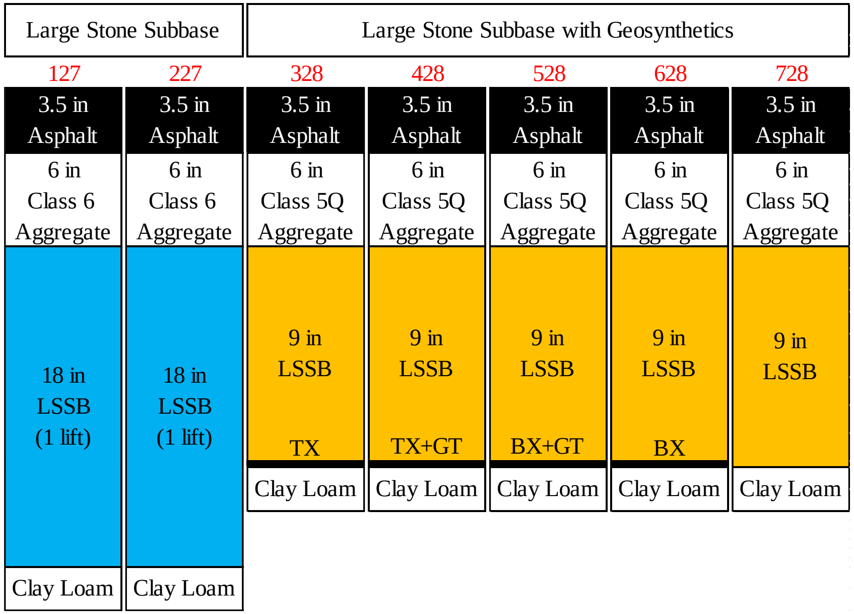
100 AADTT	Recycled Aggregate Base Layer Thickness Alternative to 12 in Limestone (in)							
	Alternative Material	Based on IRI		Based on Rutting		Based on Alligator Cracking		Based on Longitudinal Cracking
		Sand Subgrade	Clay Subgrade	Sand Subgrade	Clay Subgrade	Sand Subgrade	Clay Subgrade	Sand Subgrade
	Coarse RCA	12	10	10	6	4	4	6
	Fine RCA	10	6	10	4	4	4	6
	RCA+RAP	10	4	10	4	4	4	8

500 AADTT	Recycled Aggregate Base Layer Thickness Alternative to 12 in Limestone (in)							
	Alternative Material	Based on IRI		Based on Rutting		Based on Alligator Cracking		Based on Longitudinal Cracking
		Sand Subgrade	Clay Subgrade	Sand Subgrade	Clay Subgrade	Sand Subgrade	Clay Subgrade	Sand Subgrade
	Coarse RCA	12	8	10	6	4	4	6
	Fine RCA	8	6	10	4	4	4	6
	RCA+RAP	8	6	10	4	4	4	8

1,000 AADTT	Recycled Aggregate Base Layer Thickness Alternative to 12 in Limestone (in)							
	Alternative Material	Based on IRI		Based on Rutting		Based on Alligator Cracking		Based on Longitudinal Cracking
		Sand Subgrade	Clay Subgrade	Sand Subgrade	Clay Subgrade	Sand Subgrade	Clay Subgrade	Sand Subgrade
	Coarse RCA	8	6	10	6	4	4	6
	Fine RCA	6	6	10	4	4	4	6
	RCA+RAP	6	4	10	4	4	4	8

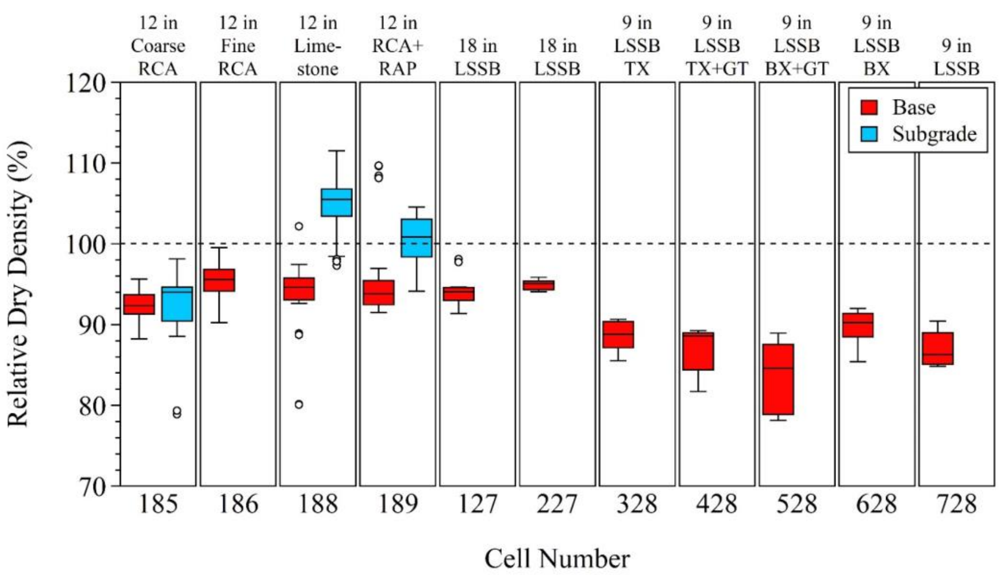
TASK 7

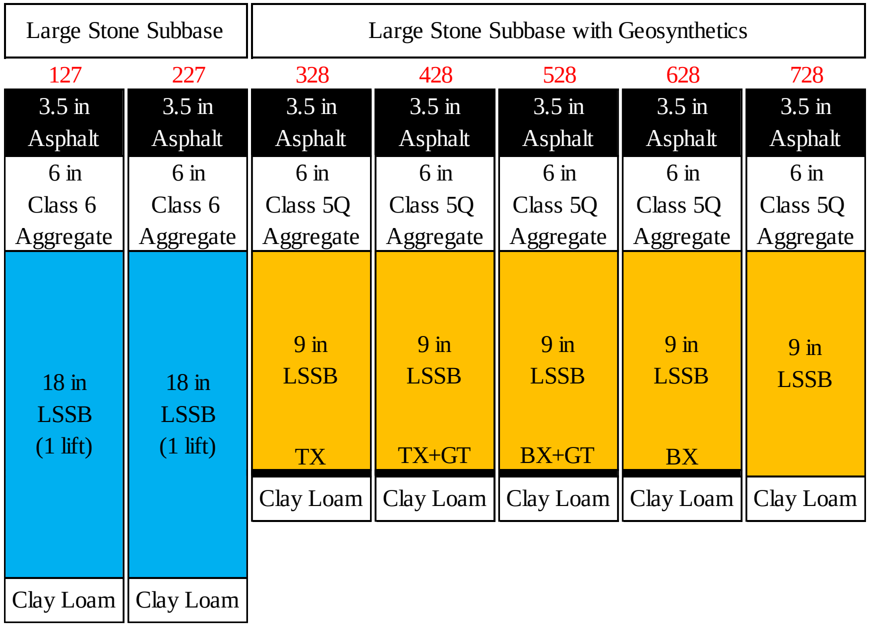
- Pavement ME performance models
  - LSSB groups
    - LSSB thickness
      - 18 in (original thickness)
      - 15 in
      - 12 in
      - 9 in (original thickness)
    - LSSB M_R
      - 10,000 psi (69 MPa)
      - 30,000 psi (207 MPa)
      - 50,000 psi (345 MPa)
    - Base layer type
      - Class 6 aggregate
      - Class 5Q aggregate
    - Subgrade type
      - Clay loam subgrade



TASK 7

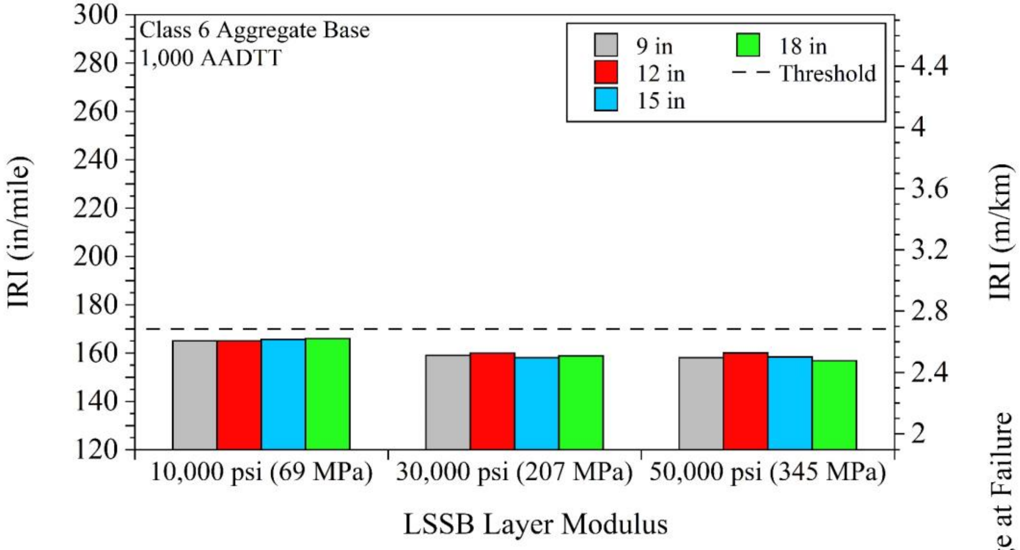
- Pavement ME performance models
  - Large stone subbase groups
    - Problems
      - Lack of information for LSSB (MR, LL, PI, MDD, K_{sat}, OMC)
      - No geosynthetic application in Pavement ME
      - Lower field degree of compaction for aggregate base layers

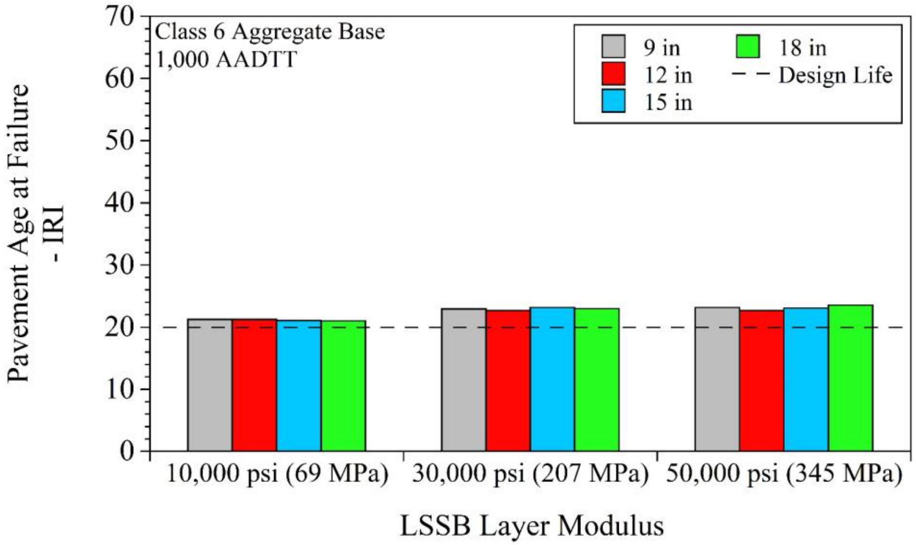




TASK 7

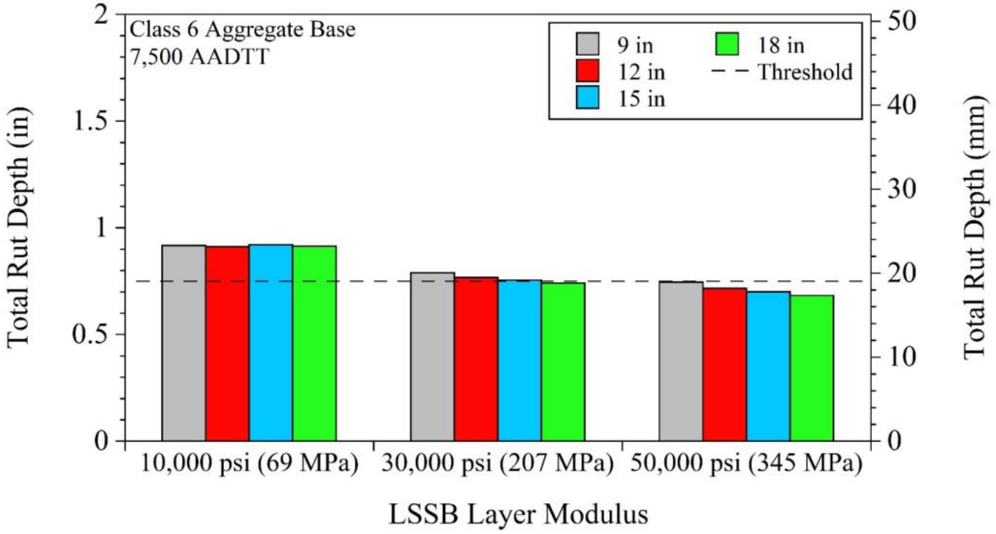
- Pavement ME performance models
  - Effect of LSSB thickness
    - Thickness ↑ IRI ↔ pavement age at alligator failure ↔

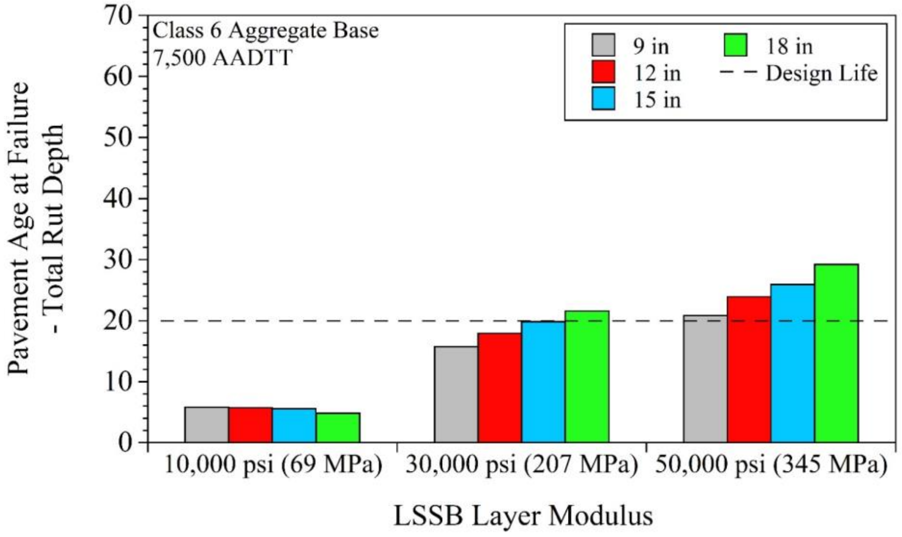




TASK 7

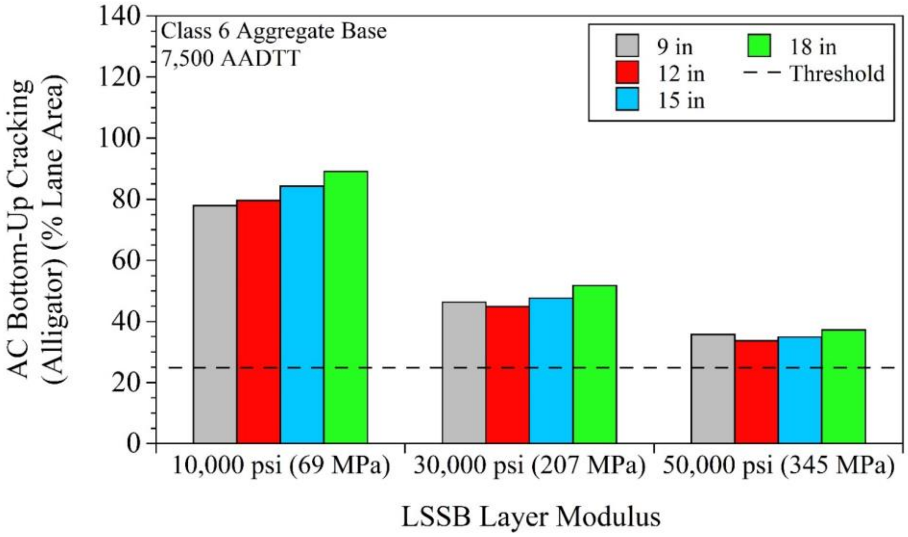
- Pavement ME performance models
  - Effect of LSSB thickness
    - Thickness ↑ rutting ↓ pavement age at rutting ↑ [not for 10,000 psi (69 MPa)]

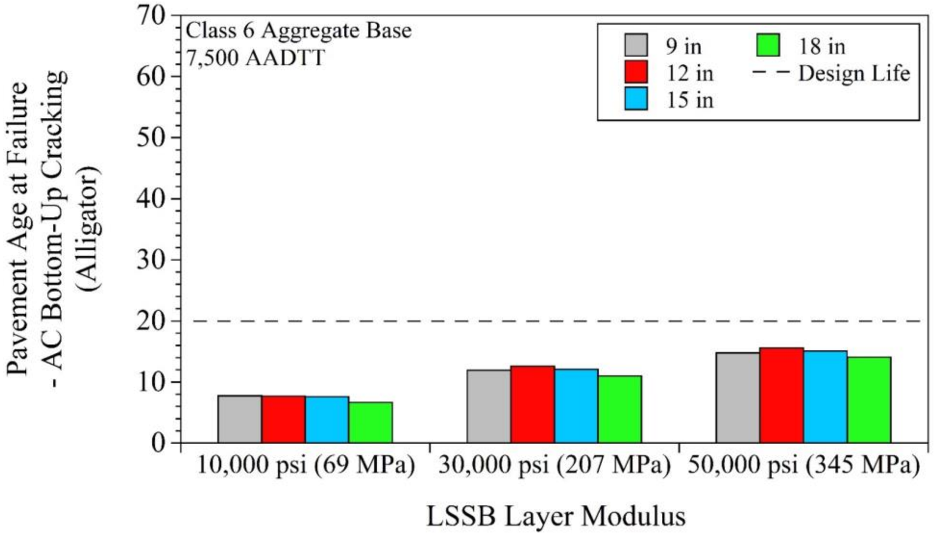




TASK 7

- Pavement ME performance models
  - Effect of LSSB thickness
    - Thickness ↑ alligator cracking ↑ pavement age at alligator failure ↔





CONCLUSIONS & RECOMMENDATIONS

- Material selection for aggregate base layers
  - Water absorption capacity
    - Fine RCA > coarse RCA > class 5Q aggregate > RCA+RAP > class 6 aggregate > limestone
    - Water content ↑ frost heave & thaw settlement ↑ F-T durability ↓
    - Mixing RAP with RCA to reduce hydrophilicity
  - Abrasion
    - Granularity ↑ breakage potential ↑
    - Granularity ↑ + residual mortar content ↑ + roundness ↓ total breakage ↑
    - Class 5Q aggregate > coarse RCA > fine RCA > class 6 aggregate > RCA+RAP > limestone
    - Abrasion ↑ permeability ↓
    - Abrasion ↑ unhydrated cement content ↑ tufa formation ↑
    - Lower degree of compaction to avoid excessive RCA abrasion
    - Gradation characteristics after laboratory compaction

CONCLUSIONS & RECOMMENDATIONS

- Material selection for aggregate base layers
  - Permeability
    - Fine RCA > class 5Q aggregate > coarse RCA > RCA+RAP > class 6 aggregate > limestone
    - Porosity ↑ permeability ↑
  - Laboratory M_R
    - Coarse RCA > fine RCA > RCA+RAP > limestone
    - Longer curing period
      - Standard 7-day curing
      - Standard 28-day curing
      - Accelerated 7-day curing at 105°F to simulate 28-day curing

CONCLUSIONS & RECOMMENDATIONS

- Material selection for aggregate base layers
  - Based on Tasks 5 & 6, the following material selection was recommended:
    1. Fine RCA
    2. Coarse RCA
    3. RCA+RAP
    4. Limestone

Recycled Aggregate Base

185	186	188	189
3.5 in Asphalt	3.5 in Asphalt	3.5 in Asphalt	3.5 in Asphalt
12 in Coarse RCA	12 in Fine RCA	12 in Limestone	12 in RCA+RAP
3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow
Sand	Sand	Clay Loam	Clay Loam

CONCLUSIONS & RECOMMENDATIONS

- Recycled aggregate base design - general
  - RCA base layers - lower thickness than limestone
  - Drainage improvement for RCA base layers due to high absorption
    - More permeable subbase layer
    - Geosynthetic(s) between base and subbase layers

CONCLUSIONS & RECOMMENDATIONS

- Recycled aggregate base design - inputs

Parameter		Coarse RCA	Fine RCA	Limestone	RCA+RAP	Class 6 Aggregate	Class 5Q Aggregate
AASHTO Classification		A-1-a	A-1-a	A-1-b	A-1-a	A-1-a	A-1-a
Layer Thickness (in)		12	12	12	12	6	6
Poisson's Ratio		0.35	0.35	0.35	0.35	0.35	0.35
M_R (psi)		18128.98	17760.86	13926.32	16487.71	16478.93 (Estimated)	18651.14 (Estimated)
LL		NA	32.7	17.9	27.4	27.4	NA
PI		NP	NP	NP	NP	NP	NP
Corrected MDD (pcf)		128.6	121.7	143.2	125.8	128.5	128
K_{sat} (ft/hr)		3.15E-02	5.73E-02	5.74E-03	2.44E-02	2.26E-02	3.44E-02
★ Combined OD G_s		2.25	2.17	2.66	2.28	2.35	2.28
Corrected OMC (%)		9.48	11.07	6.28	9.97	8.26	9.63
★ Percent Passing (%)	No. 200	3.42	7.11	15.06	8.55	6.27	3.24
	No. 100	5.28	10.82	20.09	12.41	9.27	4.83
	No. 60	7.59	15.01	23.80	17.17	14.58	6.84
	No. 40	11.36	21.07	27.12	24.23	23.94	10.42
	No. 20	18.15	30.56	30.49	32.57	37.10	15.76
	No. 10	26.69	43.57	35.87	43.55	49.30	22.84
	No. 4	38.27	61.68	47.72	58.95	64.94	34.11
	3/8 in	53.35	81.02	64.66	75.80	79.91	48.38
	3/4 in	75.38	99.65	94.99	99.30	98.33	76.07
	1 in	85.11	100.00	100.00	100.00	100.00	89.32
	1 1/2 in	100.00	100.00	100.00	100.00	100.00	100.00
	2 in	100.00	100.00	100.00	100.00	100.00	100.00
	2.5 in	100.00	100.00	100.00	100.00	100.00	100.00
	3 in	100.00	100.00	100.00	100.00	100.00	100.00

→ Abrasion of RCA may need to be considered. Gradation after laboratory compaction may be required.

→ ASTM C127 & C128 (for G_s and absorption)

CONCLUSIONS & RECOMMENDATIONS

- Recycled aggregate base design - inputs
  - Estimation of M_R (1-day curing) (MPa)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.9121*Residual Mortar Content (%) + 95.0309 (may not be practical)	0.999	0.998	0.5105	4	< 0.05	< 0.05
13.9035*Coarse Absorption (%) + 69.9919	0.993	0.990	1.3203	4	< 0.05	< 0.05
5.4794*OMC (%) + 61.4114	0.981	0.972	2.1925	4	< 0.05	< 0.05
-39.5364*Fine OD G_s + 201.5303	0.970	0.954	2.7988	4	< 0.05	< 0.05
-118.4860*Coarse OD G_s + 409.3854	0.946	0.919	3.7272	4	< 0.05	< 0.05
-8.4659*MDD (kN/m^3) + 284.6113	0.941	0.912	3.8926	4	< 0.05	< 0.05
-143.1262*Coarse SSD G_s + 482.0049	0.917	0.876	4.6148	4	< 0.05	< 0.05
2.4855*Fine Absorption (%) + 95.5617	0.917	0.876	4.6171	4	< 0.05	< 0.05
-56.4223*Combined OD G_s + 246.2814	0.907	0.861	4.8854	4	< 0.05	< 0.05

  - To consider cementation
    - Longer curing period
      - Standard 7-day curing
      - Standard 28-day curing
      - Accelerated 7-day curing at 105°F to simulate 28-day curing

CONCLUSIONS & RECOMMENDATIONS

- Recycled aggregate base design - inputs
  - Estimation of corrected MDD (kN/m^3)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
5.4563*Combined OD G_s - 0.4420*Asphalt Binder Content - Ignition (%) + 8.7018	0.994	0.990	0.1156	6	< 0.05	< 0.05
6.4234*Combined OD G_s + 0.0551*D_{60} (mm) + 4.8986	0.989	0.981	0.1561	6	< 0.05	< 0.05
3.2017*Fine OD G_s - 0.7433*Asphalt Binder Content - Ignition (%) + 15.1387	0.989	0.981	0.1585	6	< 0.05	< 0.05
4.2779*Fine OD G_s + 0.1074*D_{60} (mm) + 10.0510	0.977	0.961	0.2258	6	< 0.05	< 0.05
3.9122*Fine OD G_s + 0.6678*Gravel-to-Sand Ratio + 10.8568	0.970	0.950	0.2555	6	< 0.05	< 0.05
4.3220*Fine OD G_s + 0.1350*D_{50} (mm) + 10.0800	0.968	0.947	0.2634	6	< 0.05	< 0.05
8.5169*Combined SSD G_s - 0.5435	0.964	0.954	0.2448	6	< 0.05	< 0.05
6.4424*Combined OD G_s + 5.2901	0.949	0.936	0.2904	6	< 0.05	< 0.05
-0.6590*Corrected OMC (%) + 26.3182	0.907	0.884	0.3909	6	< 0.05	< 0.05
3.9711*Fine OD G_s + 11.5752	0.829	0.786	0.5303	6	< 0.05	< 0.05
12.4780*Coarse SSD G_s - 11.5034	0.664	0.580	0.7427	6	< 0.05	< 0.05

CONCLUSIONS & RECOMMENDATIONS

- Recycled aggregate base design - inputs
  - Estimation of K_{sat} (cm/sec)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.002991655*Void Ratio - Based on Apparent G_s - 0.000136146*Fine Apparent G_s - 0.000221884	0.999	0.998	7.16E-06	6	< 0.05	< 0.05
0.002534332*Void Ratio - Based on Apparent G_s + 1.77713E-05*Corrected OMC (%) - 0.000611369	0.998	0.996	8.98E-06	6	< 0.05	< 0.05
-0.000189822*Corrected MDD (kN/m^3) + 0.001357674*Combined Apparent G_s + 0.000522604	0.995	0.992	1.25E-05	6	< 0.05	< 0.05
0.00508301*Porosity - Based on Apparent G_s - 0.00084454	0.988	0.985	1.75E-05	6	< 0.05	< 0.05
0.003073*Void Ratio - Based on Apparent G_s - 0.000598	0.986	0.982	1.90E-05	6	< 0.05	< 0.05
-0.000182804*Corrected MDD (kN/m^3) + 0.000933374*Fine Apparent G_s + 0.001538639	0.975	0.958	2.95E-05	6	< 0.05	< 0.05
0.016696071*$e^3/(1+e)$ - 4.0528*E-05	0.956	0.945	3.36E-05	6	< 0.05	< 0.05
5.5193E-05*Combined Absorption (%) - 4.5053E-05	0.914	0.892	4.71E-05	6	< 0.05	< 0.05
7.80017E-05*Corrected OMC (%) - 0.000463028	0.810	0.763	6.99E-05	6	< 0.05	< 0.05
2.90566E-05*Fine Absorption (%) + 3.46191E-05	0.745	0.682	8.10E-05	6	< 0.05	< 0.05
-0.000106*Corrected MDD (kN/m^3) + 0.002409	0.722	0.653	8.46E-05	6	< 0.05	< 0.05

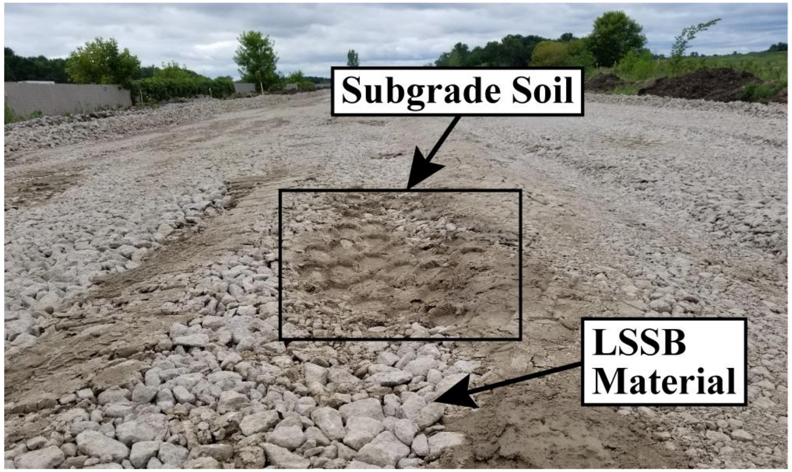
CONCLUSIONS & RECOMMENDATIONS

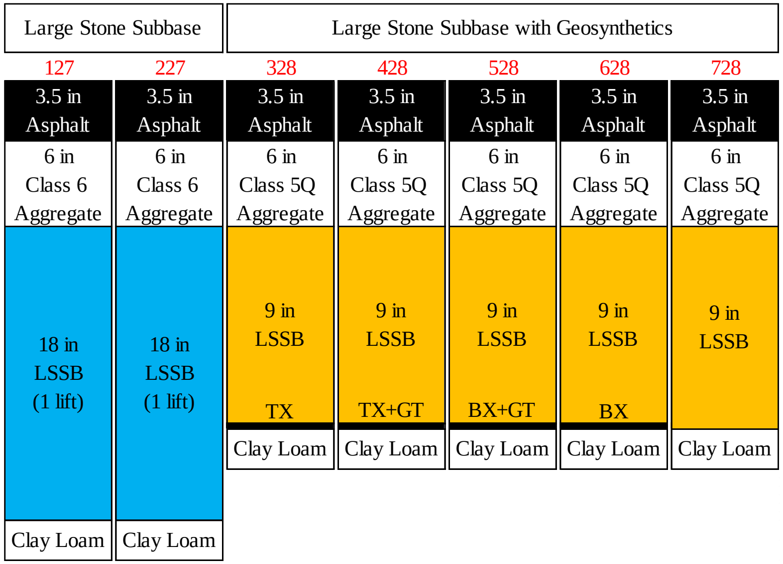
- Recycled aggregate base design - inputs
  - Estimation of corrected OMC (%)

Equation	R^2	Adjusted R^2	Standard Error	Obser-vations	P-value	Signifi-cance F
0.5026*Combined Absorption (%) - 6.0058*Fine Apparent G_s + 22.0333	0.964	0.939	0.4075	6	< 0.05	< 0.05
-9.1895*Combined OD G_s + 30.5418	0.924	0.905	0.5102	6	< 0.05	< 0.05
-8.1230*Fine SSD G_s + 28.2286	0.890	0.862	0.6149	6	< 0.05	< 0.05
-5.9208*Fine OD G_s + 22.1405	0.882	0.853	0.6359	6	< 0.05	< 0.05
-11.7635*Combined SSD G_s + 37.9200	0.880	0.850	0.6415	6	< 0.05	< 0.05
0.5912*Combined Absorption (%) + 5.9768	0.787	0.734	0.8547	6	< 0.05	< 0.05

CONCLUSIONS & RECOMMENDATIONS

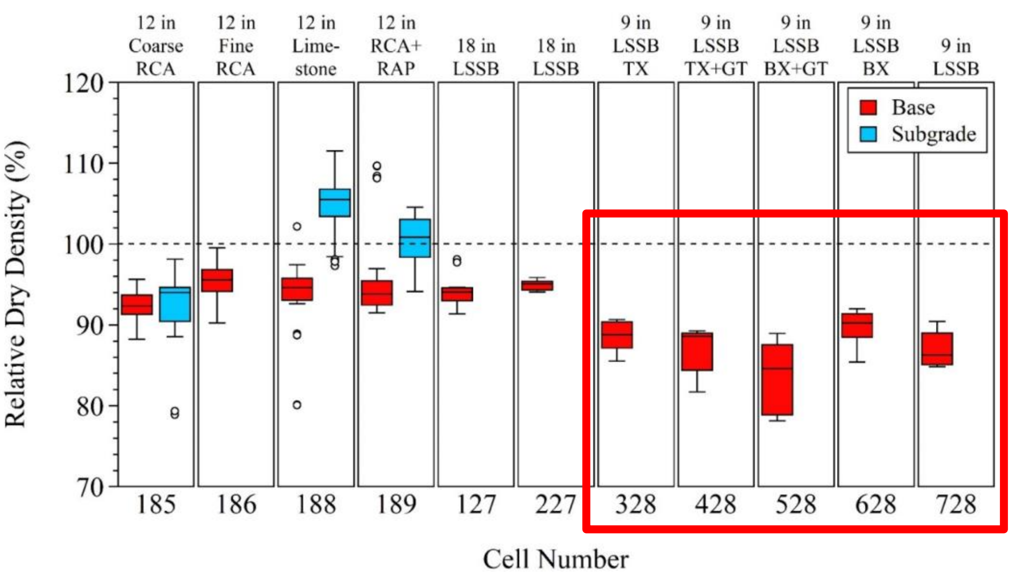
- LSSB design - general
  - Performance of 18 in LSSB > 9 in LSSB
  - Combination of fine RCA base + 18 in LSSB - maximum performance
  - 9 in LSSB
    - Subgrade soil pumping during construction
    - Permeability ↓
    - Geosynthetic(s) in the middle of LSSB layers

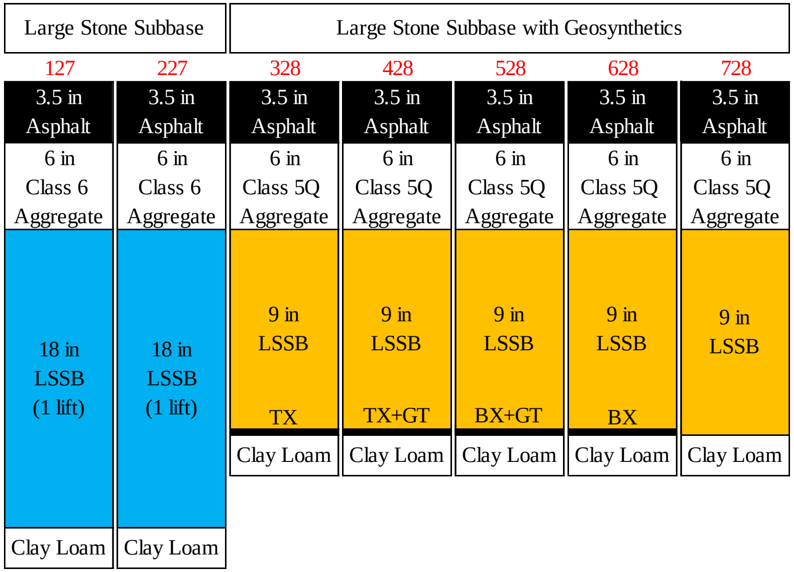




CONCLUSIONS & RECOMMENDATIONS

- LSSB design - general
  - 9 in LSSB - cont'd
    - Lower field DOC for aggregate base layers
    - Instability of thinner LSSB under loading
    - M_R and K_{sat} of aggregate base layers at lower DOC
    - Geosynthetic(s) between aggregate base and LSSB layers





CONCLUSIONS & RECOMMENDATIONS

- LSSB design - inputs

Parameter		LSSB
AASHTO Classification		A-1-a
Layer Thickness (in)		18 or 9
Poisson's Ratio		0.35
M_R (psi)		
LL		
PI		
Corrected MDD (pcf)		
K_{sat} (ft/hr)		
Combined OD G_s		2.60
Corrected OMC (%)		
Percent Passing (%)	No. 200	0.08
	No. 100	0.14
	No. 60	0.18
	No. 40	0.23
	No. 20	0.29
	No. 10	0.36
	No. 4	0.42
	3/8 in	0.94
	3/4 in	6.28
	1 in	13.15
	1 1/2 in	35.84
	2 in	70.21
	2.5 in	96.89
	3 in	100.00

Lack of information for LSSB

Size limitations of lab equipment

No standard

Thank You!

QUESTIONS??