Mechanistic Investigation of Granular Base and Subbase Materials A Saskatchewan Case Study

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ABSTRACT

Saskatchewan Highways and Transportation commonly specify three types of subbase course and three types of base course materials for conventional road building. These specifications are primarily based on grain size and were developed years ago at a time of lower variation in pit run quality. Today, Saskatchewan Highways and Transportation are experiencing reduced pit run availability and increased variability in pit run quality, especially with respect to fines content. This is resulting in higher pit wastage and with the increased opportunity for undesirable material, there is a higher risk for varied performance in the field. At the same time, traffic loadings have exceeded the original safety margin incorporated into the empirical based granular specifications used today.

This study investigated a mechanistic characterization protocol of typical Saskatchewan Highways and Transportation specified granular materials to quantify any significant difference that exist may in the mechanistic behaviour as a function of fines content, moisture content and cement modification.

Samples were characterized using unconfined compressive strength and dynamic frequency sweep analysis to characterize the relative elastic and inelastic bulk behaviour of the various granular materials. Based on the findings of this research, significant variability in the mechanical behaviour of typical Saskatchewan specified granular materials was observed across varied fines content and cement treatment under typical Saskatchewan field state conditions.

Key Words: granular subbase and base, frequency sweep characterization, cement modified granulars

INTRODUCTION

Aggregate materials are the primary road strengthening material systems used today. However, aggregates are also a non-renewable natural resource. Many highway agencies in North America are experiencing depletion of high quality aggregate sources and are now considering the use of marginal quality aggregates. However, many marginal quality aggregate sources have the risk of higher pit wastage, poor performance in the field, and may require modification in order to ensure adequate field performance.

To illustrate, in summer of 2002, a high fines content base course was mistakenly placed on Highway 11-06 near Craik, Saskatchewan as a granular base overlay on a full depth asphalt concrete pavement. Shortly after placing the bottom lift of asphalt concrete over the high fines base course, localized failures began to appear as illustrated in Figure 1. As a result, Saskatchewan Highways and Transportation began a forensic structural evaluation of Control Section 11-06 in an attempt to determine the cause of the failures. As part of the forensic testing, non-destructive structural assessment included a ground penetrating radar and falling weight deflection survey. From the non-destructive testing, back-calculated moduli of the granular base is summarized in Table 1 and illustrated in Figure 2. The base moduli was found to range from 284 MPa to 7812 MPa, resulting in a coefficient of variance in the granular base moduli of 147.3 percent. This clearly shows that low quality base can have a detrimental effect on the mechanical behaviour of the granular base in the field.

Cement Modified Granular Materials

In time, cement treatment of soils has gained wider usage and became an important tool for road engineers. The addition of cementitious and pozzolanic binders has been widely used for the construction of pavements (1), even as the load-bearing structure itself (3). As a result, one design option when confronted with marginal granular materials is to modify the granular material with cementitious binders to reduce the plasticity and improve the mechanical performance. Nevertheless, the research of cement-stabilized roads usually has been limited to conventional geotechnical parameters such as Atterberg limits, or unconfined compressive strength (4).

The traditional approach to designing cement-treated bases has usually been to reduce the plasticity of high fines content granular materials and/or target an empirical unconfined compressive strength. However, this approach may not always be directly mapped to performance in the field in terms of cracking, climatic durability, and structural integrity, especially across varied soil types, field conditions, fines contents and cement contents.

STUDY OBJECTIVE

The objective of this research was to investigate mechanistic laboratory characterization methods to study the climatic and mechanical behaviour of different quality granular materials typically used for Saskatchewan base and subbase layers, with and without cement modification. The hypothesis of this research was increased fines content reduce the mechanical and climatic performance of granular materials and cement-treatment improves the mechanical and climatic behaviour of granular materials.

STUDY SCOPE

This research investigated the effect of fines content, moisture content and cement modification on typical Saskatchewan granular base and subbase materials. The characterization methods employed in this research included moisture susceptibility, unconfined compressive strength, California bearing ratio, and triaxial frequency sweep testing. Triaxial frequency sweep characterization was used to measure three linear visco-elastic material properties: dynamic modulus, Poisson's ratio and phase angle. As well, a duplicate set was mechanistically characterized after saturation. Statistical analysis was employed to quantify partial correlation coefficients between independent and dependent variables, and to identify the materials that did not yield statistically significant different behaviour.

This research was performed across four granular types as summarized in Table 2. The poor graded materials were created by adding a total of 10 percent medium plastic clay fines to the well graded Type 33 base and Type 10 subbase granular materials. This level of fines content was selected to simulate the material properties experienced on Control Section 11-06. Continuum specimens of 150 mm diameter and 150 mm height were prepared at standard Proctor optimum moisture content and dry density as determined per ASTM D697, with and without cement modification, as summarized in Table 2.

Climatic Moisture Characterization

Climatic characterization was performed by providing samples with access to free water and measuring the resulting sample conductivity over time (5). Figure 3 illustrates the plateau conductivity values across the samples without cement modification. As seen in Figure 3, the plateau conductivity (moisture susceptibility) was higher for the granular base and subbase materials with increased fines content.

Unconfined Compressive Strength Characterization

After climatic moisture content characterization, the samples were subjected to unconfined compressive strength characterization. The stiffness and toughness at ultimate strength were also calculated across the samples. The unconfined compressive strength properties obtained are illustrated in Figure 4, Figure 5 and Figure 6.

As summarized in Figure 4, samples containing no cement modification exhibited no unconfined compressive strength, stiffness or toughness. The unconfined compressive stiffness of the well graded base, poor graded base, well graded subbase and poor graded subbase samples with three percent cement were 1091 kPa, 613kPa, 1001 kPa and 432 kPa respectively. Therefore, gradation was found to influence the mechanical stiffness of the cement treated granular materials. As summarized in Figure 5, ultimate strength for the well graded base, poor graded base well graded subbase and poor graded subbase samples with three percent cement were 15388 Pa, 4411 Pa, 4592 Pa and 2811 Pa respectively. As summarized in Figure 6 toughness at ultimate strength for the well graded base, poor graded base, well graded subbase and poor graded subbase samples with three percent cement were 124.4 J/m^3, 22.3 J/m^3, 10.9 J/m^3 and 11.1 J/m^3 respectively.

Of the unconfined compressive test parameters, toughness at ultimate strength appeared to be the most sensitive material property that correlates with empirical performance observation in the field. This indicates that the well graded base material would have considerably better field performance across the samples if modified with cement. However, the unconfined compressive strength characterization of the unmodified granular materials yielded no results. Therefore, unconfined compressive strength is not a good characterization measure of field performance across various quality granular materials.

California Bearing Ratio Characterization

Given the limitations of unconfined compressive strength testing of granular materials, California bearing ratio (CBR) is currently used by Saskatchewan Department of Highways as a material classification system for structural design purposes. As a result, soaked CBR characterization was performed across the various granular samples considered in the study. As can be seen in Figure 7, significant reduction in the CBR of Type 33 Saskatchewan base (from 33 percent to 1 percent) occurred if the total plastic clay fines increased to ten percent by total dry weight. The CBR of well graded base material increased from 33 percent to 171 percent with cement modification. The CBR of poor graded base material increased from 1 percent to 95 percent with cement modification. The CBR of well graded subbase material increased from 5 percent to 28 percent with cement modification. The CBR of poor graded subbase material increased from 3 percent to 25 percent with cement modification. Therefore, fines content and cement modification appears to have a considerable impact on the CBR value of granular materials.

Triaxial Frequency Sweep Characterization

As seen previously, unconfined compressive strength characterization of unmodified granular materials is inconclusive. California bearing ratio testing is a purely empirical-phenomenological test method whose results cannot be used in a mechanistic road modeling framework. As a result, triaxial frequency sweep characterization was investigated in this study across the various granular materials in an attempt to develop a more mechanistic based characterization of modified and unmodified granular materials.

All the specimens tested in the frequency sweep characterization were characterized at four applied traction states, as summarized in Table 3. The range of applied tractions was chosen to simulate typical field loading conditions and the resultant stress states common within granular layers. The first invariant of stress tensor (I_1) ranged from 450 kPa to 1200 kPa, and the second invariant of deviatoric stress tensor (J_2) ranged from -16875 kPa to -120000 kPa. The range of applied frequency was chosen to simulate typical traffic speeds ranging from near highway speeds to slow speeds.

Data recorded from each frequency sweep test was used to calculate dynamic modulus, Poisson's ratio and phase angle. If a specimen failed, during the frequency sweep characterization, values of 0 kPa, 0.9, and 25 degrees were assigned for dynamic modulus, Poisson's ratio and phase angle, respectively.

As seen in Figure 8, Figure 9 and Figure 10, all saturated specimens without cement failed the triaxial frequency sweep test. In addition, the poor graded base and subbase, as well as the well graded Saskatchewan subbase without cement at optimum water content failed in the triaxial frequency sweep test. This mechanical behaviour clearly illustrates that moisture content and grain size has a significant impact on the mechanical behaviour of granular base when characterized across test conditions representative of field state conditions. These results from the triaxial frequency sweep test also correlate with empirical performance observations of Control Section 11-06.

The mechanical behaviour of all specimens with three percent cement at optimum moisture improved significantly with a dynamic modulus ranging from 232 kPa to 1145 kPa. As seen in Figure 9, all specimens with three percent cement at optimum moisture as well as saturation exhibited a significant decrease in Poisson's ratio, ranging from 0.028 to 0.366.

As seen in Figure 10, the good granular base materials without cement at optimum moisture yielded a relatively high phase angle ranging from 13.24 degrees to 17.99 degrees. All specimens with three percent cement at optimum moisture and saturated water content exhibited a significant reduction in phase angle from 0.03 degrees to 0.37 degrees.

Based on the above observed mechanistic behaviour of the granular materials in the triaxial frequency sweep test, it could be concluded that significant performance improvements existed across the granular materials as a function of reduced fines content, reduced moisture content, and cement modification across simulated field state conditions.

STATISTICAL ANALYSIS OF FREQUENCY SWEEP CHARACTERIZATION:

To statistically validate the performance observations across the laboratory characterization results, a statistical analysis of variance (ANOVA) was performed across all materials evaluated. The independent and dependent variables considered in the ANOVA are summarized in Table 3.

Figure 11 illustrates the partial correlation coefficients of the dependent variables (dynamic modulus, Poisson's ratio and phase angle) across the independent variables (material category, cement content, moisture, stress state, and load frequency). As seen in Figure 11, the correlation coefficients between all dependent variables and the independent variables with the exception of cement modification are relatively low. In addition, the correlation coefficient for the dependent variable dynamic modulus is of opposite sign of the correlation coefficients across the dependent variables. This is consistent with observed behaviour of the materials in that, specimens with low Poisson's ratios and phase angles yielded high dynamic modulus, and specimens with high Poisson's ratio and phase angles yielded low dynamic modulus or failed. As also seen in Figure 11, the correlation coefficients between all dependent variables and the independent variable cement modification are the most significant ranging from 0.686 to -0.889.

To identify which materials yielded statistically significant differences in mechanical behaviour Tuckey's homogenous group analysis was performed at a confidence level of 95 percent. The materials which yielded results not statistically different were grouped in a homogenous group are labeled with a capital letter for that group. Table 4, Table 5 and Table 6 summarize the Tuckey homogeneous grouping for dynamic modulus, Poisson's ratio, and phase angle, respectively. As seen in Table 4, Table 5 and Table 6, cement treatment across the various granular materials showed improved performance as a function of cement modification. In addition, it can be seen that significant difference existed in the mechanical behaviour of each granular material as a function of grain size distribution.

SUMMARY AND CONCLUSIONS

Granular materials are the primary road building material used today. With the depletion of natural quality aggregate resources, road agencies are now considering the use of marginal aggregate sources. However marginal aggregates can exhibit significant reductions in mechanical and climatic durability in the field. Conventional unconfined compressive strength and California bearing ratio do not provide the material constitutive relations required to perform reliable road structural modeling. As a result, triaxial frequency sweep characterization was investigated in an attempt to develop a more mechanistic based characterization of various granular materials

The objective of this research was to investigate mechanistic based laboratory methods to study the climatic and mechanical behaviour of different quality granular materials at different moisture contents with and without cement modification. The hypothesis of this research was increased fines content and moisture reduced the mechanical and climatic behaviour of granular materials and cement-treatment improves the mechanical and climatic behaviour of granular materials.

All granular base materials without cement at saturated water conditions failed in the frequency sweep testing, illustrating that even road bases and subbases constructed with good quality materials are susceptible to poor performance under unfavourable moisture conditions. All granular materials treated with three percent cement performed significantly better than untreated granular materials at both optimum and saturated moisture contents. The addition of cement significantly homogenized the mechanical response of all granular materials. These findings show that marginal quality aggregates may be used with higher confidence in road construction when treated with cement binders.

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ACKNOWLEDGEMENTS

The authors would like to thank the Portland Cement Association and the Canadian Association of Cement Producers for sponsoring this research.

Table 1 Moduli Values of Granular Base Layer of Control Section 11-06

Chainage (km)	Granular Base Moduli (MPa)
16.972	456
15.992	407
15.345	421
14.930	6307
14.875	3264
14.738	324
14.222	381
13.754	312
13.683	306
13.287	3144
13.140	7812
13.134	284
13.129	356
13.123	556
13.121	365
Average:	1646
Minimum:	284
Maximum:	7812
Standard Deviation:	2425
Coefficient of Variance (%):	147.3

Table 2 Granular Base Material Types Considered in Study

Material Category	Material	Type
Well Graded Granular	Saskatchewan Well Graded Base	Type 33
	Saskatchewan Well Graded Subbase	Type 10
Poor Graded Granular	Saskatchewan Poor Graded Base	Type 33 w/10 % Fines
	Saskatchewan Poor Graded Subbase	Type 10 w/10 % Fines

Table 3 **Triaxial Frequency Sweep Test Parameters**

Applied Tractions (kPa)				Frequency (Hz)				
Vertical	**Confinement**	I_1	J_2	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Block 5**
300	75	450	-16875	10	5	1	0.5	0.125
400	100	600	-30000	10	5	1	0.5	0.125
600	150	900	-67500	10	5	1	0.5	0.125
800	200	1200	-120000	10	5	1	0.5	0.125

Table 4 Tuckey Homogenous Grouping of Dynamic Modulus

Material	Average Dynamic Modulus (MPa)	Tukey's Homogenous Groups				
0% Cement @ Optimum Moisture						
Saskatchewan Poor Graded Subbase	0	A				
Saskatchewan Well Graded Subbase	0	A				
Saskatchewan Poor Graded Base	0	A				
Saskatchewan Well Graded Base	107		B			
3% Cement @ Saturation						
Saskatchewan Poor Graded Subbase	240			C		
Saskatchewan Well Graded Subbase	298			C		
Saskatchewan Poor Graded Base	836				D	
Saskatchewan Well Graded Base	1379					E

Table 5 Tuckey Homogenous Grouping of Poisson's Ratio

Material	Average Poisson's Ratio	Tukey's Homogenous Groups					
0% Cement @ Optimum Moisture							
Saskatchewan Well Graded Subbase	0.675				D		
Saskatchewan Well Graded Base	0.676				D		
Saskatchewan Poor Graded Subbase	0.900					E	F
Saskatchewan Poor Graded Base	0.900					E	F
3% Cement @ Saturation							
Saskatchewan Well Graded Base	0.058	A	B				
Saskatchewan Poor Graded Base	0.087		B				
Saskatchewan Poor Graded Subbase	0.087		B				
Saskatchewan Well Graded Subbase	0.193			C			

Table 6 Tuckey Homogenous Grouping of Phase Angle

Material	Average Phase Angle (degrees)	Tukey's Homogenous Groups					
0% Cement @ Optimum Moisture							
Saskatchewan Well Graded Base	17.99					E	
Saskatchewan Well Graded Subbase	25.00						F
Saskatchewan Poor Graded Subbase	25.00						F
Saskatchewan Poor Graded Base	25.00						F
3% Cement @ Saturation							
Saskatchewan Well Graded Base	6.47	A	B				
Saskatchewan Poor Graded Base	7.42		B				
Saskatchewan Well Graded Subbase	10.21			C			
Saskatchewan Poor Graded Subbase	11.92				D		

Figure 1 Sample Failure of Control Section 11-06

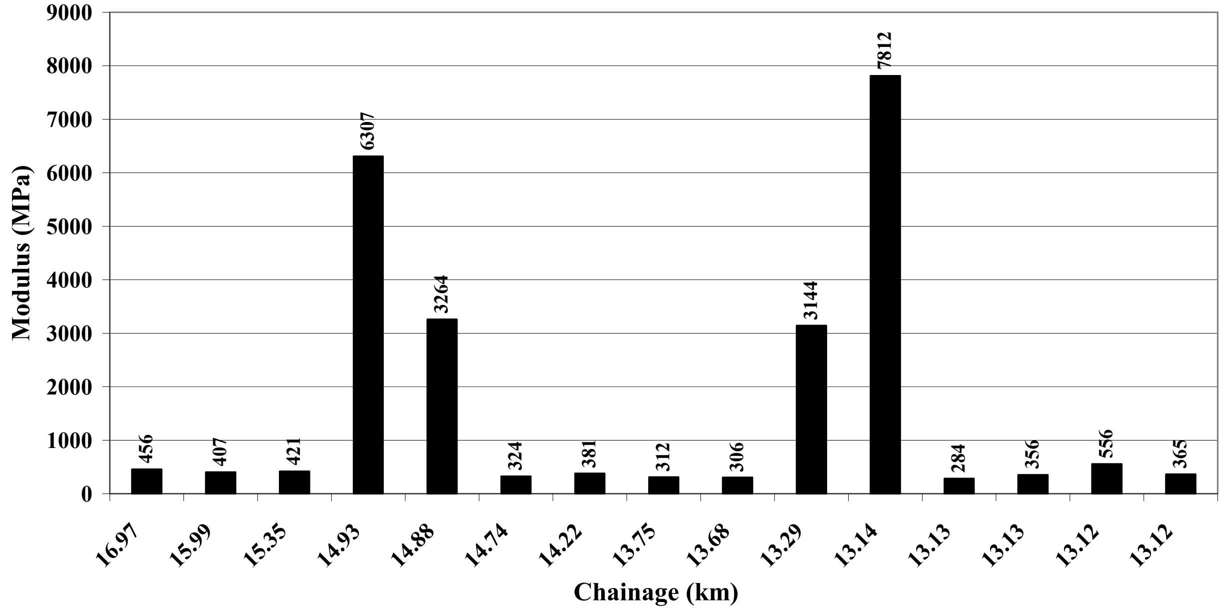

Figure 2 **Granular Base Moduli Profile of Control Section 11-06**

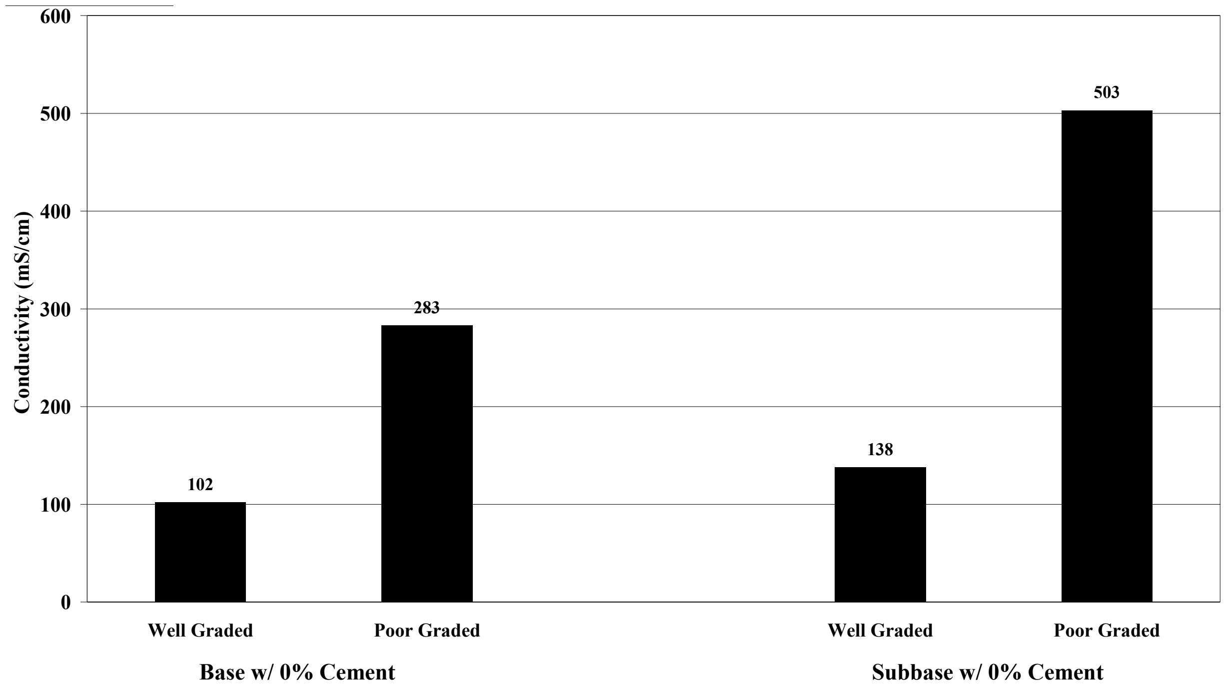

Figure 3 Plateau Conductivity of Saturated Granular Materials

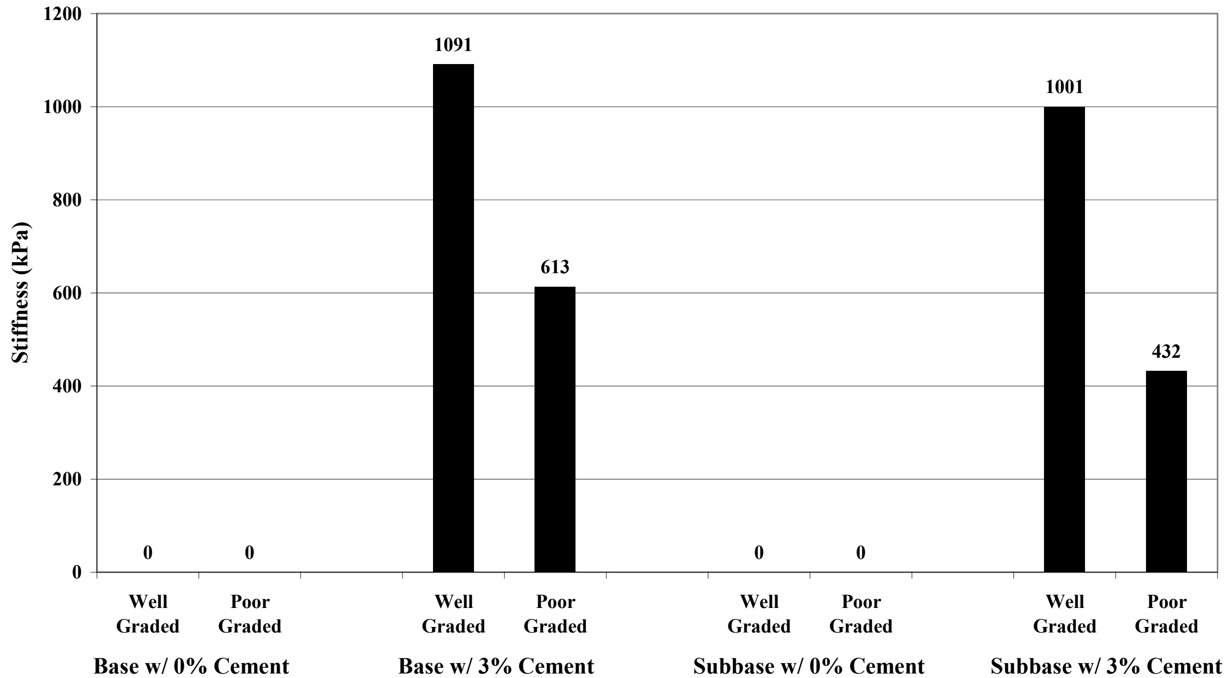

Figure 4 Unconfined Compressive Stiffness

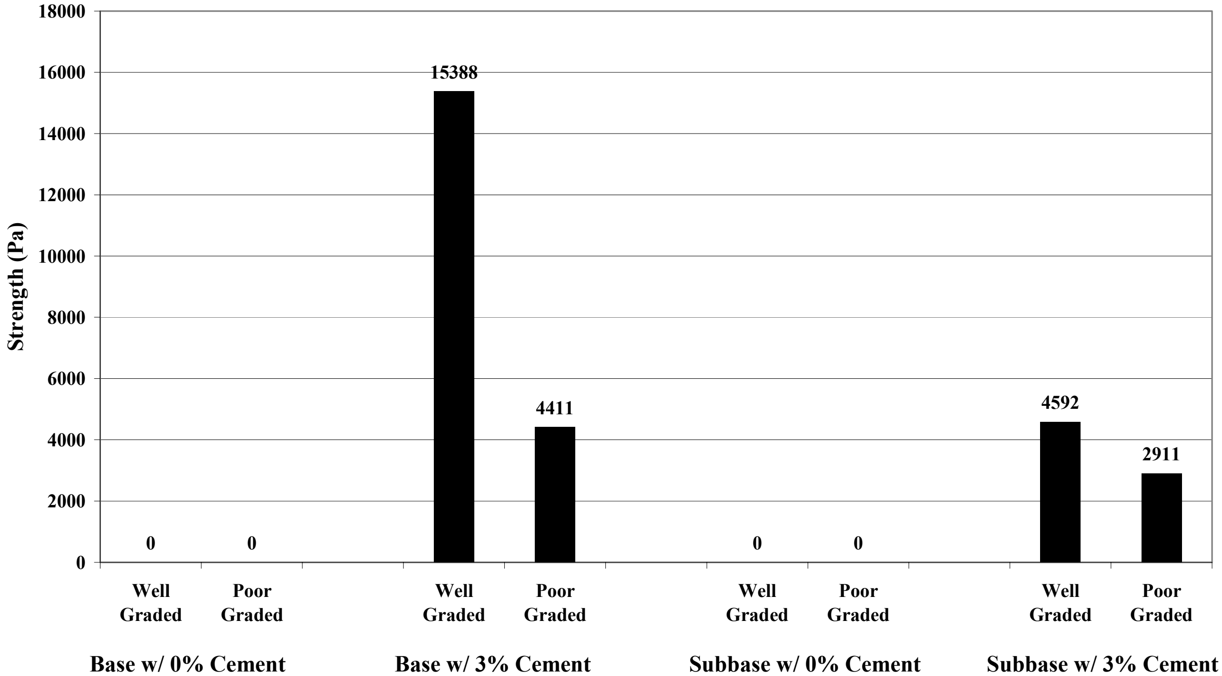

Figure 5 Unconfined Compressive Strength

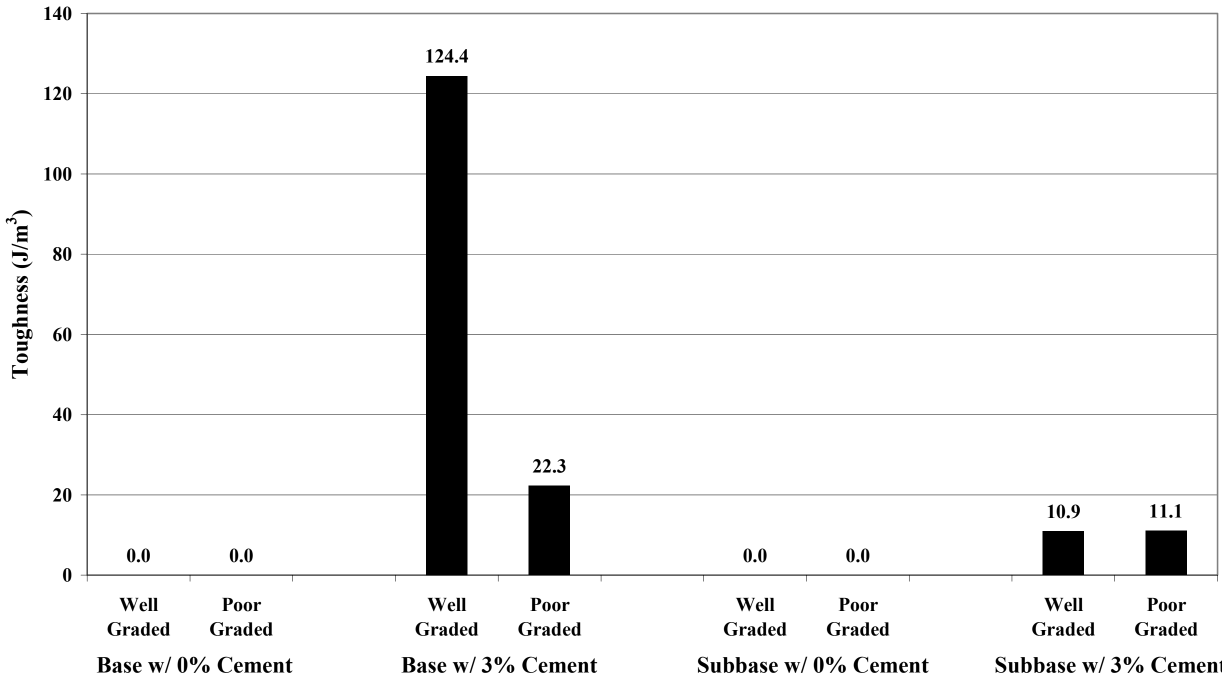

Figure 6 Unconfined Compressive Toughness at Ultimate Strength

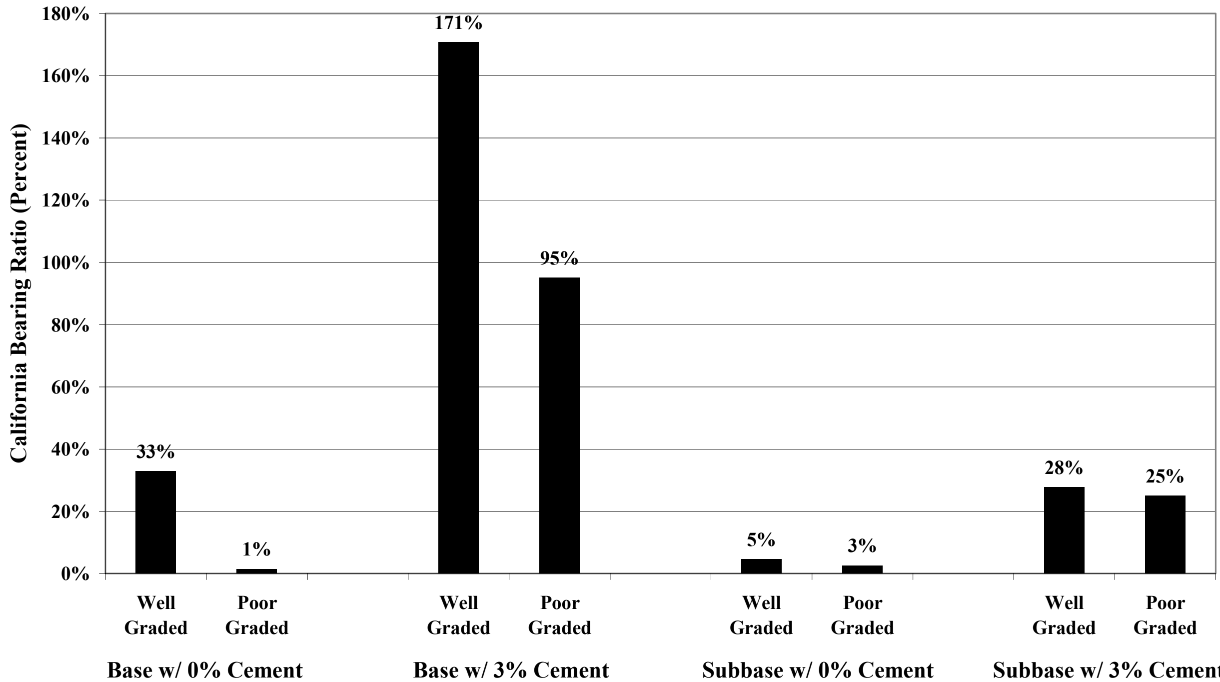

Figure 7 California Bearing Ratio

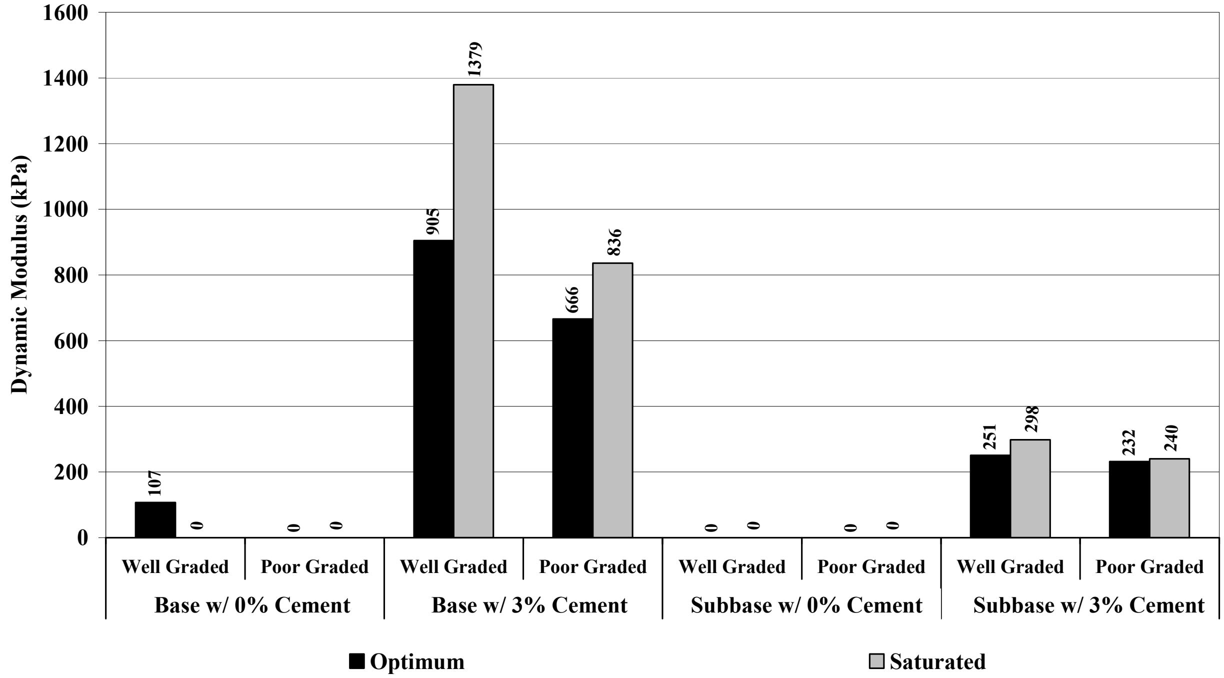

Figure 8 Mean Dynamic Modulus across Stress State and Frequency

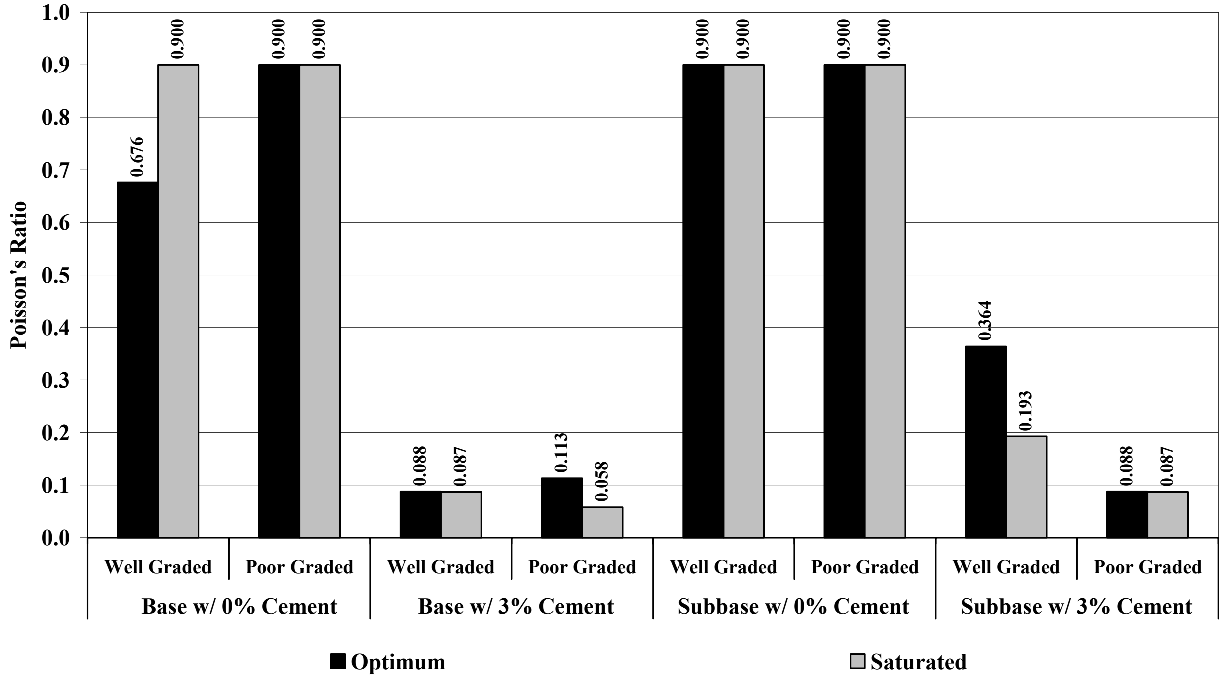

Figure 9 **Mean Poisson's Ratio across Stress State and Frequency**

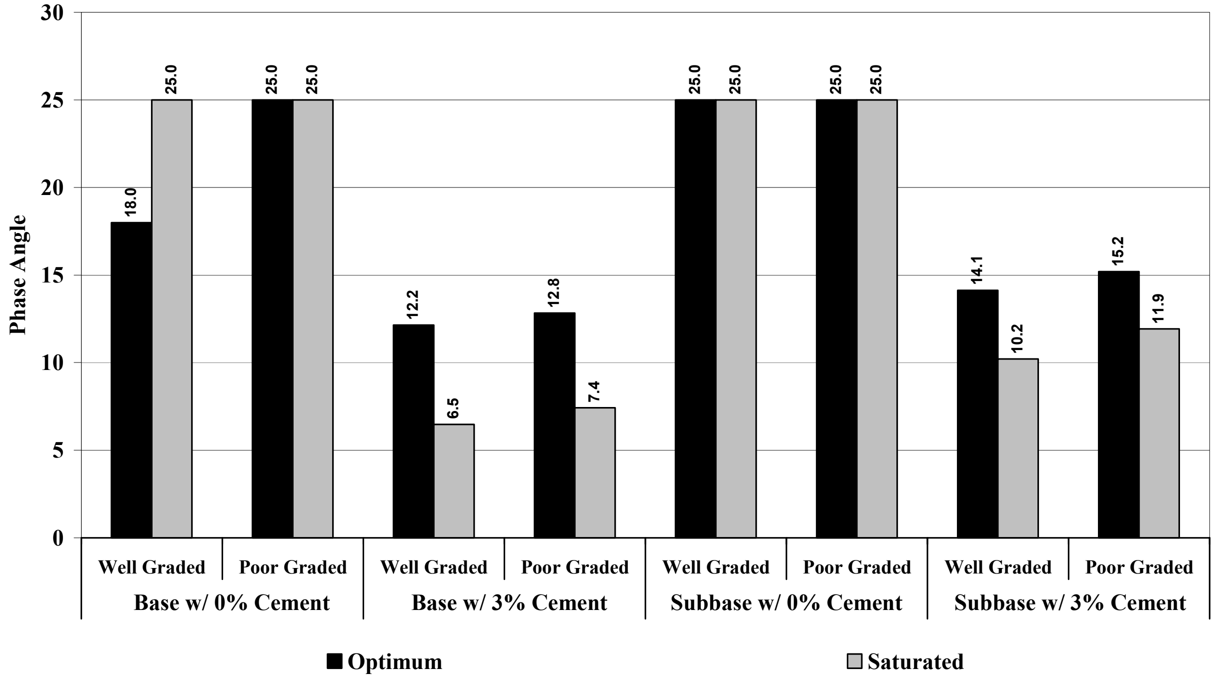

Figure 10 Mean Phase Angle across Stress State and Frequency

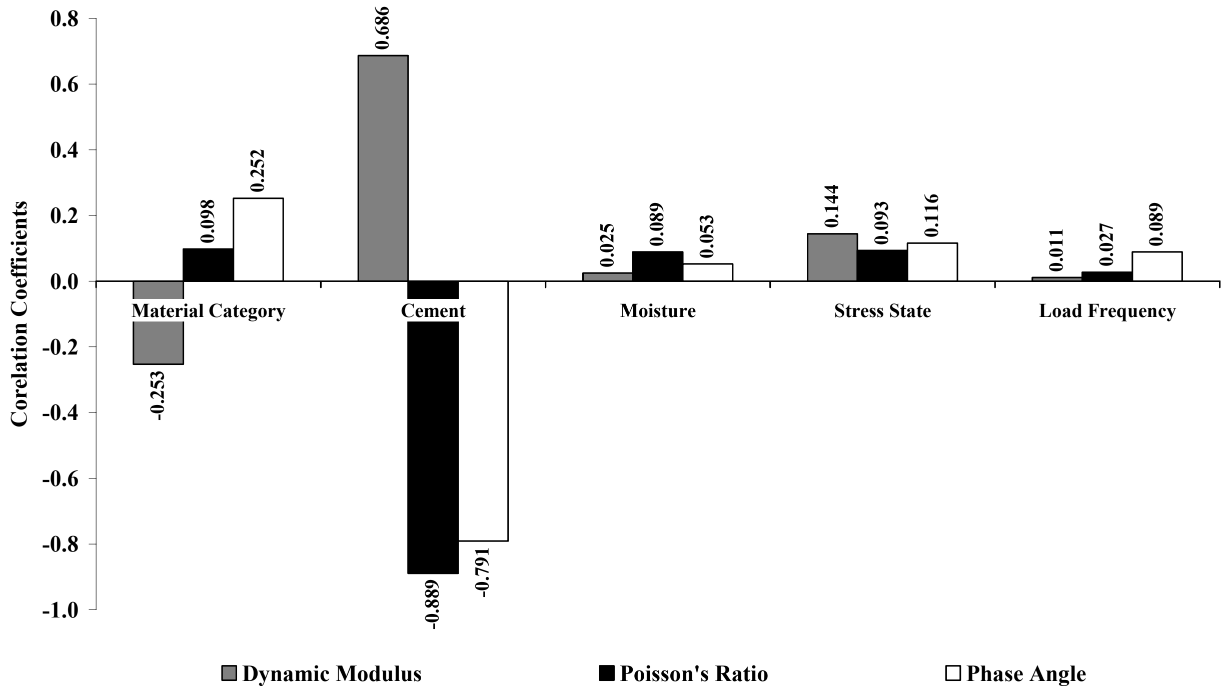

Figure 11 Partial Correlations of the Dependent Variables with the Independent Variables