Material Characterization and Inherent Variation Analysis of Soil-Cement Field Cores

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A knowledge of the variation in fundamental engineering properties of the various construction materials is essential for a comprehensive evaluation of the performance of various road sections. Support is provided for the Louisiana Experimental Base Project, an in-service experimental road project constructed to aid in an evaluation of design performance characteristics of a number of experimental test sections. The expected variation in the static and resilient (fatigue) properties of the materials that make up the layers of the pavement structure can provide an inherent variation data base from which continuing evaluation and analysis of pavement behavior and performance of these layers can be undertaken. Results are presented of material characterization and inherent analysis of a resilient (fatigue) test program undertaken to establish the magnitude, scope, and expected variation in fundamental engineering properties of laboratory-prepared specimens and field cores of the cement-stabilized materials used in the base and subbase layers of some of the test sections of the Base Project. Variation analyses were completed for such fundamental properties as modulus, Poisson's ratio, tensile stress, tensile strain, and fatigue cycles to failure. Regression analysis techniques were also used to quantify those factors that significantly affect the fatigue life of the various construction materials used in the Base Project. This information, when combined with the in-service performance results from the Base Project, should produce a better knowledge of the important mix variables affecting the fundamental engineering performance properties, which should result in changes and improvements in quality control measures.

Knowledge of the magnitude, scope, and expected variation in the fundamental engineering properties of the various construction materials used in pavement structural sections is essential for a comprehensive evaluation of the performance of roadway sections. Support is provided to the Louisiana Experimental Base Project, an in-service experimental road project constructed to aid in an evaluation of design-performance characteristics of a number of experimental test sections.

A repetitive (fatigue) testing program was undertaken (see Table 1) to establish the magnitude and scope of inherent variation in the fundamental resilient properties of field cores representative of in-service conditions and to develop material characterization information from field cores and laboratory specimens (see Table 2) of the three types of cement-stabilized base materials (sandy soil, sandy loam, and sand-clay-gravel) used in the Base Project.

Regression analysis techniques were used to quantify those factors that significantly affect the fatigue life of the various construction materials used in the Base Project. This information, when combined with the in-service performance results from the Base Project, should produce a better knowledge of the important mix variables affecting the fundamental engineering performance properties and could lead to changes and improvements in quality control measures.

The project is situated on a portion of US-71–167 that accommodates a moderate volume of mixed vehicular traffic. To ensure that the flow of traffic would not be affected by its experimental status, the Base Project was completed as a part of a construction project upgrading US-71–167 to a four-lane facility.

The terrain at the Base Project is generally flat with poor drainage. The subgrade material is basically a fine-grained soil ranging from a silty clay loam to a heavy clay. The range in mean ambient air temperatures is from approximately 39°F (40°C) to 84°F (29°C); the mean annual rainfall is approximately 55 to 60 in. (140 to 150 cm).

The projected average daily traffic at the time of construction was 7,990 vehicles, including approximately 15 percent trucks. All test sections were included in a portion of a newly constructed two-lane roadway adjacent to an existing two-lane highway.

The Base Project consisted of 18 test sections—14 experimental sections and 4 control sections (see Figure 1). The factors investigated in the project included three different base types, four different pavement design lives, and two surface thicknesses. The Control Sections C1 through C4 and Test Sections 2, 4, 6, 8, 9, 10, 12, and 13 all included soil-cement base and subbase layers.

Each test section is approximately 550 ft (168 m) long with a 50-ft (15-m) transition zone interconnecting each adjacent test section. The randomization scheme for locating the various test sections included a complete randomization of the 10- and 15-year design sections, but limited randomization of the 5-year sections. The latter sections were grouped together to allow for maintenance of the 5-year design sections at the same time. Detailed information on the construction of the Base Project is available from the Louisiana Department of Transportation and Development (LA DOTD).

The coring program established for soil-cement base test sections of the Base Project is presented in Table 3. The program was structured to provide for an investigation of the variability in material properties of the various pavement and materials used throughout the Base Project. The coring plan

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TABLE 1 RESILIENT (FATIGUE) TESTING PROGRAM—SOIL-CEMENT FIELD CORES

PAVEMENT LAYER	TEST TYPE	VARIATION EVALUATED	FUNDAMENTAL MATERIAL PROPERTIES ESTIMATES
Soil Cement Bases and Cement Stabilized Sand-Clay-Gravel Base	Repetitive Indirect Tensile Test	Longitudinal - 10' spacing Longitudinal - 1' spacing Lateral - 4' spacing Lateral - 1' spacing Depth - vertical Stress levels - sandy soil 45 to 75 psi sandy loam 35 to 65 psi sand-clay-gravel 20 to 50 psi	N_f, Cycles to Failure E_r, Resilient Modulus μ_r, Resilient Poisson's Ratio ϵ_r, Resilient Tensile Strain S_r, Resilient Applied Tensile Stress

allowed for variational analysis in the longitudinal (along the road), lateral (across the road), and vertical (depth into pavement) directions. In addition, the plan included various spacings of the coring locations to provide for evaluation of inherent variation within close spacings (±1 ft) as well as larger spacings (±10 ft).

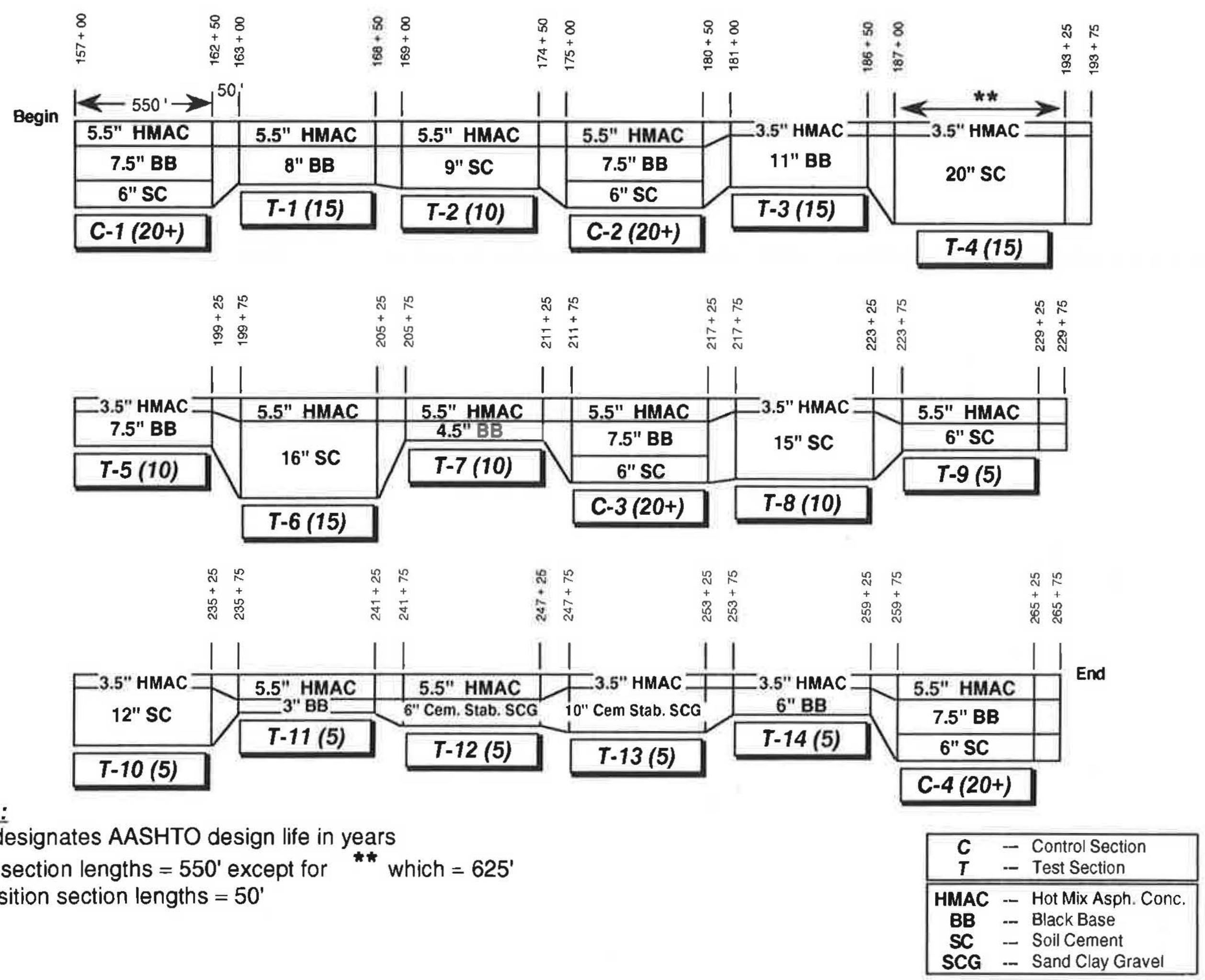
The fundamental engineering properties investigated in this phase included resilient modulus, resilient Poisson's ratio, and cycles to failure (Log N_f). Because the specimens were field cores, the only controllable variable that could actually be varied was the tensile stress repeatedly applied to the specimens during the fatigue test. Properties associated with the cores, such as percent clay balls, percent flushing (concentration or migration of cement to crack or flaw), and total percent flaws, could only be measured sample by sample and could not be established as fixed values. All tests were conducted at a test temperature of 75°F (24°C) and at 1 Hz (sinusoidal waveform).

CONSTRUCTION CONSIDERATIONS

The soil-cement construction procedure used in the construction of the Base Project apparently does not provide a uniform

TABLE 2 RESILIENT (FATIGUE) TESTING PROGRAM—LABORATORY-PREPARED SOIL-CEMENT SPECIMENS

PAVEMENT LAYER	TEST TYPE		FACTORS EVALUATION TYPE EVALUATED	FUNDAMENTAL MATERIAL CHARACTERISTICS ESTIMATES
Soil Cement Base: Sandy soil Sandy loam Sand-Clay-Gravel	Repetitive Indirect Tensile Test	Extended mix cond.		N_f, Cycles to Failure E_r, Resilient Modulus μ_r, Resilient Poisson's Ratio ϵ_r, Resilient Tensile Strain S_r, Resilient Applied Tensile Stress
		a) Cement content	3.6-0.9% sandy soil 5.3-8.8% sandy loam 3.4-6.6% S/C/G	
		b) Moisture content	10.9-17.9% sandy soil 12.0-19.0% sandy loam 12.5-17.3% S/C/G	
		c) Age at test	11 to 365 days	
		d) Delay	0 to 240 minutes	
		e) Stress level	73 to 87% of static strength	



NOTES:

-- ( ) designates AASHTO design life in years
-- Test section lengths = 550' except for ** which = 625'
-- Transition section lengths = 50'

FIGURE 1 Experimental base project layout.

product; in fact the procedure apparently resulted in a number of flaws in the various cement-stabilized base layers. Evidence of this condition can be drawn from the initial LA DOTD coring operation established to obtain 7 and 28 days' cores for job verification purposes. During this coring operation, only 60 intact cores could be obtained from 187 different boring operations (a recovery rate of 32 percent).

Similar results were obtained in the coring program presented in Table 1 where 65 good test specimens were obtained from a total of 154 test specimens (a recovery rate of 43 percent). From this information, it can be postulated that over one-half of soil-cement areas would have internal flaws. Some flaws encountered in the cement-stabilized material include lamination, cracks, compaction planes, cutter planes, flushing (migration of cement to flawed areas), and clay balls. As a result of this condition, the field cores were separated into two groups. One group, called "clear specimens" (having minimum flaws), is representative of those specimens with the percent of cross section of specimen composed of flaws less than approximately 20 percent. The other group, called "flawed specimens," represented those specimens with a percent flawed area exceeding approximately 20 percent. In most cases, the flaws in the cores could not be observed by the naked eye but would become apparent after only a few cycles of the fatigue-resilient test.

INHERENT VARIATION ANALYSIS OF FIELD CORES

The inherent variation information for the clear and flawed specimens is presented in Table 4. In these data, the cement content variability as well as modulus and Poisson's ratio variation are similar for the clear and flawed specimens. In addition, the repeated applied stress and resulting tensile strain are also similar in magnitude. The principal differences, of course, are in the amount of flushing, clay balls, total flaws (percent flushing plus percent clay balls), and, more important, Log N_f (fatigue). There are obvious significant differences between clear and flawed specimens.

The inherent variation information associated with longitudinal, lateral, and vertical directions is presented in Tables 5 and 6 for clear and flawed specimens, respectively. The combined inherent variation is given in the bottom row of each table. Statistical F tests indicated, as expected, a significant difference in variances for resilient modulus, resilient

TABLE 3 RANDOMIZED BORING PLAN—LOUISIANA EXPERIMENTAL BASE PROJECT: SOIL-CEMENT SUBBASES AND BASES

SECTION DESIGNATION	DESIGN LIFE YRS	SAMPLING DIRECTION AND GROUPING	STATION	LANE	COMMENTS
Control 1	20	longitudinal	160 + 24	outside	outside
		within	160 + 25		wheel path
			160 + 26		
Test 1	15	longitudinal	166 + 74	inside	outside
		within	166 + 75		wheel path
			166 + 76		
Test 2	10	longitudinal	171 + 15	outside	outside
		among	171 + 25		wheel path
			171 + 35		
Control 2	20	longitudinal	178 + 15	outside	outside
		among	178 + 25		wheel path
			178 + 35		
Test 4	15	lateral	192 + 25	outside	9′ Rt of CL
		within	192 + 25		10′ Rt of CL
			192 + 25		11′ Rt of CL
Test 6	15	lateral	202 + 00	inside	2′ Lt of CL
		among	202 + 00		6′ Lt of CL
			202 + 00		10′ Lt of CL
Control 3	20	lateral	213 + 50	inside	2′ Lt of CL
		among	213 + 50		6′ Lt of CL
			213 + 50		10′ Lt of CL
Control 3 (cont.)	20	lateral	213 + 50	outside	2′ Rt of CL
		among	213 + 50		6′ Rt of CL
			213 + 50		10′ RT of CL
Test 8	10	longitudinal	221 + 40	outside	outside
		among	221 + 50		wheel path
			221 + 60		
Test 9	5	longitudinal	227 + 99	inside	outside
		within	228 + 00		wheel path
			228 + 01		
Test 10	5	longitudinal	231 + 49	outside	outside
		within	231 + 50		wheel path
			231 + 51		
Test 12	5	lateral	245 + 00	outside	2′ Rt of CL
		among	245 + 00		6′ Rt of CL
			245 + 00		10′ Rt of CL
Test 13	5	longitudinal	251 + 99	outside	outside
		within	252 + 00		wheel path
			252 + 01		
Control 4	20	lateral	261 + 50	outside	9′ Rt of CL
		within	261 + 50		10′ Rt of CL
			261 + 50		11′ Rt of CL

TABLE 4 INHERENT VARIATION DATA FOR CEMENT-STABILIZED FIELD CORES, CLEAR AND FLAWED SPECIMENS

		FLAWED SPECIMENS (69 SPECIMENS)			CLEAR SPECIMENS (65 SPECIMENS)		
VARIABLE	MEAN VALUE	STANDARD DEVIATION	COEFFICIENT* OF VARIATION, %	MEAN VALUE	STANDARD DEVIATION	COEFFICIENT OF VARIATION	RANGE
Cement, %	8.93	1.00	11.25	9.14	1.00	10.92	8 - 10
E, 10^5 psi	4.7817	2.0421	42.7	5.4561	1.8829	34.5	0.54 - 9.687
μ	0.2686	0.1053	39.2	0.2739	0.1062	38.8	0.107 - 0.500
ϵ_{tm}, μin/in	774.36	658.43	85.0	623.48	487.85	78.2	256 - 4073
STS	121.75	18.99	15.6	123.15	15.52	12.6	79.3 - 155.5
Flushing, % Area	41.4	33.9	81.9	4.9	10.9	222.5	0 - 60
Clay balls, % Area	4.7	8.1	171.9	4.6	4.6	100.0	0 - 22
Flaws, % Area	46.1	35.5	77.0	9.5	11.7	122.7	0 - 69
Log N_f	1.8892	1.151	60.9	4.4356	1.7283	39.0	

E - Resilient modulus

ϵ_{tm} - Resilient tensile strain

μ - Resilient Poissons Ratio

STS - Applied tensile stress psi

Log (N_f) - Logarithmn (Cycles to Failure)

$$* \text{ Coefficient of Variation} = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100$$

Poisson's ratio, and Log N_f. On the other hand, there were no significant differences in the mean values of resilient modulus and Poisson's ratio for the clear and flawed specimens. As indicated previously, there was a significant difference in the fatigue life of clear and flawed specimens. In terms of cycles to failure at a given applied stress (e.g., 122-psi tensile stress), the clear specimen on the average exhibited a life of 27,300 cycles, whereas the flawed specimen exhibited a life of 77 cycles. These values represent a great difference in the fatigue lives of the clear and flawed specimens. This fact, combined with low recovery of good cores from the cement-stabilized base layers, leads to the conclusion that there are two levels (or populations, in statistical terms) of base materials that have the same basic behavioral response (i.e., E and μ are similar) but drastically different performance characteristics (i.e., consideration of fatigue in producing the fracture distress mode).

Comparisons between field core results for the cement-stabilized sandy soil (Type A) and sandy loam (Type B) base materials were completed for the clear specimen group (Table 7) to ascertain whether or not there were significant differences in the means and variances of the three engineering properties. If there were no significant differences, then the results could be pooled and any subsequent use of the data would be simplified.

Table 7 indicated that there were no significant differences in either the variances or means for the two base materials. These results were combined to provide fundamental engineering property estimates compatible with the cement-stabilized sandy soil and sandy loam base materials. From these analyses the following information was developed:

Property	*Mean Value*	*Standard Deviation*	*Degrees of Freedom*
Resilient modulus, 10^5 psi	5.457	1.909	64
Resilient Poisson's ratio	0.274	0.108	64

which could be applied to either the cement-stabilized sandy (Type A) or sandy loam (Type B) base materials. In addition, the fatigue results for these two material types could be combined because no significant difference was found in the fatigue life of these two materials.

TABLE 5 INHERENT VARIATION IN FUNDAMENTAL MATERIAL PROPERTIES FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS FOR SOIL-CEMENT FIELD CORES, CLEAR SPECIMENS

		RESILIENT MODULUS		RESILIENT POISSON'S RATIO		LOG OF CYCLES TO FAILURE	
TYPE VARIATION	DESIGN LEVEL	MEAN SQUARES	DEGREES FREEDOM	MEAN SQUARES	DEGREES FREEDOM	MEAN SQUARES	DEGREES FREEDOM
A - longitudinal	1,2	1.679945	1	0.000924	1	0.923435	1
direction - 1'	3						
spacing	4	5.912301	3	0.001804	3	0.763232	3
B - longitudinal	1,2	1.129505	1	0.001800	1	0.720361	1
direction - 10'	3						
spacing	4						
C - lateral	1,2	1.404053	8	0.005158	8	0.602582	8
direction (outside	3						
lane)-2' spacing	4						
D(O) - lateral	1,2	0.939809	3	0.010016	3	0.293517	3
direction (outside	3						
lane) 4' spacing	4						
D(i) - lateral direction (inside lane)-4' spacing	1,2	0.618001	4	0.000663	4	0.737277	4
H - longitudinal	1,2						
direction - spacing	3						
greater than 50'	4	2.598060	1	0.017672	1	0.254222	1
E - vertical	1,2	2.078457	11	0.008254	11	2.818147	1
	3	0.146395	2	0.000833	2	1.162119	2
	4	0.322401	3	0.004150	3	0.726061	3
Combined results		1.771980	37	0.005686	37	1.000291	37

TABLE 6 INHERENT VARIATION IN FUNDAMENTAL MATERIAL PROPERTIES FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS FOR SOIL-CEMENT FIELD CORES, FLAWED SPECIMENS

		RESILIENT MODULUS		RESILIENT POISSON'S RATIO		LOG OF CYCLES TO FAILURE	
TYPE VARIATION	DESIGN LEVEL	MEAN SQUARES	DEGREES FREEDOM	MEAN SQUARES	DEGREES FREEDOM	MEAN SQUARES	DEGREES FREEDOM
A - longitudinal direction @ 1' spacing	4	1.635848	5	0.004797	5	0.785509	5
B - longitudinal direction @ 10' spacing	1,2	4.629924	1	0.000005	1	0.016989	1
	3	4.057256	9	0.012570	9	6.322710	9
C - lateral direction (outside lane)-2' spacing	4	2.609158	2	0.028428	2	0.038738	2
D(O) - lateral direction (outside lane)-4' spacing	4	0.013448	1	0.057970	1	0.113822	1
D(i) - lateral direction (inside lane)-4'spacing	1,2	4.835846	3	0.000311	3	0.477943	3
G - longitudinal direction @ 10-50' spacing	4	0.056785	1	0.000050	1	4.699919	1
H - longitudinal direction @ > 50'	1,2	0.154013	1	0.005000	1	0.195573	1
	4	6.399537	6	0.032275	6	4.727870	6
E - vertical	1,2	8.278179	10	0.013283	10	0.505976	10
	3	8.864214	4	0.010393	4	3.772197	4
	4	1.628167	6	0.006172	6	2.169734	6
Combined results		4.909988	49	0.011045	49	1.290111	49

LABORATORY SPECIMENS VERSUS FIELD CORES

A perplexing problem associated with experimental analysis and evaluation based on laboratory-prepared specimens is the uncertainty of the premise that laboratory results are applicable to field conditions. In order to obtain information concerning the existence of a correlation between field and laboratory core results, statistical comparisons were completed between the resilient properties of laboratory specimens and field cores for the combined results of cement-stabilized sandy soil and sandy loam base materials (Table 8).

Table 8 indicated that significant differences occurred for resilient modulus, Poisson's ratio, and particularly fatigue life. There may not have been a practical difference in the modulus values (4.711 versus 5.456 × 10^5 psi), but there were surely differences in Poisson's ratio (0.101 versus 0.274) and Log N_f (2.2103 versus 4.4356). Therefore, there are two separate groupings (or populations).

A subsequent comparison was made between the laboratory results and flawed field core results (Table 9) to check any correlation that may have existed. This comparison indicated that there were no significant differences in mean modulus values, whereas significant differences did exist in Poisson's ratio (0.101 versus 0.269) and Log N_f (2.2103 versus 1.8892). It is, however, believed that the difference between the Log N_f values is not of practical significance (162 cycles versus 77 cycles). Differences in ages at time of test between the field cores (approximately 2½ years) and laboratory specimens (1½ weeks to 1 year) could affect comparison of the results. However, this time difference may not be critical, and the laboratory fatigue-resilient data developed in this study are generally compatible with the results from the flawed core specimens.

Consequently, the laboratory fatigue data may well represent the majority of the soil-cement material in place at the Base Project. The low recovery rate of good field cores and the high moisture contents present in the cement-stabilized base layers are apparently correlated, as was found in the laboratory fatigue-resilient testing program for cement-stabilized sandy (Type A) and sandy loam (Type B) base materials.

Only a few fatigue tests were completed for field cores of the cement-stabilized sand-clay-gravel base material because few good core specimens could be extracted during the coring operation. Consequently, the resilient-fatigue results for laboratory-prepared specimens (Table 10) will have to be considered as representative of in-service conditions. When considering the earlier results, this premise seems reasonable.

ANALYSIS OF VARIANCE

The analysis of variance results for Log N_f of the combined cement-stabilized sandy (Type A) and sandy loam (Type B) field cores are presented in Tables 11 and 12 for clear field cores and in Tables 13 through 15 for flawed field cores.

Resilient Modulus for Clear Field Cores

The resilient modulus was significantly affected by a combination of percent tensile stress applied, measured percent tensile strain, and cement content. In general, a higher resilient modulus is generally associated with a lower strain value and a higher applied percent stress. In addition, higher values of cement content and tensile strain correspond to higher modulus values. The main effect of tensile strain ε can then be ameliorated by the addition of higher amounts of cement (Table 11).

Resilient Poisson's Ratio for Clear Field Cores

No factors were found to significantly affect the resilient Poisson's ratio; therefore, an overall mean value of 0.274 should be used as the best estimate of this property.

Log N_f for Clear Field Cores

The analysis of variance (Table 12) presents the main effects that significantly influence the fatigue life of the combined results. The approximate unit variation (AUV) values indicate that a longer life would be associated with a higher modulus, higher cement content, higher flushing (up to 20 percent), and lower stress levels.

Log N_f for Flawed Field Cores

No significant factors affected the resilient modulus (at a 5 percent level); however, the variable resilient modulus was significant at the 10 percent level (Table 11). In this instance, it was considered practical to include this variable in a later regression analysis. Increases in Log E would then result in higher fatigue lives.

Resilient Poisson's Ratio and Resilient Modulus for Flawed Field Cores

There were two variables that had a significant impact both on the resilient Poisson's ratio and on the resilient modulus of the flawed cement-stabilized field cores (Tables 14 and 15). Increases both in resilient tensile strain and applied stress levels would produce higher values of Poisson's ratio. On the other hand, higher resilient moduli values would be associated with lower resilient strain at higher stress levels.

REGRESSION ANALYSIS

The centered data technique was used in this study to develop regression equations by a stepwise regression technique. The terms included in each equation correspond to those factors and interactions found to be of practical engineering significance in the analysis of variance. The resulting equations can provide estimates of the various dependent parameters measured in the study within some standard errors. Included with the equations are the standard errors of estimate, $\hat{S}r$, and the coefficients of determination, R^2. Explanations of the centered data values are included in the legends of the appropriate tables.

TABLE 7 COMPARISON OF INHERENT VARIATION IN CEMENT-STABILIZED SANDY (TYPE A) AND SANDY LOAM (TYPE B) FIELD CORES—CLEAR SPECIMENS

MATERIAL PROPERTY	SANDY SOIL (A)			SANDY LOAM (B)			SIGNIFICANT DIFFERENCE IN	
	MEAN	STANDARD DEVIATION	DEGREES FREEDOM	MEAN	STANDARD DEVIATION	DEGREES FREEDOM	VARIANCE	MEAN
Modulus, 10^5 psi	5.397	2.042	37	5.536	1.679	28	No	No
Poisson's Ratio	0.280	0.100	37	0.266	0.115	28	No	No
Log of cycles to failure	4.2567	1.7913	37	4.6721	1.6430	28	No	No

Clear Field Cores

The regression equations for the clear field cores follow. There are two forms of the equation for Log N_f. The first form provides for the effects of all the independent or associated variables. The second equation is one that provides for the effect of the single variable most correlated with Log N_f. All the equations presented have been checked for fit and can be considered as having adequate predictive capabilities.

$$\text{Log } N_f = 4.4354 + 1.1052\,(\text{CEM}) + 1.0796\,(E) - 1.0330\,(\text{STL}) + 0.3278\,(\text{FLG})$$

$R^2 = 0.3961$ $\hat{S}r = 1.3985$

For the single most correlated variable:

$$\text{Log } N_f = 4.4356 - 5.3471\,(\text{Log } \varepsilon_t - 2.7433)$$

$R^2 = 0.3145$ $\hat{S}r = 1.4422$

Resilient Poisson's ratio:

$\mu_r = 0.274$ $\hat{S}r = 0.1062$

Resilient modulus:

$$E_r = 5.3081 - 2.016\,(\varepsilon_t) + 1.1030\,(\text{STS}) + 1.8396\,(\text{CEM} \times \varepsilon_t)$$

$R^2 = 0.5238$ $\hat{S}r = 1.3310$

TABLE 8 COMPARISON OF INHERENT VARIATION IN FUNDAMENTAL PROPERTIES FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS—LABORATORY SPECIMENS VERSUS CLEAR FIELD CORES

FUNDAMENTAL PROPERTY	COMBINED RESULTS SANDY SOIL (A) & SANDY LOAM (B) LABORATORY PREPARED RESULTS			COMBINED RESULTS SANDY SOIL (A) & SANDY LOAM (B) CLEAR FIELD CORES			SIGNIFICANT DIFFERENCE IN	
	MEAN	STANDARD DEVIATION	DEGREES FREEDOM	MEAN	STANDARD DEVIATION	DEGREES FREEDOM	VARIANCE	MEAN
Resilient Modulus, 10^5 psi	4.711	2.7580	128	5.456	1.8830	65	Yes	Yes
Resilient Poisson's Ratio	0.101	0.0317	128	0.274	0.1060	65	Yes	Yes
Log of cycles to failure	2.2103	1.0828	128	4.4356	1.7283	65	Yes	Yes

TABLE 9 COMPARISON OF INHERENT VARIATION IN FUNDAMENTAL PROPERTIES FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS—LABORATORY SPECIMENS VERSUS FLAWED FIELD CORES

	COMBINED RESULTS SANDY SOIL & SANDY LOAM LABORATORY PREPARED SPECIMENS			COMBINED RESULTS SANDY SOIL & SANDY LOAM FIELD CORES			SIGNIFICANT DIFFERENCE IN	
FUNDAMENTAL PROPERTY	MEAN	STANDARD DEVIATION	DEGREES FREEDOM	MEAN	STANDARD DEVIATION	DEGREES FREEDOM	VARIANCE	MEAN
Resilient Modulus, 10^5 psi	4.711	2.758	128	4.782	2.042	69	Yes	No
Resilient Poisson's Ratio	0.101	0.0317	128	0.269	0.1053	69	Yes	Yes
Log of cycles to failure	2.2103	1.0828	128	1.8892	1.1510	69	No	Yes

TABLE 10 INHERENT VARIATION IN FUNDAMENTAL MATERIAL PROPERTIES FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST FOR CEMENT-STABILIZED SAND-CLAY-GRAVEL, SOIL-CEMENT LABORATORY MIX DESIGN CONDITIONS

			DUPLICATE VARIATION				REPLICATE VARIATION			
			WITHIN SPECIMEN		WITHIN BATCH		BATCH TO BATCH			
MATERIAL PROPERTY	MEAN VALUE	DEGREES FREEDOM	MEAN SQUARES	DEGREES FREEDOM	MEAN SQUARES	DEGREES FREEDOM	MEAN SQUARES	DEGREES FREEDOM	RECOMMENDED VARIANCE	DEGREES FREEDOM
Resilient Modulus, 10^5 psi	3.9785	55	2.30357	35	0.036856	1	4.568606	8	2.790735	42
Resilient Poisson's Ratio	0.201	55	0.017023	35	0.000861	1	0.013544	8	0.016786	42
Log of cycles to failure	2.1344	55	0.645534	35	0.105363	1	1.241348	8	0.776901	42

TABLE 11 ANALYSIS OF VARIANCE FOR RESILIENT MODULUS FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS FOR CLEAR SOIL-CEMENT FIELD CORES, SANDY (TYPE A) AND SANDY LOAM (TYPE B) SOILS

SOURCE OF VARIATION	DEGREES FREEDOM	MEAN SQUARES	F VALUES	SIGNIFICANCE LEVEL	APPROXIMATE UNIT VARIATION*
ϵ_L	1	50.60315	27.76	0.01	-1.715
STL	1	59.46342	32.63	0.01	+1.103
cemxϵ_L	1	8.78757	4.82	5.0	+0.693
Residual	41	1.746721			
Error	35	1.822608			

* The Approximate Unit Variation represents the effect on the dependent variable (i.e. resilient modulus) of a change in an independent variable (e.g. tensile strain) equal to one standard deviation from mean value.

Factor Legend

ϵ_L - % ultimate elastic tensile strain, μin/in

STL - % ultimate tensile strength

CEM - % cement

TABLE 12 ANALYSIS OF VARIANCE FOR LOG N_f FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS FOR CLEAR SOIL-CEMENT FIELD CORES, SANDY (TYPE A) AND SANDY LOAM (TYPE B) SOILS

SOURCE OF VARIATION	DEGREES FREEDOM	MEAN SQUARES	F VALUES	SIGNIFICANCE LEVEL	APPROXIMATE UNIT VARIATION*
E	1	40.7394	29.24	0.01	+0.57
STL	1	22.2706	16.12	0.05	-0.93
CEM	1	6.9428	5.03	5.0	+0.69
FLG	1	4.2179	3.05	10.0	+0.30

* The Approximate Unit Variation represents the effect on the dependent variable (i.e. resilient modulus) of a change in an independent variable (e.g. tensile strain) equal to one standard deviation from mean value.

Factor Legend

E - Modulus of elasticity, 10^5 psi

STL - % of ultimate tensile strength

CEM - % cement

FLG - % flushing (migration of cement)

TABLE 13 ANALYSIS OF VARIANCE FOR LOG N_f FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS FOR FLAWED SOIL-CEMENT FIELD CORES

SOURCE OF VARIATION	DEGREES FREEDOM	MEAN SQUARES	F VALUES	SIGNIFICANCE LEVEL	APPROXIMATE UNIT VARIATION*
Log E	1	10.48272	3.90	<5%	+0.39
Residual	47	0.55102			
Error	48	2.68549			

* The Approximate Unit Variation represents the effect on the dependent variable (i.e. resilient modulus) of a change in an independent variable (e.g. tensile strain) equal to one standard deviation from mean value.

Factor Legend

E = resilient modulus

TABLE 14 ANALYSIS OF VARIANCE FOR POISSON'S RATIO FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS FOR FLAWED SOIL-CEMENT FIELD CORES

SOURCE OF VARIATION	DEGREES FREEDOM	MEAN SQUARES	F VALUES	SIGNIFICANCE LEVEL	APPROXIMATE UNIT VARIATION*
ϵ_{tm}	1	0.076179	5.52	5.0	+0.029
SL	1	0.069516	5.03	5.0	+0.030
Residual	46	0.007205			
Error	48	0.013813			

* The Approximate Unit Variation represents the effect on the dependent variable (i.e. resilient modulus) of a change in an independent variable (e.g. tensile strain) equal to one standard deviation from mean value.

Factor Legend

ϵ_{tm} - Measured tensile strain

SL - Stress Level:

$$SL = \frac{\text{Applied tensile stress}}{\text{Ultimate tensile strength}}$$

TABLE 15 ANALYSIS OF VARIANCE FOR RESILIENT MODULUS FROM FATIGUE-RESILIENT INDIRECT TENSILE TEST RESULTS FOR FLAWED SOIL-CEMENT FIELD CORES

SOURCE OF VARIATION	DEGREES FREEDOM	MEAN SQUARES	F VALUES	SIGNIFICANCE LEVEL	APPROXIMATE UNIT VARIATION*
ϵ_{tm}	1	74.89069	15.25	0.05	-1.15
SL	1	43.14413	8.79	0.5	+0.81
Residual	46	1.463888			
Error	48	4.910197			

* The Approximate Unit Variation represents the effect on the dependent variable (i.e. resilient modulus) of a change in an independent variable (e.g. tensile strain) equal to one standard deviation from mean value.

Factor Legend

ϵ_{tm} - Measured tensile strain

SL - Stress Level: $SL = \dfrac{\text{Applied tensile stress}}{\text{Ultimate tensile strength}}$

where

CEM = (cement − 9.1385)/1.9590;
Cement = (percent cement − 9.1385)/1.595;
flg = percent of flushing or cement migration (internal flaw);
FLG = (flg − 0.4908)/0.11005;
STS = (applied tensile stress − 123.15)/15.519;
ε_t = (ε_t measured − 623.48)/573.60;
μ_r = resilient Poisson's ratio;
E_r = resilient modulus (10^5 psi);
ε_{tm} = measured tensile strain (microinch/inch);
STL = (stress level − 0.75110)/0.11110;
SL = stress level, defined by (applied tensile stress)/(ultimate tensile strength); and
E = (E_r − 5.4561)/18,829.

The regression equation for resilient modulus represents the effects of strain, applied tensile stress, and cement content on the resilient modulus of cement-stabilized sandy (Type A) and sandy loam (Type B) field cores.

As noted in the analysis of variance section, no significant factors affected Poisson's ratio; therefore, no regression equation could be developed. A value of 0.274 should then be used as a best estimate of Poisson's ratio for a cement-stabilized sandy (Type A) and sandy loam (Type B) base materials.

Flawed Field Cores

The regression equations for Log N_f, resilient modulus E_r, and resilient Poisson's ratio μ_r follow. The coefficient of determination, R^2, values range from 0.116 to 0.416. All three equations exhibit adequate fit and should be considered adequate for estimating the fatigue life, resilient modulus, and Poisson's ratio for cement-stabilized sandy (Type A) and sandy loam (Type B) base materials.

$$\operatorname{Log} N_f(\text{mean}) = 1.8892 + 1.7792\,(\operatorname{Log} E - 0.6324)$$

$$R^2 = 0.1164 \qquad \hat{S}r = 1.0900$$

Resilient modulus:

$$E_r = 4.7815 - 1.0663\,\varepsilon_{tm} + 5.1140\,(\text{STS})$$

$$R^2 = 0.4162 \qquad \hat{S}r = 1.5838$$

Resilient Poisson's ratio:

$$\mu_r = 0.2687 + 0.0260\,\varepsilon + 0.1903\,(\text{STS})$$

$$R^2 = 0.1831 \qquad \hat{S}r = 0.097$$

where

S = standard deviation,
ε_{tm} = [measured tensile strain (microinch/inch) − 774.36]/592.86,
STS = [applied tensile stress (psi) − 121.76]/120.20, and
E = resilient modulus, 10^5 psi.

CONCLUSIONS

As in any controlled experimentation, the findings and conclusions resulting from this study are limited to the range of variables considered. On the basis of the data and the analysis described earlier in this report, the following general conclusions are offered.

A series of regression equations has been developed that includes the significant variables that have statistically significant effects on the appropriate fundamental engineering property. They can be used to provide estimates of the various dependent parameters within the standard error of estimate, $\hat{S}r$. All regression equations included in the report have been checked to ensure adequate fit of the data and have been judged to have adequate predictive capabilities.

The inherent variations in the fundamental properties of a cement-stabilized base material in longitudinal (along the road), lateral (across the road), and vertical (depth) directions could be combined individually for the clear and flawed field cores.

The fundamental resilient engineering properties were essentially the same for cement-stabilized sandy (Type A) and sandy loam (Type B) base materials obtained from the field or laboratory.

The resilient modulus and Poisson's ratio values were found to be essentially the same for the clear (minimum flaws) and flawed field cores, whereas the fatigue lives for the two were found to be drastically different. Therefore, the two field conditions (i.e., clear and flawed specimens) form two separate material groups (i.e., statistical populations) that must be considered in any subsequent analyses.

On the bases of the low recovery rate in good field cores for job verification; observation of various cracks, lamination, compaction planes, and layer separations in field cores obtained during the second major coring operation to cores for fatigue-resilient testing; and the subsequent low number of clear core specimens found to exist during the material characterization study, the mixed-in-place soil-cement construction procedure presently used apparently does not provide the quality and uniformity expected in a cement-stabilized base layer. The flawed field cores exhibited an average fatigue life of 77 cycles, whereas the clear field cores displayed an average fatigue life of 27,300 cycles.

The results of the resilient-fatigue test program for mix design conditions were compatible with the flawed field core resilient-fatigue test program. It was therefore concluded that the laboratory results could adequately predict the fundamental resilient engineering properties of the flawed portions of the cement-stabilized base layer.

Publication of this paper sponsored by Committee on Soil and Rock Properties.