Estimating the Design Life of a Prototype Cement-Stabilized Phosphogypsum Pavement

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Cement-stabilized phosphogypsum (CSPG) mixtures are demonstrated to have sufficient strength at the modified Proctor compaction level to satisfy the Louisiana Department of Transportation and Development design unconfined compressive strength (UCS) criteria of 1.7 MPa at 7 days for stabilized base material. With 8-12 percent cement, at 95 percent of modified Proctor maximum dry unit weight, CSPG had greater resilient modulus and UCS values than the commonly used river silt. Life estimates for a prototype road were highly dependent on the bearing capacity of the subgrade soil. The CSPG base produced acceptable estimated design lives for secondary roads at an attractive cost compared with conventional limestone aggregate.

More than 35 million metric tons of phosphogypsum (PG), a solid by-product of phosphoric acid production, are generated annually in the United States. The combination of environmental concern associated with disposal and the increasing cost to stockpile the material has prompted a search for the commercial use of PG. To prove that PG has a use as a road pavement material, prototype pavements need to be developed and demonstrated.

A laboratory evaluation was made of a prototype road with a CSPG base, including estimates of its potential design life in equivalent standard axle loadings (ESALs) and life-cycle costs compared with conventional limestone bases. The resilient modulus studies showed that a typical CSPG mix will theoretically provide an adequate design life at a life-cycle cost less than conventional materials.

EXPERIMENTAL PROGRAM

Conventional pavement designs have been based primarily on laboratory tests that use static loading. These tests are merely strength comparisons in which materials are judged on their total or relative strengths under failure-type loading. However, rarely do materials (in the field) receive loads that approach failure, and the performance of materials can be very different at low compared with high stress levels (*1*). The Louisiana Department of Transportation and Development requires a laboratory 7-day unconfined compressive strength of 1.7 MPa for Portland cement-stabilized bases (Test Method TR432-Method *B*).

The American Association of State Highway and Transportation Officials (AASHTO) (*2*) requires that the layer coefficients used in the development of the structural number of the pavement be based on the UCS or the repeated load triaxial resilient modulus test. However, a protocol for determining resilient modulus for flexible pavement design has not been clearly established, especially in the case of stabilized materials. Values given in the Van Til nomograph of the AASHTO design guide are from a general correlation of all cement-stabilized materials.

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Phosphogypsum (PG), which is about 80 percent gypsum, is characterized by the AASHTO classification system as a silty soil (A-4) with little to no plasticity or by the Unified system as a silty material (ML).

The CSPG was compared with stabilized river silt, a material commonly used in Louisiana for secondary roads. The river silt was classified by AASHTO specifications as an A-3, fine sand, and by the Unified Soil Classification System (USCS) as an SMM or silty sand. The material was nonplastic. It was stabilized with 10 percent cement to reflect common practice. The cement used in this study to stabilize the PG and river silt was a Type I portland cement.

The subgrade at the proposed trial site was classified, according to AASHTO, as an A-4 or A-6 (depending on the plasticity index). Based on the USCS, the subgrade is classified as a SC or clayey sand. Typical laboratory CBR values for the subgrade were 5 and 8 at moisture contents of 19 percent and 17 percent, respectively.

Resilient Modulus Testing

The resilient modulus test was developed to provide a more accurate description of the behavior of soils or other paving materials under the effect of dynamic stresses similar to those generated by a moving wheel. A standard triaxial cell was modified to fit a bottom-loading Instron testing machine and to house two linear variable displacement transducers (LVDT) for the longitudinal measurement of displacement. The LVDTs were internally mounted and measured the displacement relative to the specimen end caps. The signals from the two LVDTs were averaged. A triangular loading function was used to allow changes in loading and rest periods. The raw displacement and load data were imported into a spreadsheet and converted to load and strain data. The protocol for the resilient modulus testing is presented as follows.

The triaxial resilient modulus test was conducted in load control using the Instron 8500 material-testing system equipped with a 10 Kilonewton load cell. A standard geotechnical triaxial cell was used to run these experiments. Confining pressures ranged from 5 to 15 psi. The samples used were 5.08-cm-diameter cylinders, 10.16 cm tall. All specimens were tested as cured for 7- and 28-day periods. The strain was calculated from displacements measured by 2 DC LVDTs attached at the ends of the sample. The

LVDTs had a full scale of 0.05 in. and a signal output of 10 volts. The LVDTs were calibrated independently and then each signal was channeled through a signal averager. The signal from the averager was then connected to the Strain 1 channel port on the Instron machine, which allowed viewing of the changing strain as a percent of full scale. The experimental data was collected using Instron software or BINSWARE that was installed on a 486 personal computer. The resilient modulus was calculated by dividing the change in deviator stress by the change in strain during the cyclic loading.

The following criteria and procedures were selected from the protocol listed in Barksdale et al. (*9*) for asphaltic concrete at low temperatures: The cyclic load for testing and preconditioning shall be 30 percent of the unconfined compressive strength of the specimen. Preliminary unconfined compression strength tests were run on the design mixtures to give approximate total strengths of the specimens. Seating loads shall be no greater than 3 percent of the total strength of the specimen. The loading pattern and preconditioning shall have a load duration of 0.1 sec and a rest period of .9 sec. The period of preconditioning shall be attained at a determined number of cycles in which 10 successive readings of deformation agree within 10 percent. The number of load pulses to be applied for determining resilient modulus shall be at a minimum of 30 load pulses. Continued beyond 30 until the range in deformation values of 5 successive deformation values is less than 10 percent of the average. Then the resilient modulus is the average of the resilient modulus values measured individually from 5 load cycles after deformations are stable.

The following procedure was used:

1. Measure height, diameter, and weight of the cured sample; place on porous stones; place LVDT assembly and loading cap onto specimen.
2. Place on Instron actuator platform and connect air.
3. Zero LVDTs using hand-held voltmeter.
4. Apply seating load to the triaxial assembly; ensure that the LVDTs are still reading within 5 percent of the null point of the LVDTs.
5. Set function generator of the Instron to provide a triangular loading having a 0.1 sec duration and a 0.9 sec rest period.
6. Within the first 2 min of the dynamic loading, increase confining pressure to the maximum desired pressure.
7. Allow the loading to continue until it reaches stability and record the maximum and minimum load and displacement voltages at the end of this preconditioning period. Run 30 cycles while recording the load and change in displacement with the PC. The resilient modulus will be calculated using the average value of the resilient modulus of the last 5 cycles.
8. Change function generator to a single ramp loading of 1.27 mm/min. Set up data acquisition file for recording the data at every 500 ms.

A series of tests was conducted to establish the relationship among UCS and moisture, density, cement content, and curing period, which together with research from the Institute for Recyclable Materials (*3,4*) lead to two conclusions: (*a*) the addition of cement to PG changes the compacted unit weight and optimum moisture content for a given compactive effort and (*b*) increases in stength and resilient modulus resulted from increases in cement. Therefore, the mixes tested in the study (*5*) were selected on the basis of the information already mentioned.

TABLE 1 Change in Resilient Modulus With Load Duration for Specimens Cured for 7 Days

Material	Loading Duration	Average Resilient Modulus (MPa)	Standard Deviation (MPa)
12% PC, PG 95% Modified	0.1 seconds	993	55
12% PC, PG 95% Modified	0.5 seconds	938	35
12% PC, PG Standard	0.1 seconds	286	23
12% PC, PG Standard	0.5 seconds	259	16

* Each result is the average of 3 samples.

PC = Portland cement

PG = Phosphogypsum

RS = River silt

Sensitivity of the resilient modulus value of CSPG to load duration was analyzed by altering the loading interval from 0.1 to 0.5 sec. Shown in Table 1 is the change in resilient modulus of CSPG specimens prepared at 95 percent modified and standard Proctor dry unit weight, 15 percent moisture, and a curing period of 7 days. The AASHTO-specified load duration of 0.1 sec was used for the test program. Illustrated in Figure 1 is a typical stress-strain curve for a CSPG mixture tested to failure in unconfined compression. Presented in Figure 2 is the compressive stress/strain curve for repeated load when the seating load is 270 KPa. Shown in Figure 3 is the change in resilient and plastic strain and in Figure 4 the change in modulus with the number of cycles. Based on the information presented in Figures 3 and 4, each specimen

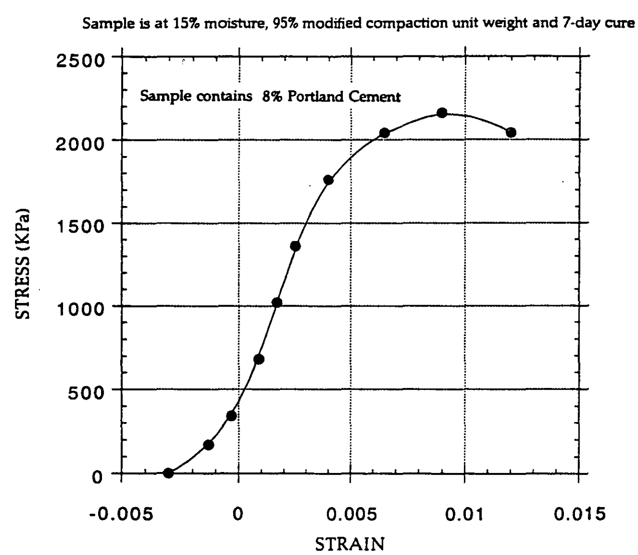

FIGURE 1 Stress-strain curve for CSPG tested to failure in compression.

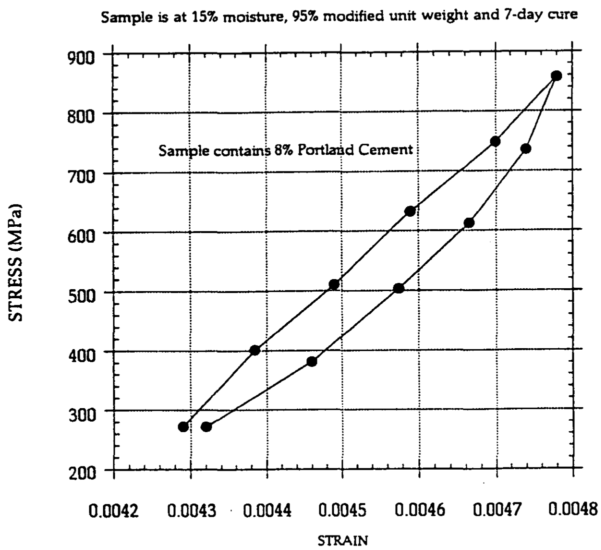

FIGURE 2 Stress-strain curve for CSPG tested in compression under repeated load.

was preconditioned with 500 cycles, at the given confining pressure (34.5 KPa), before recording stress and strain data.

Unconfined Compressive Strength Test

On completion of resilient modulus testing, the specimens were loaded to failure at the ASTM D1633 constant loading rate of 1.3 mm/min. Presented in Table 2 are the average UCS and resilient modulus results for PG and river silt specimens stabilized with Type I portland cement. Twenty-eight-day strength and resilient modulus values for the river silt could not be determined because of damage that occurred to the samples during the curing process. Three samples were molded for each mix and tested for resilient modulus at a repeated load of 30 percent of the UCS. The samples were then tested for UCS.

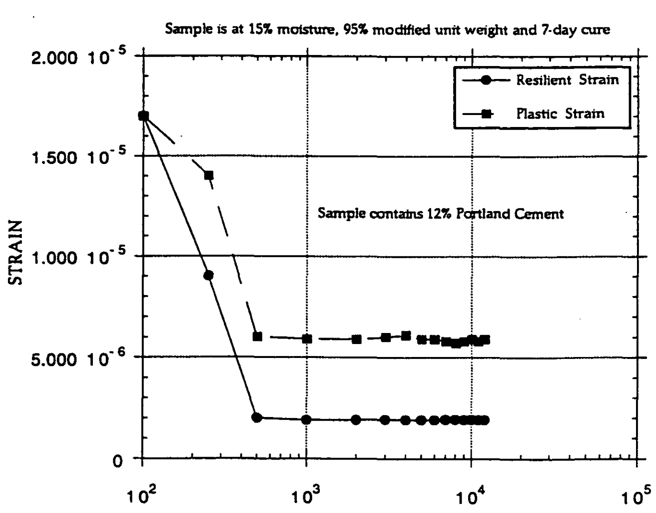

FIGURE 3 Changes in resilient and plastic strain with number of cycles.

DESIGN LIFE EVALUATION

The elastic layer program ELSYM5 (*6*) was used to estimate the stress and strain magnitudes, within certain pavement geometries, for selected moduli. The range of (compressive) stresses (190 to 760 kPa) used in the laboratory measurement of resilient modulus falls within the theoretical range of magnitude of (tensile) stresses (100 to 760 kPa) calculated by ELSYM5.

Design Lives

The design life estimates were calculated using the AASHTO DARwin program (*7*). Pavement geometries and structural coefficients were entered into the specified thickness design layer analysis in order to calculate a structural number for the proposed pavement. This structural number was then used to calculate a life for the pavement in ESALs given the lifetime change in present serviceability and roadbed resilient modulus.

Selected Material Properties

Shown in Table 3 are the structural values assigned to the materials used in the pavement stress analysis and design life estimates. The Louisiana design procedures were referenced for the average resilient modulus values for asphaltic concrete, limestone, and subgrade used in the design of roads in Louisiana. The CSPG layer coefficient of 0.2 was given to the material based on the 28-day strength.

Life Cycle Estimates

The estimated life of each of the selected pavement configurations is given in Table 4. A base thickness of 210 mm was used, which is the standard in Louisiana. By increasing the modulus of the subgrade, larger values of allowable ESALs were predicted. Two values have been presented to show the sensitivity of the roadbed soil to moisture content [20.7 MPa = California bearing ratio (CBR) of 2 at 22 percent moisture and 51.7 MPa = CBR of 5 at 19 percent]. The standard relationship M_r = 10.34 MPa × CBR was used to calculate these values. The higher moisture content represents the average in situ moisture content of the subgrade soil located at the proposed experimental test section during the summer of 1993, and the lower moisture content is the material compacted near optimum. Optimum moisture content for the subgrade material (American Society for Testing and Materials 1980) was 17 percent. Both subgrade modulus values represent conservative representations of life-cycle estimates.

Life Cycle Costs

To demonstrate the effective use of CSPG, the life expectancies of two bases were compared. Design 1 used a CSPG base con-

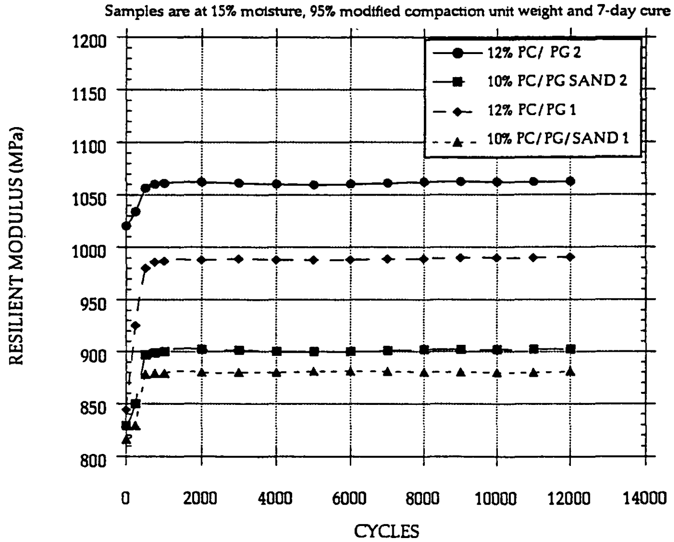

FIGURE 4 Changes in resilient modulus with number of cycles.

taining 12 percent cement. This layer was assigned an AASHTO layer coefficient of 0.2 based on its average 28-day unconfined compressive strength (3 MPa), resilient modulus (1655 MPa), and relative stiffness compared with the materials used in Louisiana. Twenty-eight day strengths were used for design because it was assumed that by the time normal traffic loadings were induced on the pavement, the CSPG would be closer to 28-day strength than 7-day strength. The second design employed a conventional limestone base with a resilient modulus of 345 MPa and a layer coefficient of 0.14. The two alternatives are compared in Table 5. Both designs assume a subgrade having a resilient modulus of 52 MPa.

TABLE 2 Average of UCS and M' Values

Material	Average UCS (KPa)	Standard Deviation (KPa)	Average Resilient Modulus (MPa)	Standard Deviation (MPa)
12% PC, PG, Standard, 7-Day	452	48	283	52
10% PC, RS, Standard, 7-Day	917	131	276	15
12% PC, PG, 95% Modified, 7-Day	2331	338	1014	62
12% PC, PG, 95% Modified, 28-Day	3082	385	1655	75
10% PC, RS,95% Modified, 7-day	1469	210	435	61
10% PC, RS, Modified, 7-Day	1489	152	441	48

* Each result is the average of 3 samples.
PC = Portland cement
PG = Phosphogypsum
RS = River Silt

Each analysis assumed a median year average daily traffic of 900, a projected daily ESAL value of 89 and a total 20-year ESAL value of 649,000. These data are typical for a rural secondary road in Louisiana (*8*). The analysis period was 20 years. Rehabilitation of the pavement consisted of a 50-mm asphaltic concrete overlay. After the first rehabilitation, this would be milled and recycled to a depth of 50 mm in order to repair cracking. The life-cycle costs are expressed in present-worth values. This analysis assumes the CSPG will have adequate durability.

CONCLUSIONS

Examined in this paper is the correlation between resilient modulus and UCS of CSPG and river silt and estimated is the design life of a CSPG base course pavement. The results and estimates show that

TABLE 3 Estimated Structural Values of Materials Used in Pavement Analysis (*2*)

Material	Resilient Modulus (MPa)	Layer Coeff.	Poisson's Ratio
AC	2413	0.42	0.35
Limestone	345	0.14	0.45
Subgrade	21 - 52	- -[a]	0.45
CSPG	1655	0.20	0.20
Lime Stabilized Heavy Clay	345	0.20	0.35
Lime Stabilized Silty Clay Subgrade	207	0.14 - 0.20	0.35

a no structural coefficient given

TABLE 4 Design Lives of Selected Pavements

Thickness	Design 1	Design 2	Design 3
AC	50	50	50
CSPG	210	210	210
Lime Stabilized Silty-Sandy Clay Subbase	150	–	–
Lime Stabilized Heavy Clay Subbase	–	150	–
Structural Number	2.77	2.95	2.35
Life in ESAL s [a]	64,000	92,000	23,000
Life in ESAL s [b]	545,000	813,000	195,000
	Design 4	Design 5	Design 6
AC	50	50	50
Limestone	210	210	210
Lime Stabilized Silty-Sandy Clay Subbase	150	–	–
Lime Stabilized Heavy Clay Subbase	–	15.2	–
Structural Number	2.32	2.5	1.9
Life in ESAL s [a]	20,000	34,000	6,000
Life in ESAL s [b]	180,000	286,000	54,000

[a] means the life was calculated with a subgrade resilient modulus of 20.7 MPa ; [b] means the life was calculated with a subgrade resilient modulus of 51.7 MPa.

TABLE 5 Life-Cycle Cost for Selected Pavements

Design	Cross Section	Initial Cost, $	Total Cost, $
3	50mm AC, 210mm CSPG	218,000	316,000
1	50mm AC, 210mm CSPG, 150mm LSSB	286,000	308,000
4	50mm AC, 210mm LS, 150mm LSSB	229,000	322,000

LSSB = Lime Stabilized Silty-Sandy Clay Subbase.

1. Stabilized PG with 10–12 percent Type I portland cement has a resilient modulus between 275 and 1655 MPa at standard and modified Proctor unit weights. ASSHTO-specified strength criteria for cement-stabilized materials can be reached, with PG, only by using modified Proctor compaction energy.

2. Resilient modulus-UCS relationships should be determined for a given mix rather than depending on one unique relationship for all mixtures.

3. For the prototype site, with a low CBR subgrade, a pavement consisting of 50 mm of asphaltic concrete with a resilient modulus of 2400 MPa and a 210-mm CSPG base containing 12 percent cement at 1.52 t/m^3 and 15 percent moisture content will result in an approximate design life of 195,000 ESALs.

4. Stabilized PG can be used effectively as a road base for a secondary low-volume road providing an appropriate cement content, adequate compaction, and proper drainage are ensured.

5. Based on the analyses, the life-cycle cost of roads built with CSPG is attractive. However, an experimental test pavement must be built to determine if CSPG can withstand the environmental conditions that occur in the field.

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