Sulfate Expansion of Cement-Treated Bases

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The causes of the destructive expansion and weakening of cement-treated bases (CTBs) on two sections of US–85 in northeastern Wyoming are examined. The research project was jointly conducted by the University of Wyoming and the Wyoming Department of Transportation. One-dimensional expansions, unconfined compressive strengths and X-ray analyses were performed to determine the causes behind the expansion of the CTBs. It was found that chemical reactions among clay, cement, and sulfate caused most of the deterioration.

The Wyoming Department of Transportation (WYDOT) has extensive experience in the design and construction of cement-treated bases (CTBs). Over the years, this type of construction has performed well and provided cost-effective service life. However, two recently built pavement sections on US–85 between Newcastle and Lusk have shown excessive deterioration. Shortly after construction, the CTB buckled substantially, requiring repeated millings to remove heaves in the road surface. Two years later the road was still expanding, and it was being milled to lower the still-growing bumps. Although the initial bumps appeared at construction joints, subsequent bumps appeared between the construction joints. The road buckled and cracked at intervals as short as a few hundred feet. Figure 1 shows the deterioration of a representative pavement section. Some local truckers used unpaved county roads parallel to US–85 instead of traveling on the rough section.

The first section just north of Mule Creek Junction was constructed in summer 1991. Expansion was first noticed after asphalt was placed over the CTB. Initially this expansion was believed to be due to a flaw in the construction process. Therefore, more attention was given to the construction of expansion joints in the second section, which was built the following summer. Excessive expansions were later observed in the second construction project. To determine the causes of pavement deterioration and to prevent similar failures in the future, the University of Wyoming and WYDOT initiated a major research project. Some of the findings from that research study are presented in this paper.

BACKGROUND

Expansion of portland cement concrete (PCC) due to freeze/thaw and alkali-aggregate reactions has been researched extensively during the past 50 years. There has been less research dealing with sulfate expansion because low C_3A cements have largely eliminated these problems (*1*).

Three sulfate sources may cause sulfate attack: the aggregate, the subgrade, and water in contact with the concrete or stabilized soil. Most problems associated with ordinary PCC sulfate attack are caused by constant or intermittent contact of concrete structures with water that contains sulfates. Consequently, most research on sulfate attack has focused on water-induced failure, particularly in marine environments. However, there is considerable evidence that sulfate-rich aggregates and soils may also be responsible for sulfate-caused expansion and weakening. This deterioration is more prevalent in cement and lime-stabilized soils, with problems being particularly common in the western United States (*2,3*).

Two factors may contribute to making CTBs more vulnerable to sulfate attack than ordinary PCCs. First, a higher cement content yields a higher resistance to sulfate damage (*4*). CTBs may be more vulnerable to sulfate attack than ordinary PCCs because of their lower cement contents. Second, ordinary PCC sulfate resistance is improved at lower water-to-cement (w/c) ratios (*5*). If one extrapolates to the CTB's higher w/c ratios and lower cement contents, a potential problem exists with sulfate attack on CTBs.

Weakening and expansion of cement-stabilized soils is due primarily to sulfate, cement, and clay reactions instead of the sulfate and cement reactions that lead to the destruction of ordinary portland cements (*6*).

CTBs lie between cement-stabilized soils and ordinary PCC in composition. Determining which of the possible destructive mechanisms caused the CTB on US–85 in Wyoming to fail is critical in developing test procedures to prevent future failures.

EXPERIMENTAL DESIGN

This research project involved laboratory and field components. The main objective was to simulate field expansions in the laboratory and to identify the factors causing the expansion.

Laboratory mixes simulating CTBs were prepared for expansion and unconfined compressive strength (UCS). UCS specimens with a 101.6 mm (4.00 in.) height and 116.3 mm (4.58 in.) diameter were prepared and tested according to ASTM D 1633. Numerous 76.2 × 76.2 × 285.8 mm (3 × 3 × 11¼ in.) CTB bars were prepared and measured for one-dimensional expansion according to ASTM C 157, which specifies curing in lime-saturated water at 23°C (73°F). The laboratory testing also included X-ray diffraction studies of the aggregate and some of the CTB samples.

In addition to laboratory testing, a field evaluation was performed to estimate actual expansion. Construction records were also examined to identify any problems related to expansion. The laboratory and field data were then summarized in a computerized data base. A comprehensive data analysis was later performed to identify the factors causing expansion.

FIELD EVALUATION

Examination of the US–85 construction records revealed that the existing subgrade soil was classified as A–7–6. This soil was covered

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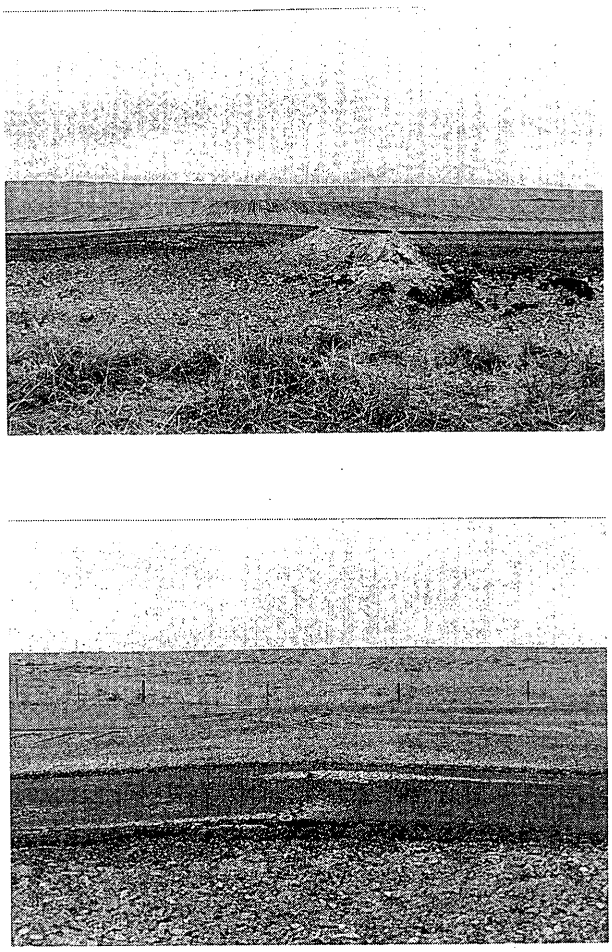

FIGURE 1 Damaged pavement sections after milling.

with an impermeable plastic membrane during construction. A 254-mm (10-in.) CTB was placed on top of the membrane with 102 mm (4 in.) of hot plant mix asphalt overlain by 19 mm (3/4 in.) of wearing course. Figure 2 shows a typical pavement cross section. The geotextile membrane was placed on top of the subgrade to maintain a constant moisture content and prevent water-related expansion.

Lateral expansion of the CTB in the field caused the delineators to tilt outward. On the basis of this deflection and assumed geometries, the field expansion was estimated to be at least 0.7 percent.

Examination of the construction records also showed that the CTB had only 2.8 MPa (400 psi) UCS after 7 days. This was partially corrected during the construction of the northern section by increasing the cement content from 7 to 9 percent. The increase in cement content did not resolve the expansion problem, though it improved the UCS.

X-ray diffraction studies were performed on cores taken from the US–85 CTB. Hydrated minerals, such as ettringite, were not found on the diffractograms of the CTB. This may have been the result of dehydration after the cores were removed from the road.

LABORATORY EVALUATION

The laboratory testing experimental design is presented in Figure 3. The effects of curing time, water concentration, clay type, aggregate type, and sulfate amount on expansion were examined. CTB bars and UCS cylinders were prepared, cured, and tested according to ASTM C 157 and ASTM D 1633 for each matrix. Bars exhibiting over 0.1 percent expansion were considered failed. Specimens with unconfined compressive strengths less than 3.45 MPa (500 psi) were also considered failed.

All laboratory mixtures had the same gradations as the average field CTB mix on US–85 except that no materials retained on the 19.05-mm (3/4 in.) sieve were included in the laboratory mix. Figure 4 shows the aggregate gradation used to prepare all CTB samples. The following sections describe the laboratory testing program and summarize its findings.

Materials Characterization

Aggregate

Several types of aggregate were used in this research. The first type was the LAK Pit aggregate, which caused expansion in the failed projects on US–85. Laboratory analysis discovered 6.7 percent gypsum (3.4 percent sulfate as SO_3) in the LAK Pit fines (passing a No. 200 sieve) as determined by a modified version of ASTM C 471. Sulfate was extracted with one volume of HCl (sp gr 1.19)

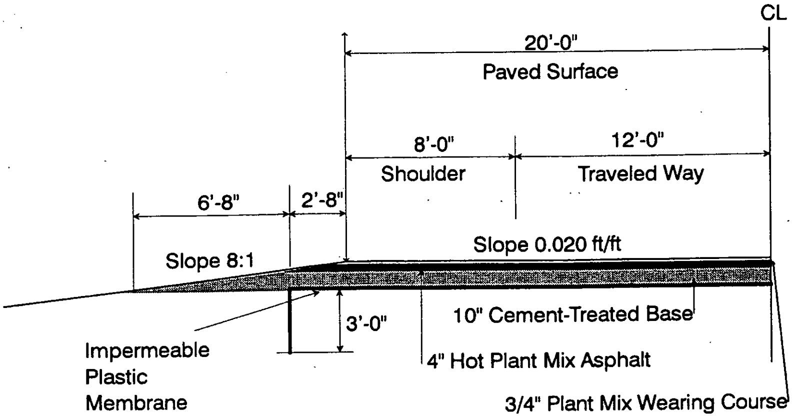

FIGURE 2 Typical cross section of US 85.

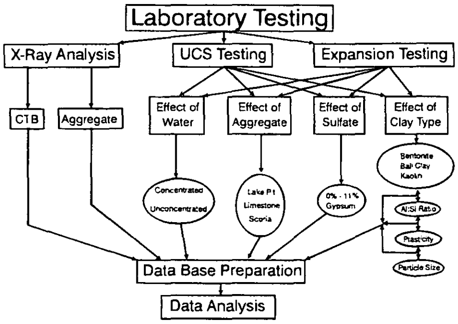

FIGURE 3 Laboratory testing experimental design.

mixed with four volumes of water as described in ASTM C 471. The portion of the LAK Pit aggregate passing the No. 16 sieve and retained on the No. 30 sieve contained 4.3 percent gypsum (2.2 percent as SO_3). This aggregate was also analyzed using X-ray diffraction. It was found to contain quartz, calcite, gypsum, polyhalite, barite, possibly some native sulfur, and the clay minerals illite and kaolinite. Figure 5 shows the X-ray diffractogram for the LAK Pit aggregate. Hydrometer tests performed according to ASTM D 422 found that 6.1 percent of the LAK Pit aggregate is clay-sized particles smaller than 0.005 mm (0.0002 in.).

The second type of aggregate used in this experiment was scoria, which is a red mudstone used in more than 50 percent of Wyoming's CTB. It was used with a river-run filler. The scoria and its filler were analyzed with X-ray diffraction. The scoria was found to contain quartz and small amounts of smectite, illite, and kaolinite. The filler contains primarily quartz, with the fines containing substantial smectite, less kaolinite, and traces of illite.

The third type of aggregate used was a crushed limestone, which is common in Wyoming road construction projects. A similar river-run filler was used with the crushed limestone.

Gypsum

In addition to the three aggregate types, a 95 percent pure gypsum ($CaSO_4 \cdot 2H_2O$) from the Mountain Cement plant in Laramie, Wyoming, was used in this experiment.

Cement

Type I–II low-alkali portland cement manufactured at the Holnam, Inc., plant in Fort Collins, Colorado, was used to prepare all laboratory samples. This cement contains 6.9 percent tricalcium aluminate (C_3A) and 11 percent tetracalcium aluminoferrite (C_4AF).

Water

The water for all laboratory experiments was obtained from the South Fork of the Cheyenne River at the crossing of US–85. The same water source was used in the failed sections of US–85. This water flows over material similar to that of the LAK Pit quarry. Some of the Cheyenne River water was evaporated to half of its original volume to increase its sulfate concentration. Sulfate tests indicated that the sulfate concentrations were 0.15 percent (1500 ppm) and 0.28 percent (2800 ppm) as SO_3 in the natural and concentrated waters, respectively.

Clays

The following five clay types were included in this experiment: an Indiana ball clay (HTP), a Kentucky ball clay (KYS), two Georgia kaolins (KIN and ROG), and a Wyoming bentonite (BHB). Chemical and physical analyses of all five clay types are presented in Table 1. The clays were used to establish the effect of various clay types on expansion and UCS.

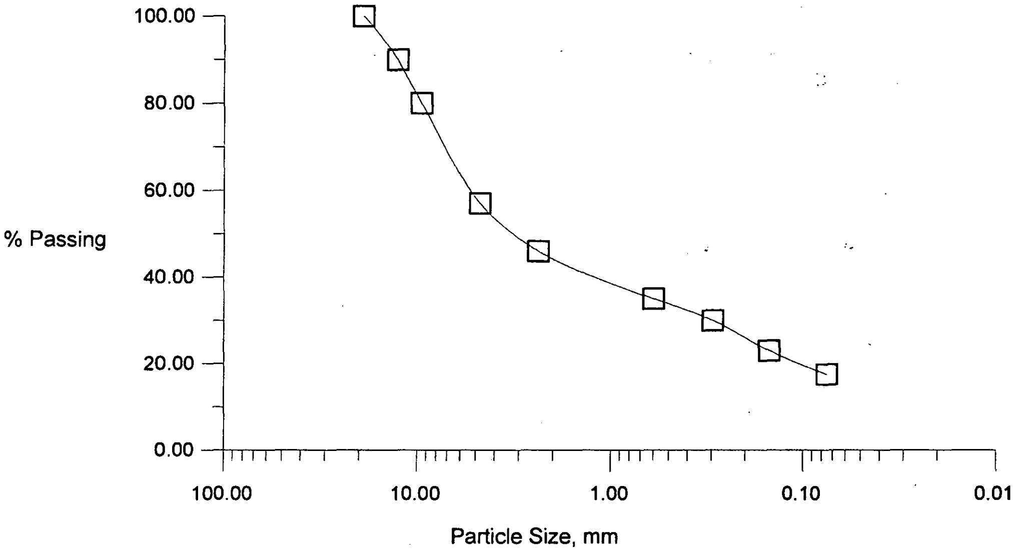

FIGURE 4 Aggregate gradation of CTB mixes.

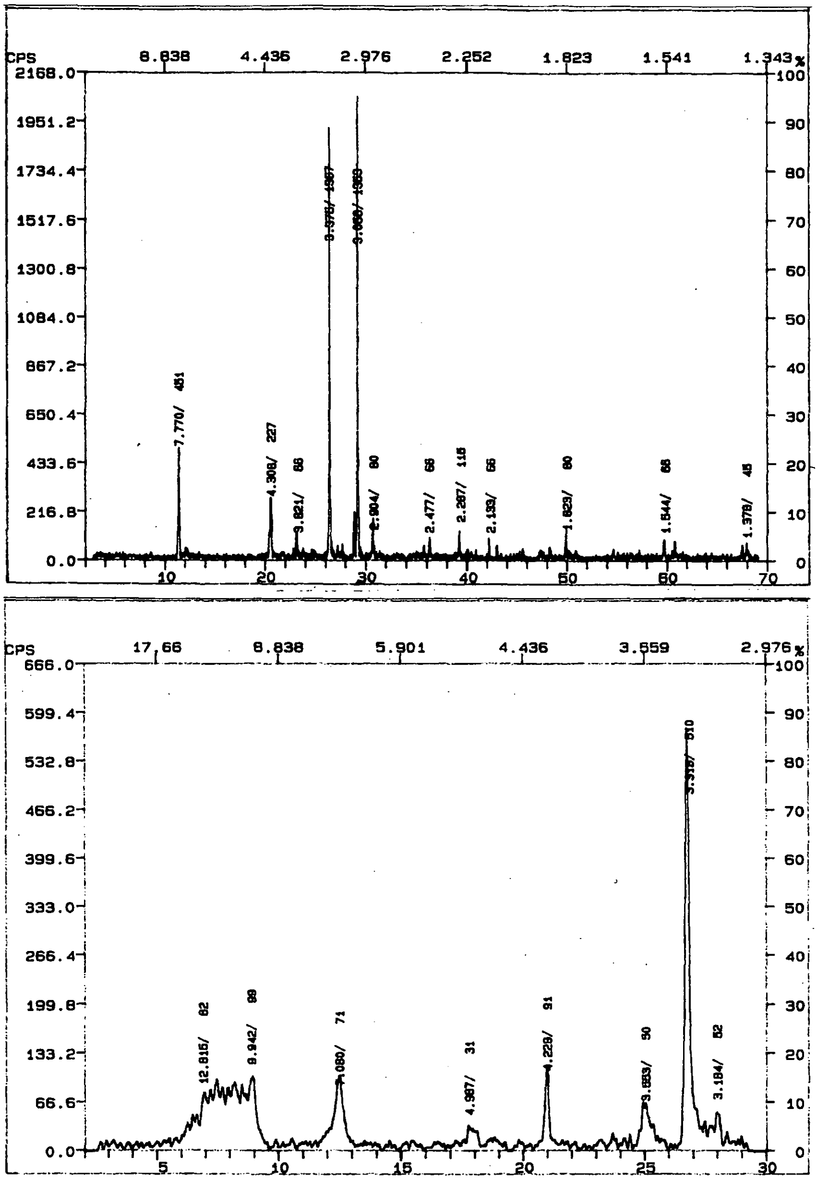

FIGURE 5 X-ray diffractogram of LAK Pit aggregate: (*top*) bulk sample; (*bottom*) fines <0.075 mm

Laboratory Testing Matrixes

Three test matrixes were prepared to examine the effect of different factors on CTB expansion and weakening. The objectives of the first matrix were to

- Reproduce the weakening and expansion experienced by US–85's CTB,
- Determine the percentage of LAK Pit aggregate that can cause excessive expansion and weakening, and
- Determine the effect of sulfate concentration in mixing water on expansion.

LAK Pit and limestone aggregate were mixed in proportions from 0 percent LAK Pit and 100 percent limestone to 100 percent LAK Pit and 0 percent limestone at 20 percent increments. Duplicate specimens were prepared with natural and concentrated Cheyenne River water for each aggregate mixture.

The objectives of the second matrix were to determine the weakening and expansion caused by adding gypsum to the CTB prepared with limestone aggregate. Gypsum was added at the following percentages of the total aggregate weight: 0, 0.5, 1, 2, 3, 5, 8, and 11 percent. This allowed researchers to estimate expansion due to the effect of sulfate and cement chemical reactions.

The third matrix consisted of CTB samples prepared with scoria and limestone aggregates spiked with the five clay types and the three levels of gypsum. The gypsum levels were 0, 2, and 5 percent. Clay was added at 6.1 percent of the total aggregate weight, which is the same percentage found in the LAK Pit aggregate. This matrix's main objective was to esti-

TABLE 1 Chemical and Physical Properties of Clays Used in Laboratory Testing

Clay	Kingsley (KIN)	Rogers (ROG)	HTP (HTP)	Kentucky Stone (KYS)	Black Hills Bond (BHB)
SiO_2	44.8%	46.5%	53.6%	67.2%	64.7%
Al_2O_3	38.4%	37.5%	32.0%	20.8%	17.6%
Fe_2O_3	0.39%	1.00%	1.1%	1.3%	4.4%
TiO_2	1.64%	1.30%	1.4%	1.4%	0.16%
CaO	0.09%	0.28%	0.3%	0.3%	1.3%
MgO	0.04%	0.26%	0.3%	0.5%	1.8%
K_2O	0.14%	0.26%	0.7%	1.3%	0.46%
Na_2O	0.11%	0.12%	0.1%	0.1%	2.5%
L.O.I.	13.60%	13.20%	10.5%	7.1%	--
H_2O (crystal)	--	--	--	--	5.9%
Plastic Limit	33	34	31	29	--
Liquid Limit	58	76	74	58	--
PI	25	42	43	29	--
% <0.005 mm	80%	95%	90%	70%	90%

mate CTB weakening and expansion in the presence of sulfate and clay.

RESULTS OF LABORATORY EVALUATION

Effect of Sulfate Concentration in Water on CTB Deterioration

Some of the specimens in the first matrix were prepared with the natural Cheyenne River water, while others were prepared with the concentrated Cheyenne River water. The expansions of all samples were measured and later analyzed statistically.

The differences in expansions due to water types were found to be significant at the 90 percent confidence level after 3, 7, and 14 days of curing. However, the differences were insignificant for all subsequent measuring times. Early chemical reactions causing expansion are affected by the composition of water used in mixing. However, with time, the expansion becomes dominated by the aggregate compositions. Thus the later expansions are not significantly affected by the mixing water's original composition.

Laramie tap water was used to prepare several bars of the 100 percent LAK Pit mix. The expansions for the tap water, natural Cheyenne River water, and concentrated Cheyenne River water were similar.

Effect of LAK Pit Aggregate on CTB Deterioration

Figure 6 presents the CTB expansions for the limestone and LAK Pit matrix. The 100 percent LAK Pit mixes successfully reproduced the field expansions and showed 0.8 percent expansion after 90 days of curing. The bars showed expansion greater than about 0.1 percent when the destructive LAK Pit aggregate's concentration was 60 percent or greater. At 40 percent LAK Pit aggregate, the expansion was marginally destructive; at LAK Pit concentrations of 20 percent or less, the expansion was insignificant. These expansions were analyzed statistically to predict expansion based on the LAK Pit percentage and days of curing. The following statistical model with 95 percent R-square was obtained:

$$\text{Exp} = 0.11 + A^2\,[B(2.4 \times 10^{-7}) + (\sqrt{B})\,(7.8 \times 10^{-6}) - (1.58 \times 10^{-5})]$$

where

Exp = percentage of expansion,
A = percentage of LAK Pit aggregate, and
B = days of curing.

Figure 7 presents the UCSs of the limestone and LAK Pit matrix. All mixes containing 40 percent or more LAK Pit aggregate showed significant loss in strength. The 100 percent LAK Pit samples had 450 psi and 400 psi UCS after 7 and 28 days, respectively. This loss of strength with time is due to continuing sulfate attack.

Effect of Sulfate-Cement Reaction on CTB Deterioration

The second matrix examined the effect of adding gypsum to limestone CTB. The limestone was spiked with gypsum contents varying between 0 and 11 percent. As shown in Figure 8, none of the specimens expanded by more than 0.08 percent after 75 days of curing. The presence of gypsum without a significant amount of clay did not lead to failure in the CTB mixes.

The expansion results can be interpreted if one considers kinetic mechanisms of expansion due to the formation of ettringite

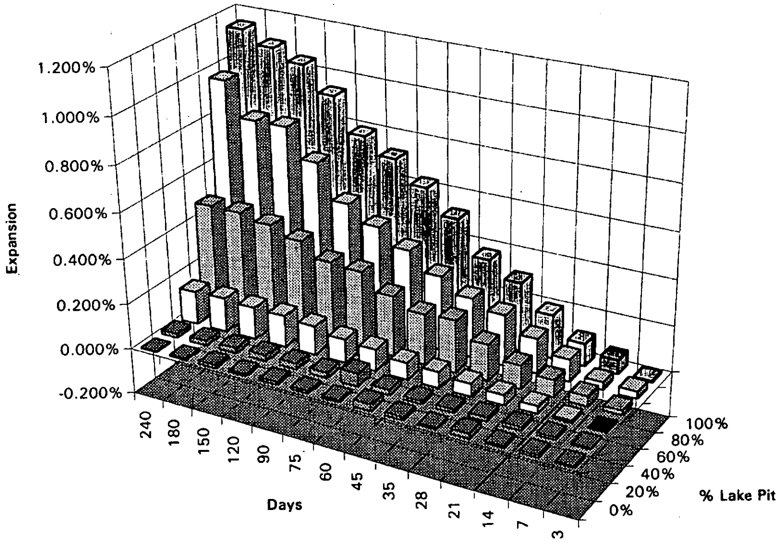

FIGURE 6 Laboratory linear expansion of LAK Pit and limestone mixes.

$[Ca_6(Al_2O_6)(SO_4)_3 \cdot 32H_2O]$ and calcium monosulfate $[Ca_4(Al_2O_6)(SO_4) \cdot 12H_2O]$. Havlica (*7*) reports that calcium monosulfate is only stable at a pH greater than 11.6, and ettringite is stable at a pH greater than 10.6. When ordinary PCC sets, ettringite forms early, consuming the available sulfate. With time, the ettringite decomposes to calcium monosulfate, a nonexpansive mineral (*8*). A postulated drop in pH may have caused the decomposition of calcium monosulfate, allowing later reformation of ettringite. Siedel et al. (*5*) have discussed similar primary and secondary ettringite formation in ordinary PCC.

The effects of spiking limestone CTB with gypsum on the 28-day unconfined compressive strengths are shown in Figure 9. It is clear from this figure that spiking CTB with variable percentages of gypsum causes losses in strength.

Effect of Sulfate, Clay, and Cement Reactions on CTB Deterioration

In the third testing matrix, limestone and scoria CTBs were spiked with clay and gypsum. Figure 10 shows the CTB expansion when the scoria CTB mixes were spiked with HTP clay and gypsum. It is clear that spiking the aggregates with clay alone produced little or no expansions. Expansions were significantly higher when gypsum was added to the clay and aggregate combination. The lack of expansion when clay is added to the CTB mix without gypsum indicates that clays alone do not cause destructive expansion in CTBs, and the combination of clay and gypsum can cause high expansions. It was interesting to note that 2 and 5 percent gypsum caused similar levels of expansions.

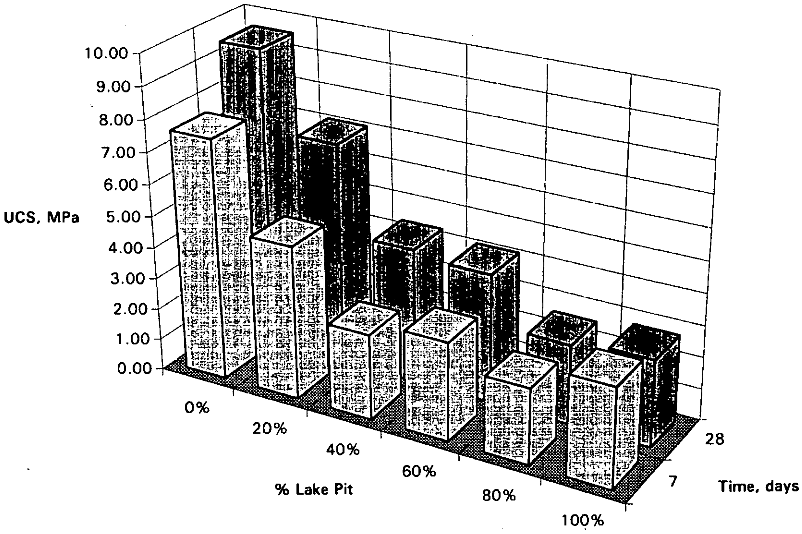

FIGURE 7 Laboratory unconfined compressive strengths of the limestone and LAK Pit matrix.

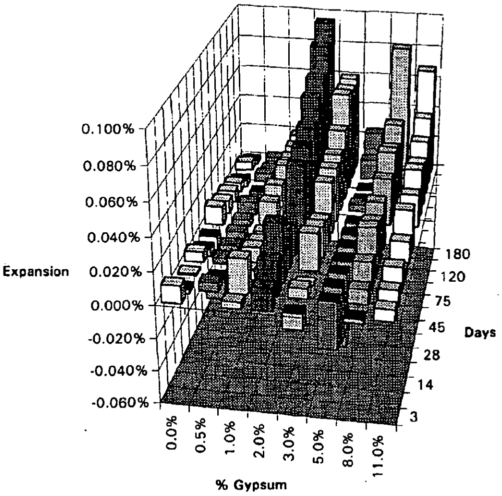

FIGURE 8 Laboratory linear expansion of limestone and gypsum mixes.

Figure 11 shows the effect of spiking scoria aggregate with HTP clay and gypsum on the UCS after 28 days of curing. Again the clay and gypsum combination resulted in similar substantial losses in strength at 2 and 5 percent gypsum.

The same overall behavior described previously was observed when spiking the limestone and scoria aggregates with the other four clay types, although the expansion levels varied. The LAK Pit aggregate shows substantial weakening and expansion in CTB. The scoria and limestone CTBs became vulnerable to expansion and weakening after sulfate and clay were added.

A major point of interest was to determine the effect of clay characteristics on expansion levels. The Al:Si ratio and the plasticity index (PI) of the clays were statistically tested for their effect on expansion.

Aluminum was considered a possibly critical factor because it is a component of ettringite. If aluminum were in short supply, ettringite formation would be inhibited, so there would be less expansion. The Al:Si ratio was found to be insignificant, which indicates that excess aluminum was available to allow ettringite to form.

The PI is largely affected by surface area and highly correlated with the proportion of clay-sized (<0.005 mm) particles. Greater surface area can allow the clays to react more quickly and completely. This mechanism may explain the significance of PI in predicting the expansion of CTBs. The following regression equation was developed for the limestone and scoria spiked with clay and gypsum:

$$\%\text{Exp} = -1.33 + 0.42*(\sqrt{A}) - 0.19*B + 0.77*C + 0.0072*B*D$$

where

A = days of curing,
B = percent of gypsum,
C = aggregate type (0 for limestone aggregate and 1 for scoria aggregate), and
D = PI of clay.

The R-squared value for this regression model is 65 percent. Clearly, clay of any type is a critical component in the destructive expansion of CTBs. However, the degree of this expansion appears to be correlated with the clay's PI.

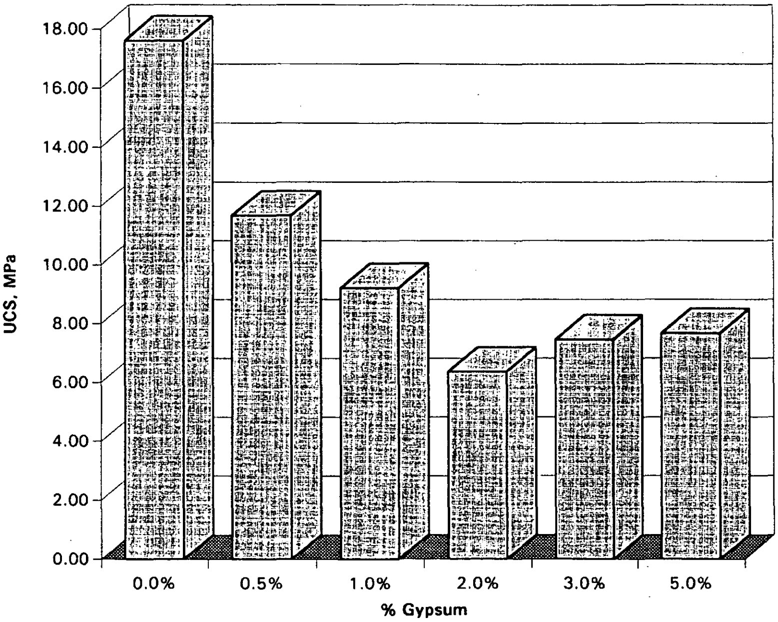

FIGURE 9 Laboratory 7-day unconfined compressive strengths of the limestone spiked with gypsum.

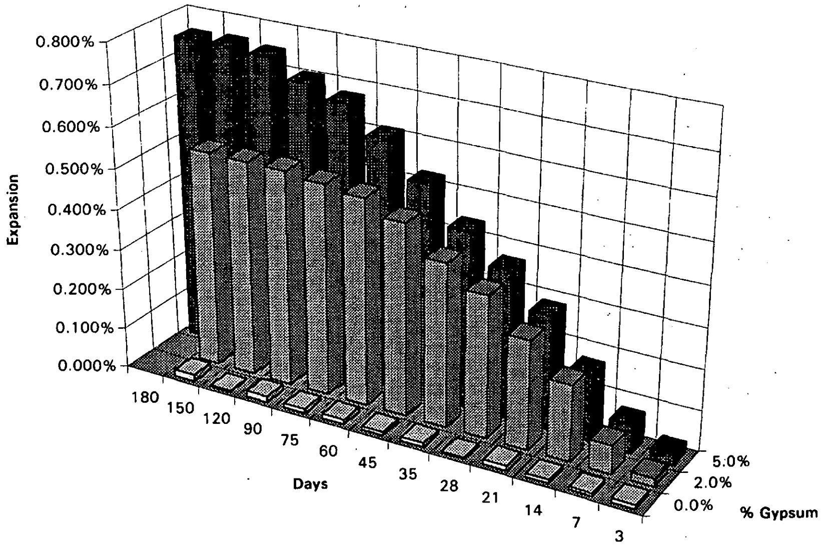

FIGURE 10 **Laboratory linear expansion of scoria spiked with 6.1 percent HTP clay and gypsum.**

CONCLUSIONS

This research project examined the causes of destructive expansion and weakening of CTBs on two sections of US–85 in northeastern Wyoming. One-dimensional expansions, unconfined compressive strengths, and X-ray analyses were performed to determine the causes behind the expansion and weakening of CTB. The following conclusions can be drawn from this study:

- Sulfate expansions in CTB can be simulated in the laboratory by using 76.2 × 76.2 × 285.8 mm (3 × 3 × 11¼ in.) bars soaked in lime-saturated water.
- CTB expansions are affected by the mixing water's sulfate concentration during the first 2 weeks of curing. Later expansions are controlled by aggregate compositions when the cement type and amount are constant.
- The presence of sulfate in a limestone aggregate without a significant amount of clay can cause relatively small expansion and moderate loss of strength in CTBs. Expansions of less than 0.1 percent were observed when spiking limestone specimens with gypsum only.
- CTB specimens spiked with clay or gypsum alone showed very small expansions; samples spiked with both clay and gypsum showed much larger expansions.
- Clays with higher PIs produced greater CTB expansions and losses in strength.
- Because clay is apparently an important factor in CTB deterioration, the actual destructive mechanism that causes weakening and expansion of CTBs is sulfate-cement-clay reactions like those of cement-stabilized soils.
- The risk of future destructive CTB expansion can be greatly reduced by controlling the amounts of clay and sulfate in the CTB mix.

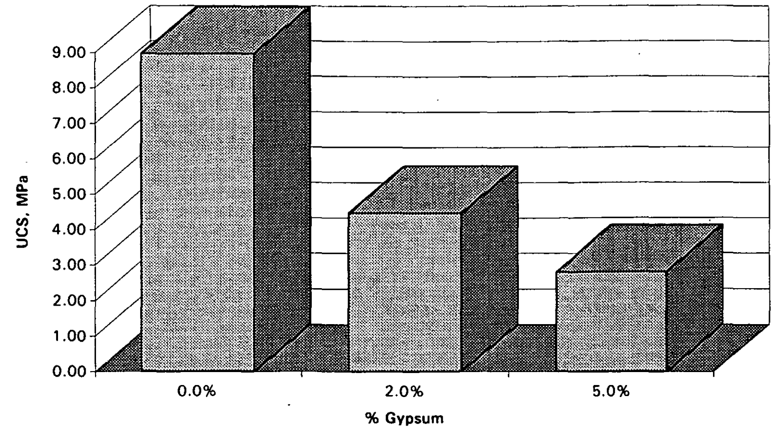

FIGURE 11 **Laboratory 28-day unconfined compressive strengths of scoria spiked with 6.1 percent HTP clay and gypsum.**

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