Long-Term Performance of a Highway Subgrade Stabilized with an Atmospheric Fluidized Bed Combustion Material

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INTRODUCTION

Using chemical admixtures[1], such as hydrated lime or cement, to improve the bearing strengths of highway soil subgrades has become a common practice in the United States in recent years. For example, based on a recent (1998) survey[2], chemical admixtures were used in at least 25 states to improve bearing strengths of soil subgrades. Admixtures included hydrated lime, cement, and fly ash. Soils with poor engineering properties can usually be improved dramatically at a reasonable cost by mixing with chemical admixtures. Improving bearing strengths of weak soil subgrades increases pavement life and reduces maintenance costs. This construction technique is a particularly useful alternative in areas where granular materials are scarce and long haul distances may be involved. Also, the technique permits the good use of in situ materials.

An attractive feature of using certain byproducts produced from industrial processes as chemical admixtures for subgrades is that some of these materials contain significant quantities of CaO (quicklime) and $Ca(OH)_2$ (calcium hydroxide, or hydrated lime). Flue gas desulfurization --FGD-- (wet and dry) processes used at some coal-fired power plants and oil refineries produce significant quantities of byproducts containing varying, but significant, quantities of CaO and $Ca(OH)_2$. When the CaO and $Ca(OH)_2$ in the byproducts are mixed with clay and water, pozzolanic reactions[1] occur. Bearing strengths of compacted byproduct-clay mixtures generally increase and are several times greater than the strengths of the same compacted clays without the chemical admixture.

In 1986, the Kentucky Transportation Cabinet sponsored research to examine the potential use of byproducts in highway construction for modifying highway soil subgrades. One byproduct selected for a trial study was a residue from an atmospheric fluidized bed combustion (AFBC) process of an oil refinery. Atmospheric fluidized bed combustion is an advanced process that provides an environmentally acceptable method of reducing sulfur dioxide emissions in the refining process. Construction and operation of fluidized bed combustion units in oil refineries and coal-fired electric generating plants in Kentucky represent high volume sources of byproducts that normally require disposal in landfills at substantial costs. The AFBC byproduct contains a significant amount of CaO and $Ca(OH)_2$ (Fig. 1). Production of byproducts represents large liability and operating expense to many industries.

The main focus of this paper is on the use of the AFBC material as a chemical admixture for soil subgrade stabilization. Short-and long-term behaviors of the AFBC-soil subgrades, and swelling problems of the AFBC-soil subgrade that arose during construction, are discussed. Performances of the flexible asphaltic pavements constructed on the AFBC-soil subgrades after 12 years are described.

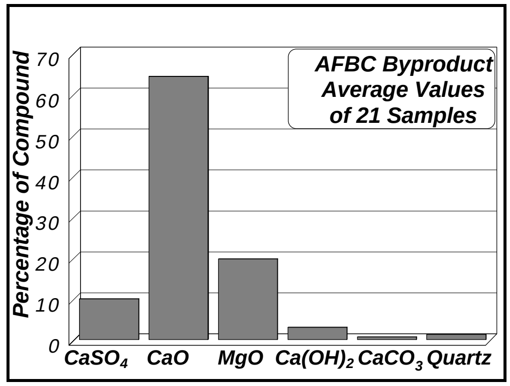

Fig. 1. AFBC Chemical Analysis

SITE LOCATION AND DESCRIPTION

Portions of Ky Route 11 were realigned and reconstructed in 1986-1988. The route is situated about 11.7 km north of Beattyville, Kentucky and is 9.6 km in length. Originally, the pavement was to consist of 19.1 cm of asphaltic pavement and 43.2 cm of dense graded limestone aggregate. A second option consisted of stabilizing the top 30.5 cm of subgrade with Portland cement (Type IP) for the entire route. However, the final plan[3] consisted of dividing the entire length of the roadway subgrade into sections, as shown in Table 1, and treating each subgrade section with different chemical admixtures. Two subgrade sections, measuring 1.74 km and 1.35 km, respectively, were treated with the AFBC byproduct.

GEOLOGY AND SOIL PROPERTIES

Geology of the highway corridor consisted of interbedded layers of shales, sandstones, siltstones, and coal. Soils along the corridor are residual derivatives of those materials and were classified as CL and ML-CL by the Unified Classification System[4] Liquid limit[4] and plasticity indices[4] of the natural soils of the two AFBC subgrade sections ranged from 36 to 43 percent and 12 to 15 percent, respectively, and were classified as CL. Approximately 70 percent of the particles[4] passed the number (U.S. standard) 200 sieve (0.075 mm). California bearing ratio [4, 5] (CBR) of a typical soil from one AFBC section compacted to 95 percent of maximum dry density and optimum moisture content, after soaking, was 3.7 percent. Theoretical studies[6,7,8,9] and practical experience[3] have shown that if the CBR value is less than about 7, then the subgrade should be stabilized to avoid pavement failure during and after construction. When the tire contact stress is 554 kPa, and as assurance against failure, stabilization should increase the subgrade CBR strength to a value of 10, or greater. CBR and unconfined compressive strength testing [3,4,5] showed that substantial strength gains could be obtained by mixing the AFBC spent lime with the subgrade soils.

Table 1. KY 11 Experimental Sections

Chemical Admixture	Percentage of Admixture	Length (km)
AFBC 1	7	1.74
Cement	7	0.92
Hydrated Lime	5	1.65
MKD	10	0.83
Cement	10	2.80
None (untreated)	0	0.3
AFBC 2	10	1.35

CBR strength of a soil from AFBC section number 1 that had been mixed with 7 percent (by dry weight) of the AFBC byproduct was 48. The AFBC-soil mixture was compacted to 95 percent of maximum dry density [4] and optimum moisture content and soaked. CBR strength of the untreated soil compacted to the same conditions was only 3.1. Unconfined strengths of the AFBC-soil mixtures were about four times larger than strengths of compacted, untreated specimens. In the initial laboratory study, testing did not show that swelling of compacted AFBC-soil mixtures would be a problem. Vertical swell of a compacted specimen, which was soaked for 96 hours[4], or less, was only 3.3 percent. Typically, maximum values of swell of compacted Kentucky soils range from about 3 to 15 percent. Soils that swell more than about 5 percent may cause damage to pavements if the swelling occurs after paving. Unfortunately, the initial laboratory testing did not detect detrimental swelling and was performed to determine the value of CBR and not swell. In retrospect, the AFBC lime-soil specimens should have been allowed to soak for longer periods to detect large swelling.

SELECTION OF OPTIMUM PERCENTAGE OF CHEMICAL ADMIXTURE

The percentage of the AFBC byproduct (and other chemical admixtures) necessary to mix with the subgrade soils to obtain optimum strength was determined using procedures described elsewhere.[3,10] Each specimen was compacted to a known volume, dry density, and moisture content. Since optimum moisture and dry density vary with admixture percentage, compacted specimens were prepared at different AFBC percentages to develop relationships between percentage and optimum moisture content and dry density. For a selected admixture percentage, those relationships were used to find (by interpolation) the correct dry density and optimum moisture content to use in remolding AFCBC-Soil specimens. All test specimens were compacted at 95 percent of standard maximum dry density and optimum moisture content. After aging the specimens in sealed containers for seven days, unconfined compression tests[4] were performed. The optimum percentage of chemical admixture is the point at which no increase (or only a slight increase) occurs in the unconfined compressive strength as the percentage increases. Maximum strength occurred when about 5 percent (by dry weight) of the AFBC material was used. To compensate for loses during field mixing, a percentage of 1.5, or 2, is usually added to the optimum percentage. Percentages of 7 and 10 of the AFBC byproduct were selected for mixing with subgrade soils of the two AFBC sections.

SHORT-TERM BEHAVIOR OF AFBC SPENT LIME-SOIL SUBGRADES

Two months after construction of the bituminous base courses, severe heave, or differential swelling, occurred. Pavement humps, occurred almost immediately after a rainy period, extended across the entire width of the pavement, and were perpendicular to the roadway centerline. Placement of the bituminous surface in all sections was delayed so that field and laboratory investigations could be performed. Pavement markers were installed on the bituminous base courses of the two AFBC-soil subgrades to monitor pavement swell. Optical survey points were also established on the bituminous pavements of the subgrades mixed with hydrated lime, cement, and multicone kiln dust. Maximum swell values from 25 different locations ranged from about 1.8 cm to 8.8 cm in the AFBC sections (See Fig. 2). In the subgrade sections treated with cement, hydrated lime and multicone kiln dust, the maximum values of swelling were only 0.1 to 1.25 cm. To observe the expansive characteristics of the AFBC lime-soil subgrade, a trench was excavated in a heaved area (station 279+80). In situ CBR values of the exposed subgrade in a humped area were not, necessarily, lower than the CBR values of areas free of humps. In one humped area, the in situ CBR was 38 percent while the CBR near the edge of the lane was 40. Each had corresponding moisture contents of about 16 percent. In April of 1988, in situ CBR tests were conducted during the milling operation of the two AFBC sections. Near station 305+55, a humped area, a field CBR of 13 was obtained. In a non-heaved area, the CBR was 37. Moisture contents were 36 and 27 percent, respectively.

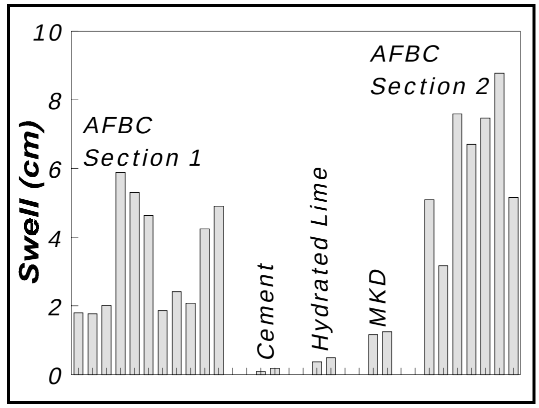

Fig. 2. Maximum measured values of swell --October 1987 to August 1988.

Specifications required that all subgrades be compacted to a minimum dry density of 95 percent of standard maximum dry density and ±2 percent of optimum moisture content. Relative compaction, or the ratio of field dry density to the laboratory dry density, was equal to or greater than 95 percent at various stations along the lengths of the two AFBC lime-subgrade sections and averaged 98.1 percent. Relative compaction of the untreated section averaged 99 percent. For the entire 9.6 km roadway subgrade at 85 locations, relative compaction averaged 98.2 percent. Compaction of all sections met the dry density specification. Moisture contents of the AFBC section number 1 averaged about 1.4 percent greater than laboratory optimum moisture content. Field moisture contents at some 17 of 24 locations of the second AFBC section (70 percent) were smaller than laboratory optimum moisture content and, generally, averaged about 1.1 percent lower than optimum moisture content. Moisture contents of the first section met specifications. Moisture contents at two-thirds of the locations selected for testing on the second section met specifications. Generally, specifications were met for all sections.

To examine the long-term swelling potential of compacted AFBC spent lime-soil mixtures, six long-term, laboratory swell tests were performed on soil specimens compacted in CBR molds and mixed at AFBC percentages of 7, 15, and 30. A long-term swell test was performed on a specimen of the untreated soil from one of the three stockpiles. Laboratory swell monitoring periods ranged from 48 to 186 days. After completion of primary swell, monitoring of swell continued until a sufficient period had elapsed to establish the pattern of secondary swell (See Fig. 3). Secondary swell is linear when the swell values are plotted as a function of the logarithm of time. One of the six AFBC-soil specimens consisted of material obtained from the field mixing operation. Another specimen was composed of material from a trench excavated at station 279+80. Swell measurements of those two specimens covered a period of some 48 days. Total values of swell of the two specimens were only 2.9 and 0.8 percent, respectively. This suggested that a large portion of the chemical reaction may have already occurred at that particular location (and probably at other locations) at the time the field specimens had been obtained. However, values of swell measured in the field at other locations were much larger than the values of swell observed in the two laboratory tests.

A typical plot of laboratory vertical swell (in percent), as a function of the logarithm of time, of an AFBC lime-soil specimen that contained 15 percent of the AFBC lime is shown in Fig. 3. The swell

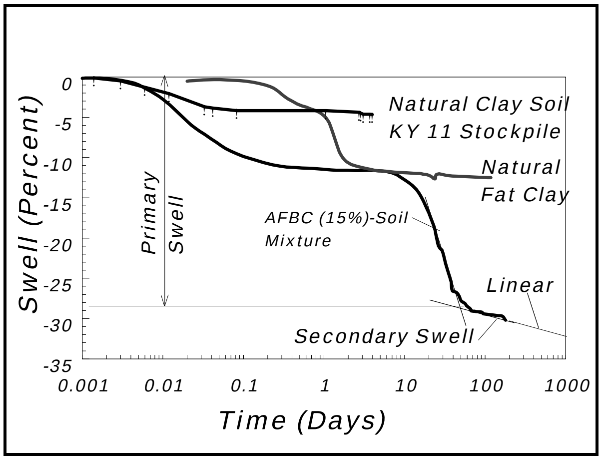

Fig. 3. Laboratory swelling curves.

of the AFBC specimen is compared to swell of a remolded clay specimen of soil from a corridor stockpile and a typical Kentucky soil that contains a high percentage of clay. Total swell of the AFBC specimen is about 30 percent while the values of swell of the two untreated soil specimens are about 5 and 14 percent, respectively. Periods of swell of the AFBC lime-soil specimen and the untreated clay specimen were 179 days and 4 days, respectively.

To predict the time required for completion of primary swell of the AFBC lime-soil subgrade in the field, the AFBC swell curve in Figure 3 was analyzed to find a coefficient of primary swell (opposite of a coefficient of consolidation) based on Terzaghi's theory[11] of consolidation. Using this concept in reverse, the estimated time for completion of primary swell was calculated to be about 400 days. The first section of the AFBC spent lime subgrade, stations 260 to 317+50, was constructed on August 8, 1987. Based on the above calculation, it was predicted that the completion of primary swell of the two AFBC sections, which were constructed at different times, would occur approximately at some date between October of 1988 and February of 1989. Similar calculations were made for the untreated specimen. Estimated time to complete primary swelling of the untreated soil subgrade was 31 days. This swelling probably occurred before paving.

After completion of primary swell, secondary swell of the AFBC lime-soil mixture occurs. Using the linear relationship (Fig. 3) between laboratory secondary swell and the logarithmic of time, a coefficient of secondary swell was computed and used to forecast the amount of secondary swelling[11] of the pavements in the AFBC sections. The total predicted value of secondary swell was 0.8 cm for a period between October of 1988 and January of 2015 (27.4 years from August 1987). Since the estimated secondary swell was small and the field and laboratory primary swelling amounts were close, the decision was made to leave the AFBC subgrades in place.

LONG-TERM BEHAVIOR OF AFBC SPENT LIME-SOIL SUBGRADES

Monitoring of the experimental sections has continued for about twelve years. Post-construction evaluation included performing optical surveys of points on the pavement to observe swelling characteristics, performing in situ CBR tests, obtaining undisturbed samples of the treated and untreated subgrade for laboratory testing, and making visual inspections of the pavement.

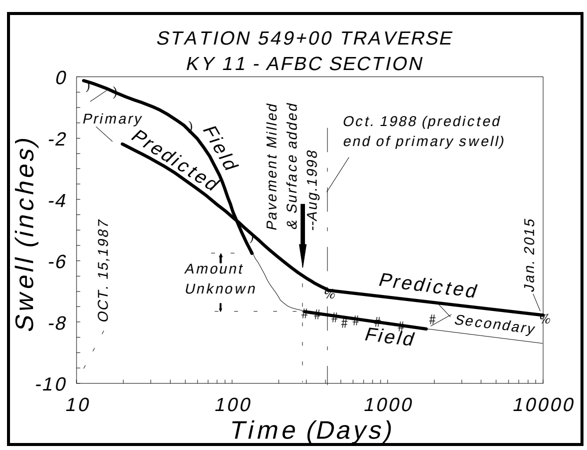

Fig. 4. Estimated and observed swell.

In August of 1988, the pavements within the AFBC sections were milled to remove portions of the heaved asphaltic surfaces. Subsequently, an asphaltic surface course was placed on the base courses of the AFBC sections and other sections of the project. All surface points had to be reestablished. Subsequently, monitoring continued at all locations. Maximum swell measured from August of 1988 to February of 1993 was about 0.6 cm (Fig. 4). Although swelling continued after placement of the surface course, the rate of swelling decreased significantly when compared with swelling before milling. The portion of the field curve before milling represents primary swell, which occurred rapidly. Shape of the field curve is similar to the shape of the laboratory curve. The portion of the field curve after milling is linear on the semi-logarithmic graph. Therefore, pavement swelling that has occurred after placement of the asphaltic surface course is secondary. Projecting the linear portion of the secondary curve, only about 0.32 cm of swell will occur from February of 1993 to March of 2015 (27.4 years after subgrade construction). After 27.4 years, the swell will be inconsequential. Swell of the pavement within the AFBC sections has been nominal since milling. However, in one isolated area of one AFBC section, substantial, non-uniform, swelling occurred and milling was required to eliminate surface humps. There also was a prominent crack within the milled area.

Moisture contents of the untreated subgrade have increased with increasing time. Moisture contents of the untreated subgrade soils measured during construction and at various times throughout the 9.6-km roadway over the twelve-year study period are shown in Fig. 5 as percentile test value curves. These curves suggest that the moisture contents of the untreated subgrades increased from 1987 to 1993. After 1993, the moisture contents appeared to remain about the same. With increases in moisture contents, large decreases occurred in CBR strengths of the untreated subgrades. After 1993, measured in situ CBR values were 6 percent, or less. Immediately, after construction in 1987, the CBR strengths had ranged from 20 to 42 percent (Fig. 6).

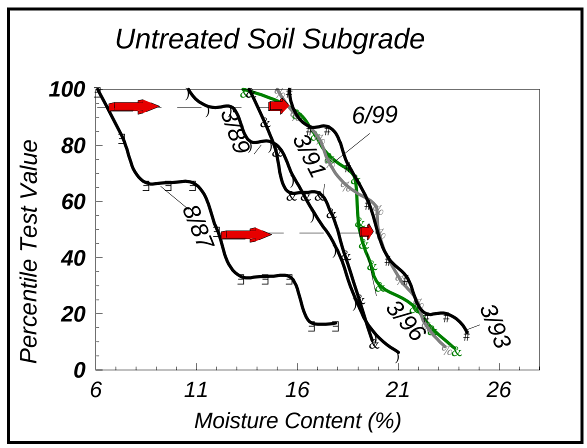

Fig. 5. Percentile test value as a function of moisture content.

Observed moisture contents of the AFBC subgrade sections ranged from about 9 to 20 percent during construction. However, subsequent measurements of moisture contents ranged from about 23 to 39 percent. Although moisture contents of the AFBC subgrades have increased over the twelve-year period, significant decreases in CBR strengths have not occurred (Fig. 7). Seven days after construction, field CBR strengths of the AFBC subgrades ranged from 34 to 53. From October of 1987 to March 1999, about 92 percent of the field

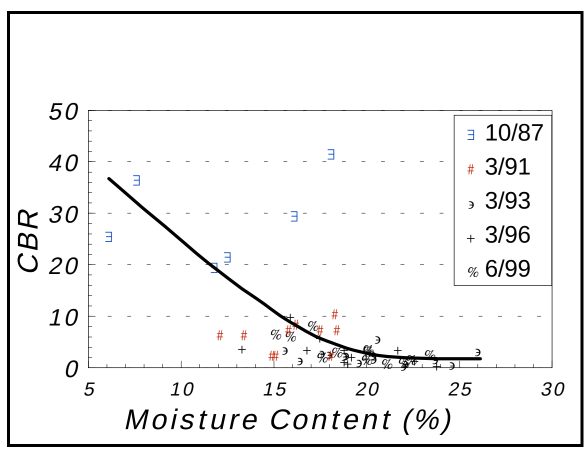

Fig. 6. CBR as a function of moisture content

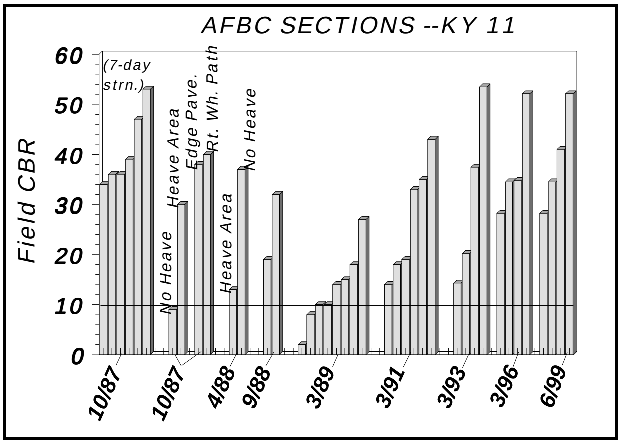

Fig. 7. Field CBR values over a 12-year span.

CBR values ranged from about 10 to 54. These values are generally much larger than minumum values required for good short-term and long-term stabilities.[7, 9]

Thin-walled tube samples[4] obtained in March 1993 were analyzed using x-ray diffraction (XRD) and Scanning Electron Microscope (SEM) methods. Ettringite, $CaAl_2(SO_4)_3(OH)_{12}$ X $26H_2O$, thaumisite, $CaSi(OH)_6(CO_3)$ X $12H_2O$, and gypsum, $CaSO_4$ X $2H_2O$ were present throughout the 30.5-cm depth interval of the subgrade. Ettringite (Fig. 8) was concentrated in the lower portions of the subgrade, although it was present throughout. Thaumisite and gypsum had approximately equal distribution throughout the depth. Exact amounts or percentages of these minerals could not be quantified. These minerals were not present in the original AFBC spent lime residue. Sulfate and portlandite, present in the spent lime can react with aluminum silicates present in the native soil in the presence of water to form ettringite and thaumisite. Gypsum can be formed by the reaction of anhydrite, $CaSO_4$, present in the spent lime with water.

SUMMARY

Two highway subgrade sections measuring 1.74 and 1.35 km were stabilized using a residue of an atmospheric fluidized bed combustion (AFBC) process of an oil refinery. The AFBC byproduct contains a significant amount of CaO and $Ca(OH)_2$ and laboratory tests showed that significant strength gains could be obtained when the byproduct was mixed with clay soils. Although swelling of the AFBC subgrades during construction occurred and caused formation of humps in the asphaltic base courses, the rate of swelling of the pavements has decreased since construction. Based on laboratory and field studies, the swelling of the AFBC-soil subgrades consists of primary and secondary swelling. Theoretical estimates of the rate and total amount of swelling, based on the laboratory tests, were made. Final paving was delayed until primary swelling**,** as shown from field measurements, was nearly complete. Predicted and observed rates and amounts of swelling were close. The humps of the asphaltic base courses were milled and the final asphaltic surface was placed. Secondary swelling measured over a period of about 5 years is very small. The small amounts of swelling that have occurred since placement of the asphaltic surface has not affected the pavement. The CBR strengths of the AFBC-treated subgrades have ranged from about 10 to 54. CBR strength of the untreated subgrade is typically less than about 6. Overall performance of the pavements resting on the AFBC-soil subgrades has been excellent over the twelve-year period. Scanning Electron Microscope

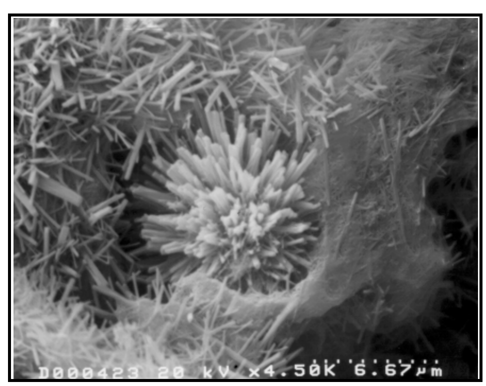

Fig. 8. View of ettringite in AFBC subgrade

(SEM) and x-ray diffraction (XRD) studies of subgrade samples in 1993 showed the presence of ettringite, thaumisite, and gysum throughout the 30.5-cm depth interval of the AFBC subgrades. These three minerals were not present in the other treated subgrade sections, or in the untreated subgrade. Apparently, the large amounts of swelling were a result of the growth of these minerals in the subgrades. AFBC byproducts, and other FGD byproducts, should not be used as chemical admixtures unless it can be shown from long-term laboratory, or field, swelling tests that a given byproduct does not exhibit large amounts of swelling. Fundamental research is needed to understand the swelling mechanism of these byproducts fully and to devise ways of mitigating the swelling tendencies of these materials.

ACKNOWLEDGMENTS

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