Measuring Thermal Expansion of Lime-Fly Ash-Aggregate Compositions Using SR-4 Strain Gages

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This report presents the results of a laboratory investigation on use of SR-4 strain gages for evaluation of the thermal expansion of lime-fly ash-aggregate compositions. The study was initially concerned with the selection of the most suitable gages, their application, waterproofing, and the interpretation of the results. Beams (12 in. long, 3- × 3-in. section) were prepared with the same aggregate but with different percentages of lime and/or fly ash. Other beams were prepared with the same percentages of lime and fly ash but using aggregates with different amounts of fines. These beams were subjected to a temperature change of approximately 200 F (from -25 F to 175 F). Six different types of strain gages were applied to the beams and the expansion caused by the temperature change was measured. A steel beam of known thermal properties was used for a thermal expansion reference in an active gage-dummy gage system of temperature compensation.

The influence of dry density, percent of lime and/or fly ash, and percent of fines in the aggregate parameters on the coefficient of thermal expansion is also discussed. It has been found for example that the coefficient of expansion increases with an increase in the percent of lime, other variables remaining constant.

•THE USE of cement and other hydraulic binders, such as a combination of lime and fly ash, has been increasingly developed in the field of highway construction. The problems involved are numerous and have been the subject of a great deal of laboratory and field research work in the United States and elsewhere. The problem of thermal expansion of stabilized subgrades is, indeed, a complex one.

In many jobs involving stabilized subgrades of a semi-rigid nature, various cracks and fractures have been observed which frequently cannot be attributed to normal degradation. In these stabilized subgrade layers, no joints are in use and a significant thermal expansion could have very well induced sufficient stresses to cause cracking, swelling and/or dislocation.

In a preliminary investigation the methods of measuring linear expansion—such as, mechanical calipers or gages, optical means (interference fringes) displacement of a fluid, and SR-4 electrical strain gages—were evaluated. SR-4 strain gages were finally chosen for accuracy, ease of reading, adaptability and consistency of results.

Applying SR-4 strain gages to a fairly homogeneous material such as the lime-fly ash-gravel combination was, in itself, a problem. It was also necessary for the gages to produce accurate and reproducible results at various temperatures ranging from -10 to 170 F.

Some of the various parameters (dry density, percent of lime and/or fly ash, percent of fines in aggregate) influencing the variation of the thermal coefficient of expansion were also investigated.

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EVALUATION OF VARIOUS SR-4 STRAIN GAGES

As a preliminary step to the evaluation of the thermal coefficient of expansion it was necessary to determine the type of strain gages to be used. The gages were to be applied to a lime-fly ash-gravel composition similar to concrete in appearance. No large aggregate was to be used in the molding of the samples and the average size of the larger particles at the surface, where the gage was to be bonded, was of the order of 0.5 mm. Due to the only fairly homogeneous quality of the material, the gages used were to be of a sufficient gage length to average out the stress or expansion difference over the many grains of the aggregate. Possible effects of a protruding piece of aggregate, or of small holes on the surface, were minimized by special preparation of the surface consisting of an application of a thin layer of cement.

A successful strain gage application is a combination of many different factors that must be studied, compared, and weighed against each other before a choice can be made. Static strain measurements over a period of alternate loading and unloading conditions at changing temperatures impose the greatest demands on strain gage performance. The selection of the strain gage and associated accessories (bonding cement, waterproofing materials, and lead wires) must be made for each application in view of the limitations of each and the effect on the overall installation performance.

Types of Gages Evaluated

Six different types of gages were used, 3 in each of the two major types: the bonded wire type—paper base or bakelite base—and the etched foil type—epoxy base (Table 1).

Operating Temperature Ranges for Gages and Adhesives

The operational temperature limit of a strain gage depends on the individual components of the gage. The generally accepted temperature limits, for static strain measurements (Table 1) are based on ideal conditions during short-term testing where slight environmental changes do not create inaccuracies beyond the normally accepted limits for experimental stress analysis. Very conservative limits for this investigation were applied because the test periods were long and environmental conditions were constantly changing.

Bonding Adhesives

The nitrocellulose (Duco, SR-4 cement) adhesive, a solvent-release type, is specified for use only with paper-type and wire and foil gages from freezing temperatures to 180 F. The main advantages are low cost, easy storage and use, and rapid curing at room temperature.

A maximum temperature of 170 F was used to test the samples. Despite this, cracking, burning, bond slipping and important changes in the strain readings were noticed over the testing period (2 weeks of alternate heating and cooling), and this type of adhesive was rejected.

The epoxy elevated-temperature curing type (EPY-400) adhesive is designed for use

TABLE 1

DESCRIPTION OF SR-4 GAGES

Gage	Description	Bonding Cement	Max. Operating Temp. (°F)	Resistance (ohms)	Gage Factor	Length (in.)	Width (in.)	Price per Unit ($)
A[1]	Constantan wire	Duco	180	300	2.10	6	1/32	2.00
B[1]	Constantan wire	Duco	180	120	2.10	1	3/32	1.60
D[2]	Constantan foil	EPY-400	300	180	2.06	1/2	1/2	3.50
C[2]	Constantan foil	EPY-400	300	180	2.05	1	1/4	4.20
E[2]	Constantan foil	EPY-400	250	750	2.11	6	0.74	9.00
F[3]	Constantan wire	EPY-400	250	350	2.08	7/8	9/32	2.20

[1]Paper base. [2]Epoxy back. [3]Bakelite back.

with foil and wire, bakelite and epoxy type gages at more than 400 F. The cement has an extremely high resistance per unit volume allowing maximum resistance to ground and heat distortion of all epoxies tested. It requires a bonding pressure of 10 to 15 psi with any one of the following time-temperature cures: 1 hour at 400 F, 2 hours at 350 F, 3 hours at 300 F, or 6 hours at 250 F. The 6 hours at 250 F cycle was used. The low temperature cure was employed to protect the gage from high desensitization. The length of the curing time was not a serious problem in this study; however, disadvantages of this adhesive are the short life of the cement after it has been mixed (24 hours unless stored at -30 F) and excessive cost (approximately $24.00 for 3 packs of 20 g each).

As an average, one 20-g pack provided 100 sq in. of bonded area (first layer of epoxy plus bonding of gage), representing roughly the preparation of 10 samples, carrying 3 gages each (gages C, D and E).

This adhesive performed satisfactorily; no cracking or noticeable slipping was noted. Some gages were retested 6 months after their initial installation and gave readings similar to the initial readings (correct to the nearest 10 to 20 μ in./in.). The EPY-400 was then used to bond all gages of a similar type throughout the test.

Selection of Gages

The final selection of the most suitable gage was based on the following criteria:

1. Greatest sensitivity to longitudinal strain (gage factor);
2. Minimum sensitivity to lateral strain (transverse sensitivity);
3. Lowest sensitivity to temperature (resistivity change coefficient);
4. Maximum electrical and dimensional stability;
5. Ease of application; and
6. Cost of installation.

Two gage types (D and F) were selected, and were both used on each sample tested. An E gage was used jointly with D and F gages on samples where determinations of the tensile and compressive stress-strain curves were to be made after the thermal expansion coefficient had been determined.

Types A and B Gages.—The two paper back gages, used only up to 160 F, were severely damaged. Cracking of the cement was observed, the stability was poor, and the readings were not consistent. Despite their low nominal and installation costs these gages were abandoned.

Type C Gage.—The C gage gave good results but was of comparatively higher cost.

Type D Gage.—The D gage is one of two gages which appeared to be most acceptable. It provided excellent stability and consistency in the results, as did type F. However, values obtained through this gage were always 0.1 to 0.2 μ in./in./^{0}F higher than those obtained through the use of type F. The explanation for this consistent difference is the comparatively higher transverse sensivity of type D which results in a greater resistance change. Thermal expansion is the same along any direction, and more specifically, the strains created by temperature change along two perpendicular axes are equal.

Type E Gage.—Type E is the same epoxy-backed, etched foil type as gage D but with a 12 times longer active gage length. It gave excellent results also, but was not used when only thermal expansion evaluation was required because of its 3 times higher total cost of installation compared with gages D and F. The same remark about a consistent difference in result with gage F is still valid.

Because of their long gage length (6 in.), these gages gave excellent results in the establishment of a stress-strain curve for the determination of a modulus of elasticity. Gages D and F, on the other hand, gave poor results in this last evaluation for two reasons: (a) they cover a small area where the stress is not representative, and (b) the failure zone which is the location where it is desired to average the strain was not covered by these short length gages.

Type F Gage.—Of the 6 gages that were evaluated this bakelite backed, constantan wire gage, 1 in. long, appears to be the most suitable. Its stability and consistency were excellent. Epoxy provided a strong carrier for the wire, which is thus less sensitive and less affected by a protruding grain of sand or irregularities in the surface on which the gage is to be bonded. J. Taylor of Lehigh University experimented on concrete with a similar gage (BLH AB-3 gage length 13/16 in.) and reported excellent results.

Compensating Materials or Standards

The coefficient of expansion of the standard had to be of the order of magnitude of the one for the compositions studied, which was assumed to be 6 μ in. in./°F. A 4340 alloy grade steel with a linear coefficient of expansion between 0 and 200 F of 6.3×10^{-6} per °F, within an accuracy of 2 percent was used. The size of the standard was 1 × 2.5 × 12 in. (Fig. 1). To verify the theory of the evaluation of thermal expansion through the uses of SR-4 gages, two other standards were used and checked against the alloy steel.

1. A ¼- × 3- × 12-in. aluminum beam with a given coefficient of expansion of 12.72 μ in./in./°F showed an expansion of 12.84 μ in./in./°F through the use of the SR-4 gages.
2. A ⅜- × 3- × 12-in. medium grade carbon steel of unknown thermal expansion coefficient was tested. A coefficient of expansion of 6.42 μ in./in./°F was found which compares with a handbook average value of 6.7.

Throughout the remaining evaluation of the thermal expansion of the lime-fly ash-aggregate compositions only the alloy steel compensating beam was used as the reference standard.

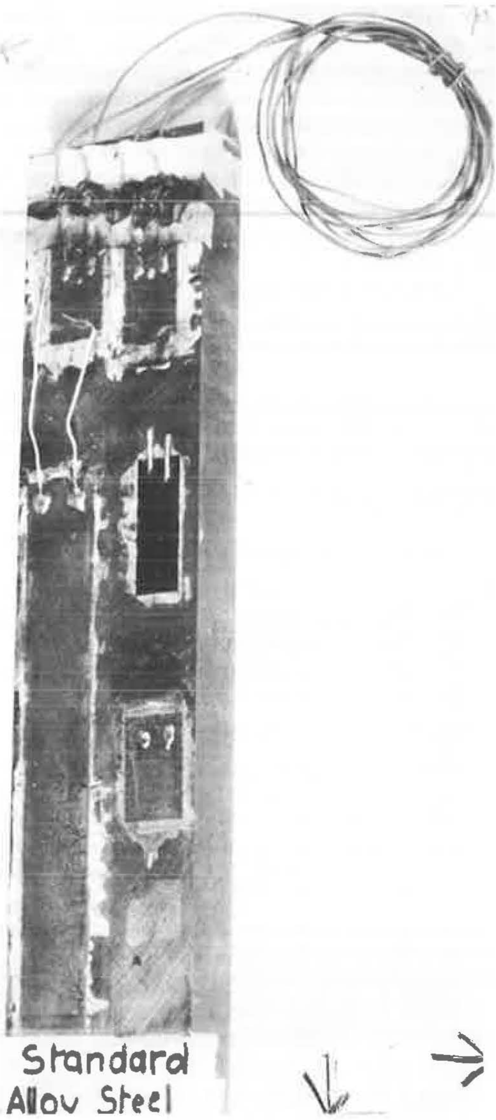

Figure 1.

THERMAL COEFFICIENT OF EXPANSION OF LIME-FLY ASH-AGGREGATE COMPOSITIONS

In all, 30 beams or cylindrical samples were used for the purpose of evaluating the influence of the dry density, percent of lime and/or fly ash, and percent of fines (material passing through No. 200 sieve) on the thermal expansion coefficient.

Materials for Molding Test Specimens

Aggregate.—The aggregate used in making the beam-type specimens was a uniform sandy gravel with less than 5 percent fines, ¾-in. maximum size particle.

Lime and Fly Ash.—A standard raw Eddystone fly ash and a commercially available hydrated lime were used.

Manufactured Aggregates.—"Manufactured gravels" that were prepared for a previous investigation (1) were used in the study portion concerned with the effect of fines on thermal expansion. The properties and grain-size distributions of these gravels were previously reported (1); however, Figure 2 is repeated herein to show the grain size curves.

Preparation of Test Specimens

Mixing of Materials. —The materials were mixed both by hand and/or with a mechanical mixer. The air-dried materials (lime, fly ash, gravel) were first blended into a uniform mixture; the water was then incorporated into the mix and evenly dis-

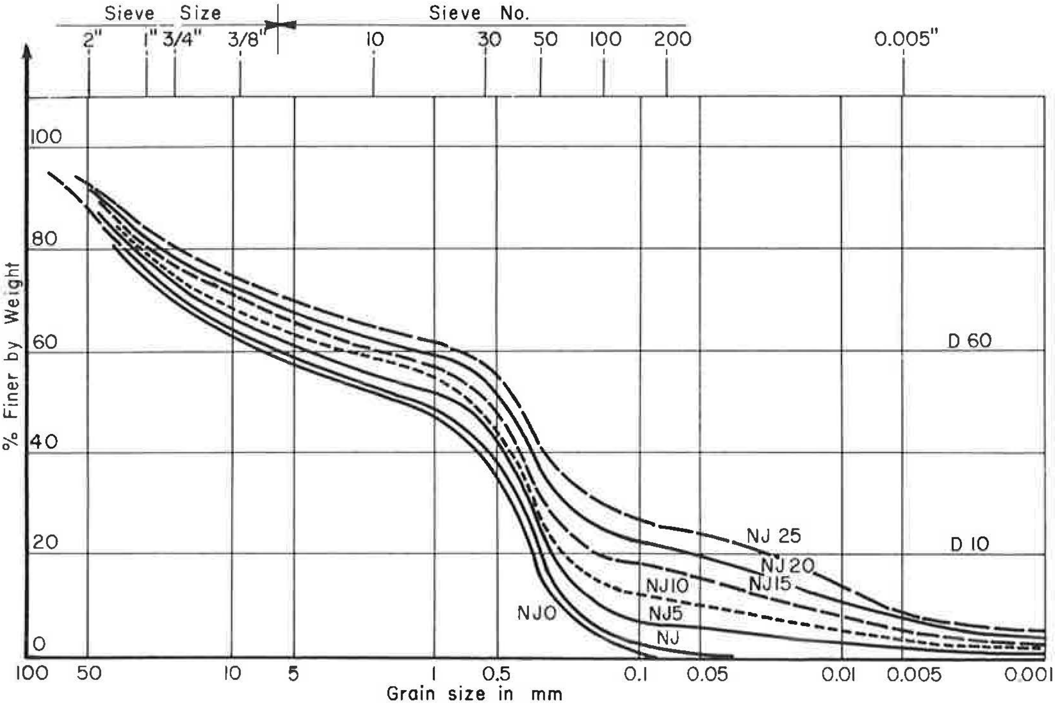

Figure 2. Grain size curves for natural and manufactured gravels.

TABLE 2

DATA FOR 3- BY 3- BY 12-IN. BEAMS

Purpose	Beam	Mix (%) Lime	Mix (%) Fly Ash	Mix (%) Gravel	Accel. Curing (days)	Comp. Strength (psi)	Dry Density	Expansion (μ in./in./°F) As Tested	Expansion (μ in./in./°F) Corrected
Effect of dry density change	4.10.91.1	4	10	90	7	920	117	5.45	–
	.2	4	10	90	7	920	122	5.62	–
	.3	4	10	90	7	920	130	5.93	–
	.4	4	10	90	7	920	134.5	6.32	–
Effect of lime and fly ash content	2.10.90	2	10	90	7	640	131.5	5.34	5.2
	4.10.90	4	10	90	7	920	130.5	5.85	5.82
	6.10.90	6	10	90	7	1,050	129.5	6.02	6.06
	2.15.85	2	15	85	7	840	127.5	5.10	5.35
	4.15.85	4	15	85	7	1,080	129.5	5.93	6
	6.15.85	6	15	85	7	1,160	125.5	6.16	6.3
	2.20.80	2	20	80	7	–	116.7	5.56	5.9
	4.20.80	4	20	80	7	–	112.5	5.56	6.17
	6.20.80	6	20	80	7	–	112	5.75	6.42
	8.20.80	8	20	80	7	–	112	6.0	6.68
Comparison	Soil cement	7.2% cement			7[a]	1,400	128.6	6.5	–
	concrete	3,000 lb			28[a]	3,000	140	5.7	–

[a]Moist cured.

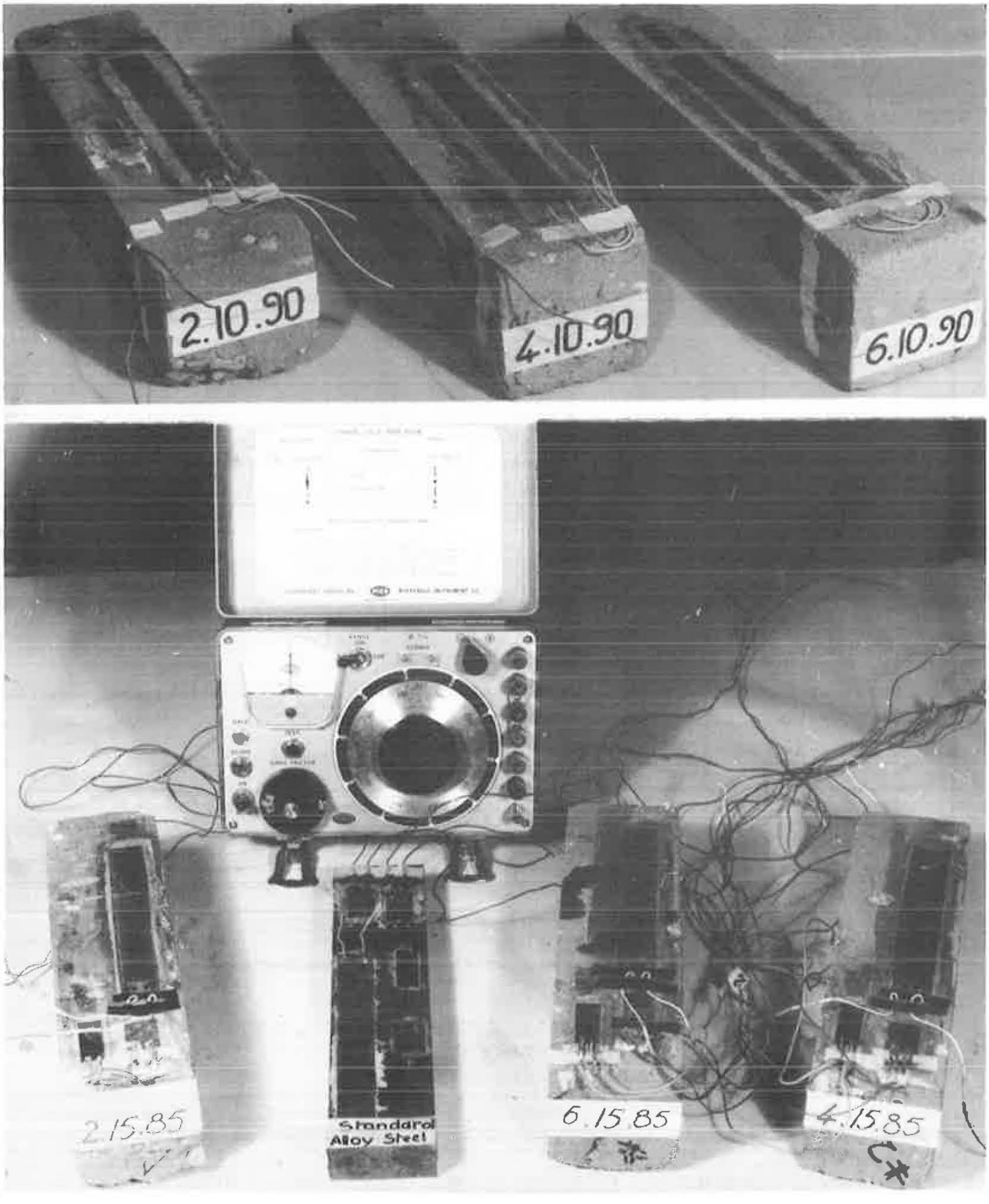

Figure 3. Sample beams and testing setup.

tributed. The amount of water added to each mixture was that required to produce the maximum dry density using Standard AASHO compaction (5.5-lb rammer).

Composition of Specimens. —A series of 4 beams, 12 in. long and 3- × 3-in. cross-section, was prepared to study the dry density effect. Beams were molded using a 4.10.90 mix (4% lime, 10% fly ash, 90% natural gravel), but with different compactions (Table 2).

Three series of beams, 12 in. long and 3- × 3-in. cross-section, were prepared with 10, 15 and 20 percent fly ash, respectively, to study the effect of percent of lime and/

or fly ash. In each series, beams with 2, 4 and 6 percent lime were molded (a beam with 8% lime was added to the 20.80 series). Natural gravel was used in all mixes (Fig. 3 and Table 2).

Seven series of two specimens each were molded to study the effect of percent of fines. Specimens were cylindrical in shape, 4-in. diameter and 4.6 in. high. A 4.12.88 mixture was used for all specimens, but for each series the mix was prepared using a different gravel (Fig. 4 and Table 3).

Curing of the Specimen.—All beams and cylinders were cured using an accelerated procedure, consisting of 7 days in a sealed container at 130 F. The specimens were then submerged for 24 hours in water. Before applying the gage, the samples were dried for two days in an oven at 250 F. After the gages were cemented on, all beams and cylinders were submitted to four 24-hr cycles of successive heating and cooling

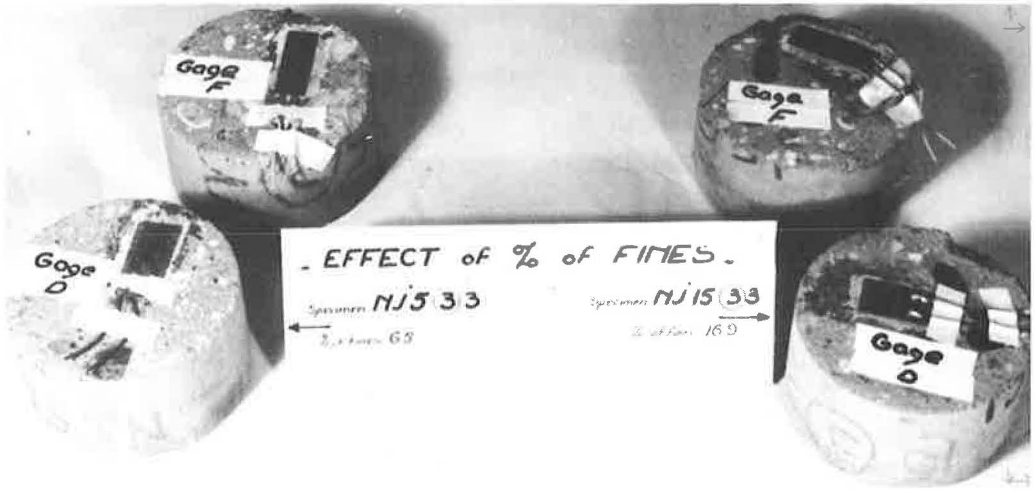

Figure 4. Cylindrical specimens.

TABLE 3

EFFECT OF PERCENTAGE OF FINES

Beam		Fines Passing No. 200 Sieve (%)	Compressive Strength (psi)	Dry Density (pcf)	Expansion (μ in./in./°F)	
					As Tested	Corrected
Nj.0	3 2	0	1,000	125.8	5.95	6.05
	3 3			123.5	6.32	6.72
Nj	3 2	1.4	1,340	129.5	5.85	5.80
	3 3			128	6.05	6.01
Nj.5	3 2	6.5	1,100	131	6.06	5.92
	3 3			130.3	6.0	5.90
Nj.10	3 2	11.7	1,050	125.1	6.0	6.10
	3 3			124	6.12	6.27
Nj.15	3 2	16.9	950	125.8	6.05	6.15
	3 3			125.1	6.20	6.30
Nj.20	5 2	22.1	905	126	6.12	6.20
	5 3			125.8	6.16	6.26
Nj.25	3 2	27.0	820	122	6.12	6.33
	3 3			121	6.22	6.47

between 200 and 0 F. All these curings were necessary to insure stability and consistency in the readings.

Application of Strain Gages to the Specimens

On the beams, gages D and F were bonded side by side. The cylindrical specimens were first sawed cross-sectionally. A fairly homogeneous area, without any particles over 3 mm, was selected on the exposed face of the cylinder. One of the gages was bonded to this area, and the other gage was bonded on its exact counterpart on the other half of the cylinder. Both were bonded with their strain sensitive axes lying in the same general direction. In addition, gage E was bonded on certain rectangular beams wherever necessary for further study.

Preparation of the Bonding Area.—The selected area of the specimen was cleaned with cotton soaked in carbon tetrachloride, until the cotton remained clean. Cleaning was continued using toluol and finally acetone. On the cleaned area, which was slightly larger than the gage used, a $\frac{1}{64}$-in. layer of epoxy was applied with a clean spatula and cured at 300 F for 4 hr. When the specimen had cooled, the epoxy layer was thinned down by using acetone applied with cloth pads. The thinning was continued until the specimen surface reappeared clean and smooth and without protuberances.

Bonding of the Gage.—The following procedure was used to apply the gages to the specimens:

1. Cleaning with acetone.
2. Application of a liberal coat of epoxy.
3. Application of the gage (squeezing out excess epoxy, and all trapped bubbles of air).
4. Taping on the top of the gage a teflon sheet and then a rubber pad slightly larger than the gage.
5. Curing for 6 hours at 250 F under a 10- to 15-psi pressure.
6. After cooling, checking resistance to ground and the gage.
7. Soldering of the lead wires.
8. Waterproofing.

The specimens were tested in a series of 4 or 5 at a time. All common lead wires were one foot long and soldered together. A common lead wire was then connected from the juncture to the strainometer. All other lead wires were 3.5 ft long.

Testing Procedure

A 215 F range of temperatures (-15 F to 200 F) was used. The specimen and compensating standard were first placed in an oven. The temperature was raised slowly to 200 F, maintained for 24 hours, and then readings of the strain were made. For the next 24 hours, the specimen was cooled to room temperature. This 48-hr cycle was then repeated 3 to 4 times; readings at the maximum temperature were taken in each cycle. At the end of this 3- or 4-cycle period, zero readings at room temperature were also taken. Zero readings at room temperature were made only for reference, and to verify roughly the linearity of the coefficient of expansion over the temperature range.

The specimens were then placed in a freezer where the preceding cycles were repeated identically but from room temperature to -15 F. Zero readings at room temperature were also taken at the end of these cycles.

The difference in expansion between the standard and the specimen over the 215 F range was then computed using the average of the readings. The coefficient of expansion was then computed. Table 4 gives data for specimen NJ 20.5.1.

Results

For all the series of specimens except those used to study the effect of dry density, the beams and cylindrical samples were compacted identically to eliminate dry density as a variable. Furthermore, to correlate all the values a standard dry density was

TABLE 4

TYPICAL DATA FOR STRAIN GAGE MEASUREMENTS

Gage Type	Cycle No.	Test Reading			Room Temperature Readings		Results			
		T° C	Readings	Average	T° C	Reading	Δ T° C	Δ Reading	Δ Expansion	Expansion
	1	+94	-2, 605							
F	2	+94	-2, 560	-2, 575	+33	-2, 545				
	3	+97	-2, 570				120	-45	-0. 38	10. 92
K = 2. 08	1	-26	-2, 530	-2, 530						
	2	-26	-2, 525		+33	-2, 550				
	1	+94	-2, 480							
D	2	+94	-2, 460	-2, 470						
	3	+97	-2, 470		+33	-2, 455	120	-50	-0. 43	10. 87
K = 2. 06	1	-26	-2, 420	-2, 420						
	2	-26	-2, 420		+33	-2, 450				

Note: Compensating material: alloy steel standard, 11.3×10^{-6}; sample NJ 20-5-1 (March 21, 1962). Readings are in µ in./in./°C.

assumed. On this basis and using the dry density curve, a correction was then applied to each coefficient of expansion obtained through testing. The resulting value was called the corrected value.

When studying the effect of percent of lime and/or fly ash, the standard dry density assumed was 130 pcf. When studying the effect of percent of fines the value taken was 128 pcf. This was assuming that all mixes tested for dry density effect would give a family of curves parallel to the curve in Figure 5. Using this curve, the thermal expansion for a 128-pcf dry density is 5.80×10^{-6} in./in./° F, and for a 126-pcf dry density is 5.72×10^{-6} in./in./° F, a difference of 0.08. If a sample with a 126-pcf dry density is tested and a value for the thermal expansion of 6.12×10^{-6} in./in./° F is obtained, the corrected value is $6.12 + 0.08 = 6.20 \times 10^{-6}$ in./in./° F. This was the case for sample NJ 20. 5. 2.

The results of the investigation are as follows:

1. Dry Density Curve (Fig. 5). —The thermal expansion increases with an increase in dry density. The 5th point on the curve was provided by the 4-10-90 beam of the 10-90 series.
2. Thermal Expansion vs Percent of Fines (Fig. 6 and Table 3). —It would appear that for a certain optimum value of the percent of fines present in the mix (value around 5%) that the thermal expansion is a minimum. On both sides of this value the thermal expansion increases. When the percent of fines increases, the curve is flattening, indicating a possible maximum value.
3. Thermal Expansion vs Percent of Lime (Fig. 7) . —Three curves were drawn showing again an increase in the expansion with an increase in the percent of lime, all other variables remaining constant.
4. Thermal Expansion vs Percent of Fly Ash (Fig. 8). —Three curves were obtained corresponding, respectively, to 2, 4, and 6 percent lime. There is an increase of the expansion with an increase of the percent fly ash, all other variables remaining constant. Apparently, the 3 curves would, if extended, converge toward the same value.
5. For the purpose of comparison, a soil-cement beam stabilized with 7. 2 percent cement and a 3, 000-lb concrete beam were molded and tested (Table 2 and Fig. 5).

This study was a part of a larger investigation of the thermal expansion of the lime-fly ash-gravel composition and its parameters. Its primary objective was to determine the value of the SR-4 strain gage in such an investigation. Parameters such as the physical properties of the gravel particles and gravel aggregate, water content, and effect of subfreezing temperatures on a moistened sample, were not considered. It was concluded that in such a study SR-4 gages would be of great value. The epoxy insured complete waterproofing of the gage.

This investigation showed that variation in the mix itself and in the compaction do affect the thermal expansion of lime-fly ash-gravel compositions. Although these results should be verified by additional data, the present study indicated the following:

1. The thermal effect increased substantially with an increase in dry density, in

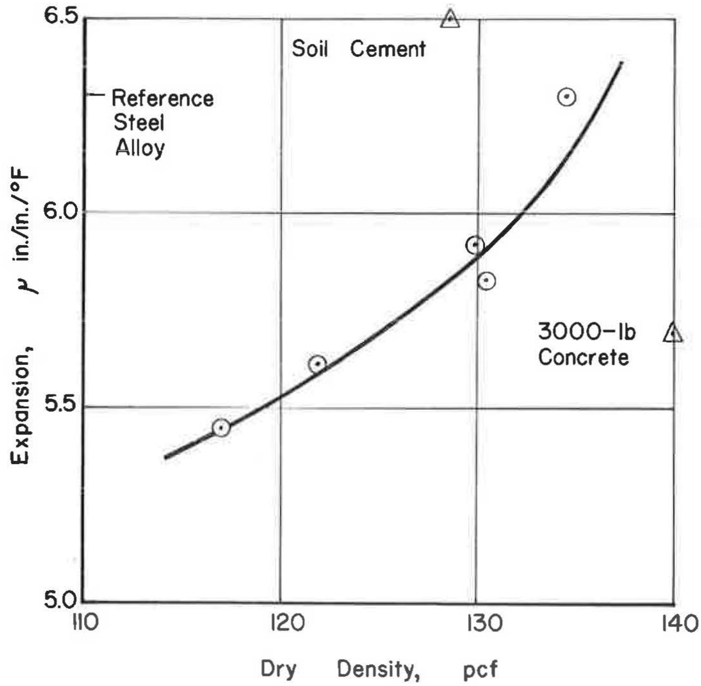

Figure 5. Thermal expansion vs dry density for a 4.10.90 mix.

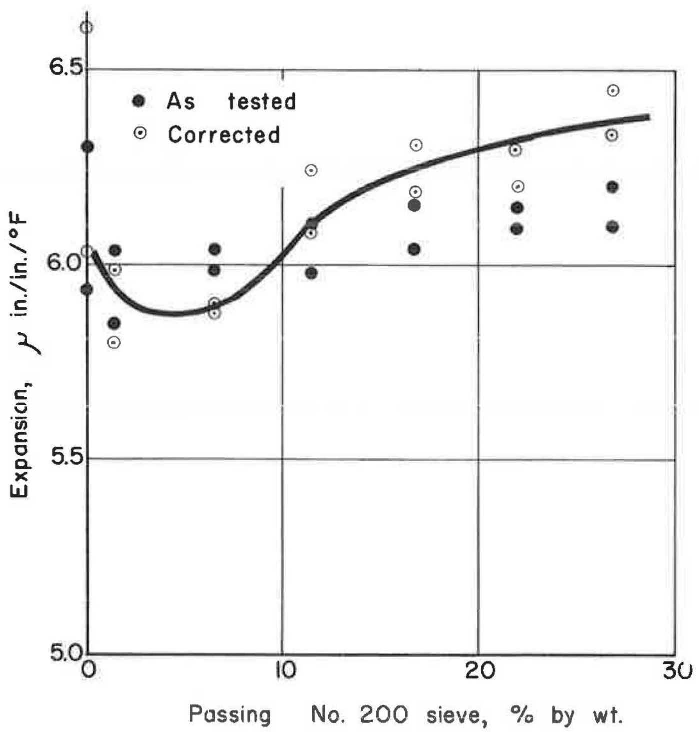

Figure 6. Thermal expansion vs percent of fines for a 4.12.88 mix.

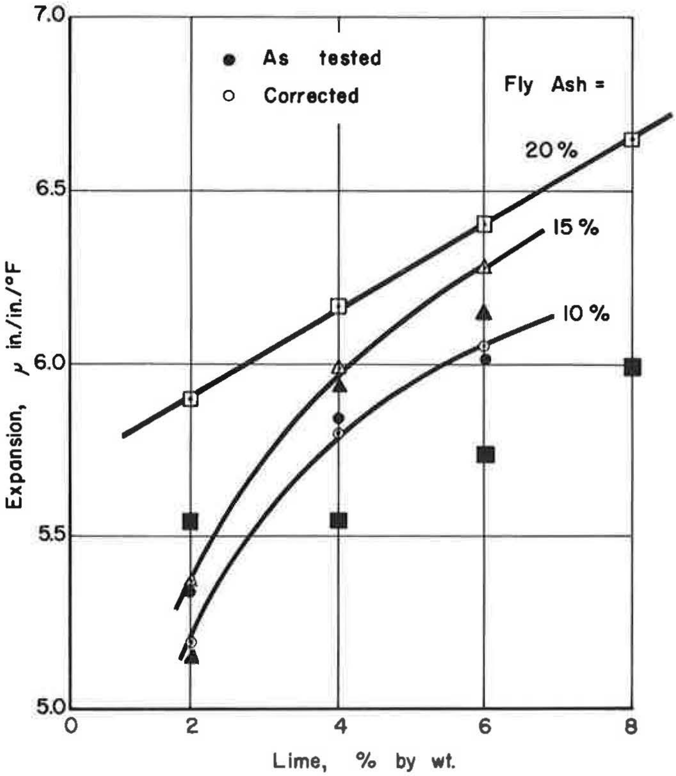

Figure 7. Thermal expansion vs percent of lime, percent fly ash constant.

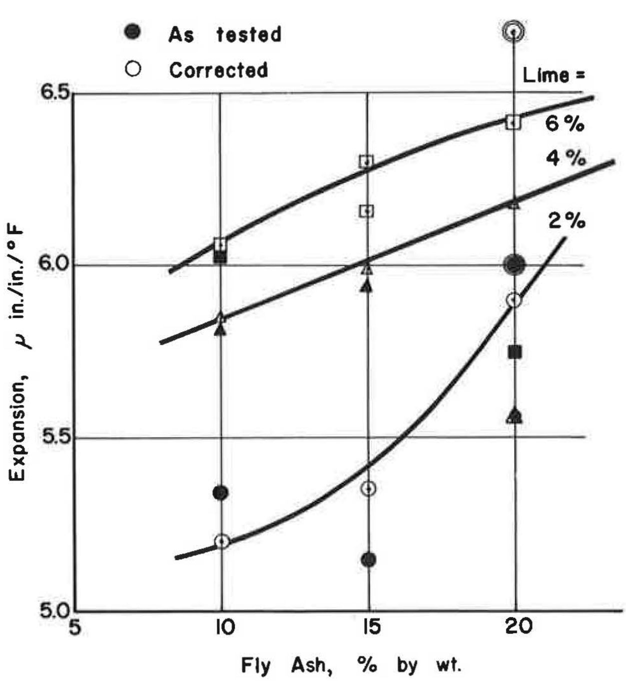

Figure 8. Thermal expansion vs percent of fly ash, percent lime constant.

percent of lime and/or fly ash—the other two variables remaining constant.

2. Lime-fly ash-gravel compositions expanded at a rate comparable to that of steel (6×10^{-6} per °F).

3. There is an optimum value of the percent of fines in the gravel for which the coefficient of expansion will be minimum.

4. After proper selection, careful installation and use, and intelligent interpretation of the data obtained, strain gages can be used successfully for a laboratory investigation of strain in lime-fly ash-gravel compositions and similar aggregates.

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