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Variations in Quality of Treated Materials Arising During Construction

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The statistical variation in quality of cement- and lime-treated materials that arises during construction was studied by comparing the flexural properties of samples recovered from nine contracts with those of samples prepared in a laboratory with the same raw materials. In this way the variations could be replicated and the significance for structural pavement design could be evaluated. The properties examined are bending strength, strain at break, and the elastic modulus. Samples recovered from the contracts indicated that, relative to the evaluated properties, a day's work may be accepted as homogeneous. The differences among sections constructed on different days were extremely significant, even when the sections were constructed with the same materials, by the same contractor, and according to the same specifications. Thus sections constructed on different days could not be regarded as of the same quality and as having the same properties, which varied significantly within a layer. The upper half of the layer seemed to have higher values than the lower half. The difference between field- and laboratory-prepared samples was significant in that the former generally tended to have lower values than the latter, but sufficient information is not available for ascertaining how much lower. It is recommended that a 30 percent reduction in the laboratory values be assumed for the interim.

The properties of materials produced during construction must match those properties assumed by the structural designer. In road construction this correspondence is generally assumed, because it is accepted that the construction controls, such as field density tests, and compliance with the construction methods outlined in the specification are adequate to ensure it. The properties of treated materials are believed to be significantly affected by variations in specifications and differences between construction techniques (mixing, compacting, and curing) of the different construction organizations.

Numerous researchers have extensively studied the effects of all these individual aspects on the different properties of treated materials, but I believe that the combined effects and interaction should be studied under the general heading of construction technique.

The objectives of this paper were therefore (a) to study and quantify the variations in the properties of treated materials constructed in the field and accepted by engineers and (b) to compare the properties of field-constructed materials with those of materials prepared in a laboratory under ideal conditions. The outcome might be useful to the eventual development of a more rational structural pavement design method, because it would indicate to the designer what allowance he or she should make to accommodate the construction process.

LITERATURE REVIEW

One of the first studies on the difference between field strengths and the design values of cement-treated materials was performed by Robinson (1), who attributed the difference largely to an insufficient distribution of the cement through a silty clay. He showed that, if the mixing efficiency could be increased to give a more even distribution of the cement, less cement would achieve the specified strength. This represented approximately a 30 percent reduction in the total stabilizing agent required and could mean significant financial savings on large contracts. This illustrates the importance of efficient mixing in reducing the difference in strength between field- and laboratory-prepared samples.

Mitchell and Freitag (2) reported that British engineers "found that normal construction methods result in a field strength equal to about 60 percent of the laboratory strength for a given cement treatment." The cement content should therefore be the amount needed to obtain a laboratory compressive strength equal to the required field strength divided by 0.6. This implies that, if a compressive strength of 1700 kPa is required, the laboratory strength should be 2800 kPa. The recommendation by Ingles and Metcalf (3) seems to have been based on this work.

Wang (4) performed compressive and bending tests on both field- and laboratory-prepared cement-treated materials. He compared the strengths and elastic moduli; Table 1 summarizes his results. He could not recover beam samples for testing from the materials treated with 6 percent cement until two months after their construction, and no beam samples could be recovered from the 3 percent cement section because the materials were too weak. He did obtain the same densities in the field as in the laboratory; nevertheless both the strength and the elastic modulus of the field samples were only about 50-60 percent of the corresponding laboratory samples. He explained the difference as the result of (a) better mixing in the laboratory than in the field, (b) less effective curing conditions in the field than in the laboratory, and (c) disturbance of field samples during cutting and extraction.

He stated that, "among the possible causes, the effect of low efficiency mixing seems to be a major factor. In addition, the differences in curing condition might be quite significant." This implies that he was not positive of the cause of the differences.

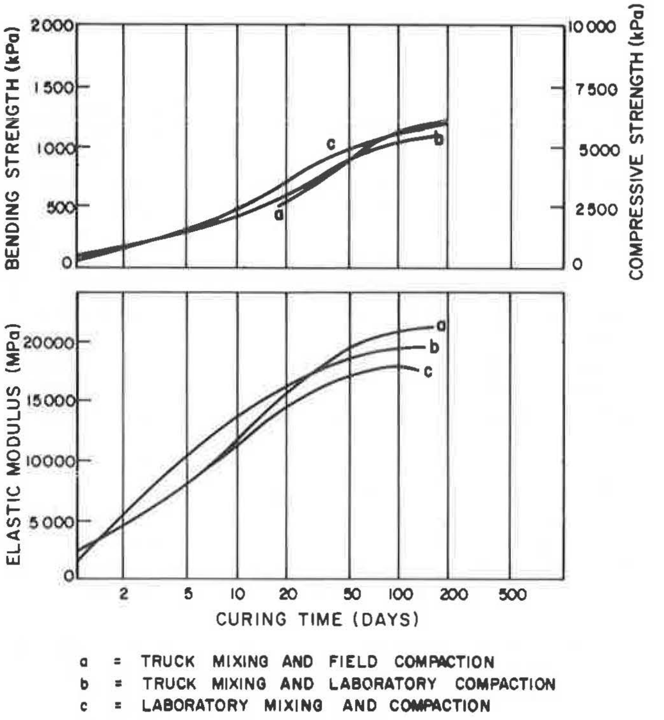
Fossberg (5) recorded the differences between three construction conditions: mixing in a ready-mix concrete truck (called truck mixing) and field compaction, truck mixing and laboratory compaction, and laboratory mixing and compaction. Approximately the same densities were obtained in all three conditions, and the recorded strength and elastic modulus values are shown against curing time in Figure 1. The differences were very small, and he obtained nearly the same strength and elas-

Table 1. Comparison of properties of field- and laboratory-prepared specimens.

	Strength				Elastic Modulus			
	Unconfined Compressive (kPa)		Bending (kPa)		Compressive (MPa)		Bending (MPa)	
Specimen Type	3% Cement	6% Cement	3% Cement	6% Cement	3% Cement	6% Cement	3% Cement	6% Cement
Field prepared	140-340	415-1030	W[a]	W[a]-450	70-66	140-1170	W[a]	W[a]-1720
Laboratory prepared	410-760	760-1720	100-280	380-660	280-1030	100-2200	410-1240	900-3030
Ratio of field prepared to laboratory prepared	0.33-0.45	0.55-0.60	W[a]	W[a]-0.69	0.25-0.64	0.13-0.53	W[a]	W[a]-0.57

[a] W = too weak to be sampled and tested.

Figure 1. Effect of mixing and compaction on elastic properties of a soil-cement.



tic modulus for all three construction conditions. He did, however, observe structural anisotropy in the field-compacted materials; that is, the elastic modulus in the direction of compaction was about 1.5 times lower than in the other two directions, an effect not found in the laboratory-prepared samples.

Structural anisotropy in field-compacted materials was also observed by Otte (6). Measurements on cement-treated crushed-stone samples from six different freeway contracts indicated less anisotropy than that recorded by Fossberg (5). The dynamic elastic moduli in the direction of the compaction (modulus A) and perpendicular to this plane (modulus B) were recorded with an ultrasonic tester. The measurements were taken on soaked and oven-dried samples, and the results are tabulated in Table 2 (6). This table indicates that anisotropy is real and can affect the relationship between field- and laboratory-prepared samples, because the outcome of the comparison between the two methods depends on the direction in which the properties of the field samples were determined.

The results of a previous study (7) indicated a strong possibility that the construction technique has a significant influence on the properties of cement-treated materials. Samples were taken from 14 pavements built by different contractors and supervised by different authorities. Although all the contracts were constructed to the same nominal specification and thus regarded by engineers to be of the same quality, the differences in the material properties were significant. The bending strength varied between approximately 400 and 4400 kPa, that is, by a factor of 10; the strain at break varied between approximately 113 and 251 $\mu\epsilon$, a factor of 2.2; and the elastic modulus varied by a factor of 10.5 between approximately 3700 and 38 900 MPa. These results indicate that cement-treated materials should not be regarded as having the same structural capacities just because they were built to the same specification.

On another contract, two adjoining cement-treated crushed-stone sections were constructed on different days. Although the same materials, specification, and construction team were used on both sections, the amount and extent of cracking differed significantly (Figure 2). The one section (the upper third of Figure 2) had a high elastic modulus and bending strength (8) and was cracked into rectangular blocks of approximately 2×2 m, while the other section (the lower two-thirds of Figure 2) had a low elastic modulus and bending strength and very few cracks reflected through the 25-mm asphalt concrete surfacing. Only construction variations between the two sections could have caused this significant difference in visible cracking and quality of material.

The literature survey seems to indicate that the four main parameters ensuring reasonable agreement between field- and laboratory-prepared samples are cement content and the uniformity of its distribution, density, delay between mixing and compaction, and efficient curing. If good agreement between the field and laboratory conditions can be maintained for these parameters, the material properties also ought to agree.

THE CONTRACTS

The cement- and lime-treated materials evaluated were taken from nine contracts under construction in South Africa between February and June 1976. A description of these contracts, information on the materials treated, and other relevant information are obtainable in other publications (6, 8).

An explanation of contract 1, which was a contract to construct the various sections of a full-scale experiment (9), is considered necessary. For this paper each experimental section 130 m long was considered individually and is referred to by the contract number and a section (S) number. Two different natural materials were treated on these sections—a lateritic soil on sections S7 and S8 and a gridstone on the others—but the percentage of compaction and the stabilizing agent discussed later were less for the lower than for the upper subbase.

The reasons for stabilizing the various materials varied. This explains why the type of stabilizer and specified strength criteria varied among contracts and

Table 2. Structural anisotropy in cement-treated crushed stone recovered from freeway contracts.

		Wet Samples					Dry Samples				
		Modulus A		Modulus B			Modulus A		Modulus B		
Contract	No. of Samples Tested	MPa	CV[a]	MPa	CV	Aniso-tropy	MPa	CV	MPa	CV	Aniso-tropy
A	6	34 600	2.3	37 000	4.6	1.069	25 100	5.3	28 700	3.1	1.143
B	12	30 100	4.0	35 900	4.3	1.192	23 200	14.5	27 800	11.2	1.198
C	12	25 200	6.5	29 200	7.4	1.158	17 300	13.5	19 500	12.0	1.127
D	12	29 700	6.3	31 900	6.6	1.074	20 700	7.7	23 900	11.9	1.154
E	9	27 444	7.2	30 178	5.5	1.099	23 666	7.2	27 266	5.8	1.152
F	10	29 000	5.0	32 200	3.6	1.110	25 000	4.2	30 400	3.3	1.216

[a] CV means the coefficient of variation in percentage.

Figure 2. Two adjoining sections, cracked and uncracked; the cracks sealed with bitumen emulsion.

various materials. Table 3 summarizes the percentage and type of stabilizer used, the use of the treated material in the pavement structure, and the criteria aimed for. Slagment is the South African trade name of commercially produced granulated blast-furnace slag.

On all the contracts, the mix-in-place technique, as generally practiced in South Africa with disc harrows and motor graders mixing the materials, was used. The materials were usually compacted with grid rollers. After compaction, the layers were kept moist for seven days, and if possible the tar prime coat was applied earlier. On contract 1 it was a condition of the contract that the curing membrane be applied immediately after the final compaction or very early the next morning.

OUTLINE OF STUDY

The site was visited and block samples (approximately 600×600 mm) were sawed from the treated pavement layer 7-27 days after construction of the layer, but usually between 20 and 27 days after construction. On one or two contracts it was necessary to remove the blocks relatively early; they were then moistened slightly, sealed in plastic, and stored in a humid room at 20°C. About 27 days after construction, the blocks were sawed into six or seven beam samples (75×75×450 mm), allowed to soak in water for 24 h, and tested in flexure according to a standard procedure (8, 10) to determine the bending strength, strain at break, and elastic modulus. In this paper these samples will be referred to as field-prepared or field samples.

Usually more than one block was removed from a particular section, because the blocks could collapse during subsequent handling. Although it was possible to recover blocks from some sections, it was not possible to saw them into beams because (a) they had fine cracks that only showed up when sawed, (b) the matrix was too weak to hold the larger (+75 mm) stones (and when sawed they pulled out and the beams crumbled), or (c) the material was too soft under wet cutting with a diamond blade. If any of these failures occurred it was not possible to obtain field samples.

During the site visit a 40-kg sample of the untreated soil and a sample of the stabilizing agent actually used by the die contractor were obtained. The relevant soil constants, such as maximum dry density and optimum moisture content, for the material used on the contract were also obtained from the site office.

These soil constants were used throughout the study, and no checks were made on the properties of the particular soil sample. Some variations can of course occur, but this was considered a realistic representation of construction practice. Eight beam samples (75×75×450 mm) were made from each soil sample for each contract. The samples were compacted for 3-4 min on a table vibrating at 50 Hz, but the soil had to be placed in three or four equal layers and tamped in order to work the predetermined mass into the mold. The samples were cured in a room at 100 percent relative humidity and tested at the same age as the corresponding field samples, generally 28 days. These will be referred to as the laboratory-prepared samples.

Throughout the study the goal was to compact the beams to the same average density and percentage compaction as measured by the engineer at the time of approving the construction of the layer. Small differences between the materials on which the soil constants were determined and the sample that was taken to prepare the laboratory specimens and between the specified optimum moisture content and that required by the vibrating compaction technique resulted in lower densities in the laboratory (Table 4).

The averages and coefficients of variation of the six or seven beams sawed from the field samples and of

Table 3. Percentages and types of stabilizer and criteria.

Contract No.	Percentage of Stabilizer	Type of Stabilizer	Layer	Specified Strength Criteria
1	3.75	50-50 mixture of Slagment and portland cement	Lower subbase	UCS[a] = 1200 kPa after 7 days
	4.0		Upper subbase	UCS = 1725 kPa after 7 days
	5.0		Lower subbase	UCS = 1500 kPa after 7 days (S7 and S8)
2	3.5	Portland blast-furnace cement	Subbase	UCS = 1500 kPa after 7 days
3	4.0	Lime	Subbase	CBR > 70
4	4.0	Lime	Base	CBR > 70
5	4.0	Portland blast-furnace cement	Subbase	UCS = 1500 kPa after 7 days
6	4.0	50-50 mixture of Slagment and portland cement	Base	UCS = 1500 kPa after 7 days
7	3.0	50-50 mixture of Slagment and lime	Lower selected subgrade	Reduction of plasticity index; did not aim for increased strength
8	4.0	50-50 mixture of Slagment and lime	Subbase	CBR > 160; laboratory values around 180 to 200
9	4.0	50-50 mixture of Slagment and lime	Subbase	CBR > 160; laboratory values on 7 samples 174, 167, 201, 163, 154, 191, and 146

[a] UCS is unconfined compressive strength.

Table 4. Difference in field and laboratory densities.

Contract No.	Maximum Dry Density of Material (kg/m³)	Field Samples			Laboratory Samples		
		Density		Percentage Relative Compaction	Density		Percentage Relative Compaction
		kg/m³	CV[a]		kg/m³	CV	
1	2140	2064	2.2	96.0	1941	1.4	91.0
	2140	2120	2.2	99.0	1954	1.8	91.0
	2160	2083	5.9	96.0	1931	1.8	89.0
2	2020	1968	0.1	97.0	1917	1.1	95.0
3	1935	-[b]			1777	1.8	92.0
4	1965	-		-	1732	2.0	88.0
5	2160	-[b]		-	1960	1.1	91.0
6	1960	2009	4.5	102.5	1803	2.2	92.0
7	2030	-[b]		-	1876	1.0	92.0
8	2200	2114	3.3	96.0	1968	0.8	89.0
9	1865	-[b]		-	1712	1.2	92.0

[a] CV means the coefficient of variation in percentage.
[b] No field samples could be obtained.

Table 5. Variation during a day's work.

Contract No.	Section No.	No. of Beam Samples	Bending Strength		Strain at Break		Elastic Modulus	
			kPa	CV[a]	$\mu\epsilon$	CV	MPa	CV
1	S7	8	785	11.4	129	11.2	7 788	7.7
		7	917	21.4	141	13.2	8 450	8.7
1	S8	5	782	18.4	116	15.4	8 500	4.3
		7	785	26.4	130	12.4	7 992	16.1
2		6	502	13.2[b]	124	16.4[b]	5 900	4.5
		5	345	7.1	92	14.5	5 460	2.1
6		7	464	17.3[b]	237	17.6	2 825	9.6
		7	362	17.1	231	27.4	2 550	17.1
		6	385	31.3	249	22.1	2 608	12.5
8		5	129	35.0	172	27.3	1 810	41.0
		5	192	37.3	196	20.1	2 570	28.5
		6	173	36.5	225	29.1	2 190	25.0
1	S3	6	843	10.1	92	7.2	10 683	9.9
1	S4	7	928	20.0	89	17.3	11 264	11.5
1	S5	5	632	34.1	128	22.1	6 199	27.2[b]
1	S6	7	762	19.2	120	11.4	8 564	12.3
1	S16	8	826	20.9	111	17.3	9 525	15.1
1	S17	8	854	16.3	100	16.0	11 100	18.7

[a] CV means the coefficient of variation in percentage.
[b] Statistically significant difference at the 1 percent level.

those prepared in the laboratory were calculated. For each contract the corresponding bending strengths, strains at break, and elastic moduli in bending (8, 10) were compared.

Table 6. Variation in quality of work performed on different days.

Contract No.	Section No.	No. of Beam Samples	Bending Strength		Strain at Break		Elastic Modulus	
			kPa	CV[a]	$\mu\epsilon$	CV	MPa	CV
1	S3	6	367	35.7	70	7.5	7 033	24.5
1	S6	9	938	12.5	130	15.0	9 005	7.6
1	S10	10	1035	24.1	99	13.0	11 996	13.3
1	S17	4	762	11.1	102	26.1	9 937	20.0
1	S19	5	1216	24.0	100	17.1	16 240	2.5

[a] CV means the coefficient of variation in percentage.

RESULTS

The information obtained from the different contracts allows various interesting observations to be made.

On eight sections it was possible to saw beam samples from at least two different sample blocks. These blocks were constructed on the same day as part of the same section; the variations in their properties will thus indicate the variation during that particular day's work.

The contractor worked some of the adjoining experimental sections (each 130 m long) on contract 1 on the same day and, although they were considered as separate contracts for the purposes of this study, their variations may also be considered as variation during a day's work. Table 5 contains the results, which indicate that there was very little statistical variation during a day's work. The standard deviations are large, and differences at the 1 percent level of statistical significance were therefore only calculated for the bending strength and strain at break on contract 2, the elastic modulus on sections S5 and S6 of contract 1, and the bending strength between two of the three samples on contract 6. This implies that a section constructed on a particular day may be considered homogeneous, although the standard deviations are very large.

Variation in Work Performed on Different Days

Samples were recovered from the lower 150 mm of the cement-treated subbase on five sections of contract 1. These were all constructed with the same material and by the same construction team, but on different days. Table 6 shows the variations in measured properties.

Engineers would normally regard these materials (Table 6) as having the same properties and structural capacity because they were all constructed of the same materials, by the same contractor, and according to the same specifications. A closer study of Table 6 will reveal that this assumption is incorrect, because the bending strength varied by a factor of 3.3, the strain at break by 1.9 times, and the elastic modulus by 2.3 times. Materials exhibiting these orders of variation should not be regarded as being of the same quality.

Variation Within a Layer

On two sections of contract 1 (S20 and S21) it was possible to saw and divide the blocks recovered from the lower 150 mm of the cement-treated subbase in such a way that beams could be sawed from both the upper and the lower 75 mm of the layer. These will be referred to as the upper and lower halves respectively. The results are shown in Table 7.

Student's t-test, at the 1 percent level of significance, showed the difference in bending strength between the upper and lower halves to be significant for both contracts. The differences in the strain at break were not significant. The elastic moduli for contract 1 (S20) were significantly different at the 1 percent level, but on contract 1 (S21) the difference was only significant at the 5 percent level.

One may conclude, then, that on both contracts, although they were constructed on the same day, the upper half had both a higher bending strength and a higher elastic modulus than the lower half of the cement-treated layer.

Motor-grader mixing was used on both these sections. This is a mixing technique that most South African engineers believe produces a uniform vertical distribution of the stabilizing agent in the layer, because the material is bladed and windrowed across the width of the road while special care is exercised to ensure that the full depth of the layer is worked and mixed. There are numerous factors affecting the strength and properties of cement-treated materials, of which the amount of stabilizer is among the most important. These results seem to indicate that, although the mix-in-place technique is generally accepted in South Africa, it may not result in a very uniform vertical distribution of the stabilizing agent.

Variation Between Field- And Laboratory-Prepared Materials

Practical problems that arise in sawing beams from the recovered blocks or in preparing the samples in the laboratory resulted in only five contracts that yielded information usable for comparing field- and laboratory-prepared materials. This information is summarized in Table 8. Contracts 3 and 9 are omitted because no reliable information could be obtained (6, 8).

The table indicates that the properties of the field samples are generally lower than those of the laboratory samples. This does not, however, apply to contract 4, probably because of the low density achieved in the laboratory (Table 4). If generally higher densities could have been obtained in the laboratory, the differences between the field and laboratory samples might have been greater.

It is of interest to compare the results from contracts 6 and 7. The specified and required strength for contract 6 was 1500 kPa, while contract 7 was only treated to reduce the plasticity. This difference was borne out by the field samples, because the quality of the material from contract 6 was better than that from contract 7—it could at least withstand the action of the saw.

Statistically speaking, the quality of the laboratory-prepared samples from the two contracts was the same. This means that the material on contract 7 could have been prepared to obtain a better-quality treated material in the field. The economics of such an improvement depend on the particular site, but I believe that it would have been economical to use the full load-bearing potential of the lime-treated material.

Variation of Compressive Strength

After the bending test was performed, samples 150 mm long were sawed from the ends of a number of the beams and tested in compression. This, however, was not possible for all the field samples, such as for contract 4. The compressive strengths and the ratios between them are given in Table 9. The results indicate a significant difference between the compressive strengths of the field and laboratory samples but give no clear indication of which method produced the highest compressive strength.

DISCUSSION

Although samples recovered from the various contracts indicated little statistical variation across a section constructed on a particular day (Table 5), significant variations were found on sections constructed on different days (Table 6). Thus a specific section, constructed in one operation, can be considered homogeneous. However, different sections of a contract constructed on different days should not be regarded as homogeneous. Neither can a layer be accepted as homogeneous in the vertical direction, since the upper part seems to have better material properties than the lower part.

The study of the difference between field- and laboratory-prepared samples generally indicated better material properties in the laboratory-prepared samples. This was to be expected, because they were prepared under ideal conditions. The lower values for the field samples indicate that, because of the construction technique, the full potential of the materials is not being realized. Some research and development on construction techniques and procedures would therefore prove worthwhile and economical in the long term.

The difference in material properties between the field- and laboratory-prepared materials is an even more important consideration in view of the future application and implementation of the developing pavement structural design procedure. Currently an unconfined compressive strength is specified (as a materials requirement). The construction controls are a method

Table 7. Variation within a layer.

Contract No.	Section No.	Position	No. of Samples	Bending Strength kPa	Bending Strength CV[a]	Strain at Break με	Strain at Break CV	Elastic Modulus MPa	Elastic Modulus CV
1	S20	Upper	6	320	16.0	94	18.3	4925	24.0
		Lower	6	245	17.0	96	16.1	3308	15.3
1	S21	Upper	5	361	13.0	104	23.0	5600	38.5
		Lower	5	162	17.1	120	14.0	2590	44.2

[a] CV means the coefficient of variation in percentage.

Table 8. Variation in field- and laboratory-prepared materials.

Contract No.	Field Prepared Bending Strength kPa	Field Prepared Bending Strength CV[a]	Field Prepared Strain at Break με	Field Prepared Strain at Break CV	Field Prepared Elastic Modulus MPa	Field Prepared Elastic Modulus CV	Laboratory Prepared Bending Strength kPa	Laboratory Prepared Bending Strength CV	Laboratory Prepared Strain at Break με	Laboratory Prepared Strain at Break CV	Laboratory Prepared Elastic Modulus MPa	Laboratory Prepared Elastic Modulus CV
1[b]							817	13.0	111	11.2	10 625	10.0
							862	15.1	106	7.1	11 475	3.6
							753	22.0	116	23.2	9 417	3.4
2	502	13.2	124	16.4	5900	4.5	443	21.1	97	11.0	7 080	25.0
	345	7.1	92	14.5	5460	2.1						
4	221	49.5	122	22.2	2750	19.1	73	48.0	86	28.0	1 535	13.4
5[c]							481	5.0	101	13.2	9 380	23.1
6	464	17.3	237	17.6	2825	9.6						
	362	17.1	231	27.4	2550	17.1	462	23.3	138	25.0	4 422	21.0
	385	31.3	249	22.1	2608	12.5						
7[d]							619	18.3	189	16.0	4 586	8.0
8	129	35.0	172	27.3	1810	41.0						
	192	37.3	196	20.1	2570	28.5	777	9.1	161	7.6	7 149	6.4
	173	36.5	225	29.1	2190	25.0						

[a] CV means the coefficient of variation in percentage.
[b] The results of the tests of the field-prepared specimens in contract 1 are presented in Tables 5-7.
[c] The field specimens could not be taken because there were so many large stones in the block it could not be sawed.
[d] The field block was too weak to be sawed.

Table 9. Variation in compressive strength of field- and laboratory-prepared materials.

Contract No.	Field Samples kPa	Field Samples CV[a]	Laboratory Samples kPa	Laboratory Samples CV	Ratio
1	4290	33.2	2443	6.7	1.75
	6367	22.0	2340	10.2	2.72
	2128	63.0	4050	13.1	0.52
2	1210	21.4	1830	9.1	0.66
3	-		432	16.0	-
4	-		488	28.2	-
5	-		1353	14.2	-
6	2303	28.3	2195	27.2	1.05
7	282	28.4	2286	12.1	0.12
8	917	42.1	2203	9.2	0.42
9	559	32.1	293	102.5	1.91

[a] CV means the coefficient of variation in percentage.

specification and a check on the specified compressive strength of the mixture and density of the final product. If the contractor complies with these specifications, the materials fit into the original design definitions and the structural pavement design virtually takes care of itself. This is essentially an empirically developed procedure based on successful previous applications of the particular structural layout with the particular type of material.

To best use the produced materials and structural layout, the designer must know the exact quality of the field-prepared materials, or he or she should know the amount by which the laboratory values should be reduced to comply with the field-prepared values. The information in Table 8 is insufficient to reliably indicate the amount of allowable reduction. More study on many more contracts will be required to obtain it. In the meantime it seems that the field bending strength is between 20 and 150 percent of the laboratory bending strength. The corresponding numbers for the strain at break and elastic modulus are between 63 and 180 percent and between 25 and 150 percent, respectively.

At present the quality of cement- and lime-treated materials is controlled by a density determination after final compaction and an unconfined compressive strength test. This test is made on a sample taken after the stabilizing agent, construction water, and material have been mixed, but just before compaction starts. The sample is taken to the laboratory where it is mixed, compacted, cured, and tested under ideal conditions to obtain either the unconfined compressive strength (UCS) or California bearing ratio (CBR), depending on whether it is a cement- or lime-treated layer. The CBR of the material produced by the construction team—i.e., the field-prepared material—may differ significantly because the mixing, compaction, and curing conditions differed significantly. Controlling the strength in this way seems inappropriate, because only the correct amount of stabilizing agent to be added in the field is controlled. Also, only the question of whether the physical and chemical properties that affect the increase in strength and CBR are the same in both materials is asked. This test therefore controls only the strength of the laboratory-prepared materials and not that of the field-prepared materials. Because it is the strength of the latter that controls the future performance of the pavement, I suggest that these be measured and controlled instead. Samples should be recovered from the completed field-prepared materials. It is the bending strength, elastic modulus, and strain at break that should be measured and controlled rather than the UCS or CBR of the laboratory-prepared materials.

CONCLUSIONS

Variation in material properties (i.e., the bending strength, strain at break, and elastic modulus) on a project as a result of the construction process is real and highly significant. Pavement designers should take cognizance of this and allow for it in the structural pavement design.

From the limited number of samples taken on a contract and the limited number of contracts suitable for this study it appears that

1. The variation in material properties in a section constructed during a particular day is not statistically significant, and for pavement design purposes the section may be regarded as homogeneous;
2. The statistical variation in material properties in sections constructed on different occasions or days is significant, and these sections may not be considered the same, even when the same materials, contractor, and specification apply to all the sections;
3. The material properties are not constant throughout the depth of the layer, and the upper half seems to have higher values than the lower half; and
4. The properties of materials constructed on a road by a contractor are significantly poorer than the values obtained on similar materials prepared in a laboratory. From this study it is not possible to indicate the degree of this difference.

Predicting the future behavior of a cement- or lime-treated layer in a pavement from laboratory-prepared samples would appear to be misleading. The extent of the difference between the design properties and the properties of the on-site material is unknown and seems to vary from contract to contract. Nor is the difference constant during the construction period; it varies from day to day. Until these differences have been studied and quantified accurately, for example by controlling the relevant properties or by tightening up the specification on the standard deviation of materials quality, it seems a very difficult task to accurately predict the long-term behavior of a pavement containing cement- and lime-treated materials.

RECOMMENDATIONS

From practical observations and until more specific recommendations become available, it is recommended that the values of the properties of field-prepared cement- and lime-treated materials be taken as 70 percent of those of laboratory-prepared materials. A 30 percent reduction in the laboratory values is thus recommended. Research along the lines indicated in the paper should be continued.

ACKNOWLEDGMENT

Acknowledgment is made to the director of the National Institute for Transport and Road Research of the CSIR, Pretoria, South Africa, for permission to use the data analyzed in this paper.

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Demonstration Project 42: Highway Quality Assurance

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The purpose of the Federal Highway Administration's demonstration project on highway quality assurance was to develop a short course for government and private administrative personnel in the highway industry to demonstrate the benefits of using statistical methods in quality assurance programs. The two-and-a-half-day course was divided into two essential parts: the first devoted to the development of basic statistical methods, the second to the application of these methods in acceptance plans. This paper discusses briefly the statistical methods covered and several of the areas in which they are applied. A limited discussion of the response to the 31 courses presented and comments on possible future programs of this type are included.

Federal Highway Administration (FHWA) Demonstration Project 42—Highway Quality Assurance, sponsored and funded by FHWA region 15, developed a short course for presentation to federal, state, and local highway and transportation administrative personnel and administrative personnel from the construction and materials production industry. The course presented statistical quality control and acceptance techniques designed to instruct course participants in judging the benefits of using statistical quality assurance programs.