CEMENT-STABILIZED MATERIALS IN GREAT BRITAIN

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The 3 types of cement-stabilized materials used in road construction in Great Britain are defined, and an indication is given of their application in highway construction. Information is also given on construction procedures and specification requirements. Views on the function of cement in stabilization are given, together with an examination of the structural properties of cement-stabilized materials and the findings from experimental roads. An attempt has also been made to summarize the attitudes of British highway engineers regarding the occurrence of cracking. Lean concrete, a pre-mixed material made with aggregates suitable for pavement-quality concrete, is the most widely used stabilized material. Its success as a base under heavy traffic conditions is dependent on the use of relatively thick bituminous surfacing and adequate base thickness to delay the advent of cracking caused by traffic-induced tensile stresses. Cement-bound granular material is used principally at subbase level, although it has also performed well as bases to lightly trafficked roads. Soil-cement has not been widely used in recent years, although it is believed that it will become more popular as a "working platform" in the upper subbase to expedite subsequent construction.

•CEMENT-STABILIZED materials have been used extensively in Great Britain, primarily as bases and subbases in flexible roads but also more recently as subbases to concrete pavings, in which case they are largely used as a construction expedient. Up until 1960, major roads in flexible construction mainly consisted of 100 mm (4 in.) of hot-rolled asphalt surfacing laid on 250 mm (10 in.) of lean concrete laid on an unbound subbase, the depth of which varied depending on the subgrade bearing value. Subsequently, the 250-mm (10-in.) base was formed of 75 mm (3 in.) of dense bituminous material on 175 mm (7 in.) of lean concrete. This form of construction is referred to as composite and was developed as a result of fears arising from cracks appearing in the surfacing; this view is also evident in current design recommendations (1).

All major road work in Great Britain is financed by the government from general taxes, and its construction is the responsibility of the Department of the Environment. The Specification for Road and Bridge Works (2), produced by the Department of the Environment, defines 3 types of cement-stabilized material: lean concrete, cement-bound granular material, and soil-cement, the grading requirements for which are given in Table 1.

Lean concrete is produced from washed and graded aggregates suitable for pavement-quality concrete. The specification (2) allows the use of any type of mixer suitable for mixing ordinary concrete, and compaction is currently by vibrating rollers or plates. The optimum moisture content for compaction is on the order of 5 to 7 percent by weight. Cement contents are in the range 5 to 6.7 percent by weight of aggregate, i.e., the water-cement ratio is approximately 1. The average 28-day compressive strength of cubes compacted to refusal is on the order of 14 MN/m^2 (2,000 lbf/in.^{2}). Wet lean concrete has been tried as a subbase to concrete pavements, the lean concrete being spread and compacted by a Guntert and Zimmerman slip-form paver to give a good standard of surface regularity. For good compaction, it was necessary to increase considerably the

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Publication of this paper sponsored by Committee on Soil-Portland Cement Stabilization.

mix moisture content. Cement contents were also varied in part of the work (3). The wet lean concrete cracked much more frequently than lean concrete, the cracks themselves being much finer, and it has performed satisfactorily as a haul road and as a subbase in the final construction. This form of lean concrete has not been tried to date beneath flexible pavings.

Cement-bound granular material is produced from "as dug" materials that are well-graded and within the limits given in Table 1. They are produced in forced-action mixers of the batch or continuous type. Free-fall mixers are not considered suitable because the aggregate may contain up to 10 percent of the material in the silt-clay particle size range. The strength is assessed from cubes compacted to field density and tested after 7 days of curing, the minimum strength (based on the average of a group of 5 results) allowed in the specification (2) being 3.5 MN/m^2 (500 lbf/in.^{2}). Cement contents are selected by the contractor and are usually on the order of 4 to 8 percent by weight. Moisture content is specified as 0 to 2 percent above the optimum as determined by the vibrating hammer method of compaction, B. S. 1924 (4). Mixed materials are usually transported in tipping lorries and spread by bulldozers, graders, or bituminous or concrete pavers. Compaction is almost invariably by steel-wheeled dead-weight or vibrating rollers, although pneumatic-tired rollers are permitted. Plate compactors or power rammers are used in areas that are difficult to reach by roller or to ensure good compaction at daywork joints. Figure 1 shows a bituminous paver fitted, in this instance, with a vibrating compacting beam at the rear. Modern versions of these pavers produce good standards of surface regularity, taking their level control from an external datum, such as a curb or guideline. However, they are generally followed by rollers to ensure adequate compaction, the standard of compaction left by the vibrating beam being sufficient to minimize surface disturbance under the action of the roller.

Soil-cement is produced from material finer than the appropriate limit in Table 1, mixing being carried out in a forced-action static mixer or by mix-in-place methods. Materials allowed include natural soils (with liquid and plastic limits not greater than 45 percent and 20 percent respectively), chalk, pulverized fuel ash, shale, or slag as long as their sulfate content is less than 1 percent (0.25 percent for cohesive materials). To ensure continuity of grading, the coefficient of uniformity is specified to be not less than 5 percent. Soil-cement may be built up in layers ranging from 75 mm (3 in.) to 200 mm (8 in.) deep, but, if the total depth is made up in 2 or more layers, mix-in-place construction is limited to the lowest layer. The strength levels specified (2) for soil-cement are similar to those for cement-bound granular materials except that greater latitude is allowed in varibility.

Lean concrete has proved to be a very popular form of construction, being easy to produce in conventional mixers and capable of being transported, placed, and compacted by equipment used for other works. The use of processed aggregates also avoids the need for elaborate pre-tender testing specified for the other forms of cement-stabilized materials. In many jobs, the cost of this testing can offset potential savings from the use of "as dug" or "on site" materials.

Road Note 29 (1) permits the use of lean concrete as base or subbase for all roads regardless of traffic intensity, although the required thickness of bituminous material is increased with an increase in the cumulative number of standard axles for which the road is designed.

Cement-bound granular materials are permitted as subbases for all roads but are limited at base level for roads with a design life of less than 5 million standard axles. A similar situation exists for soil-cement, but in this case the limit on use at base level is at 1.5 million standard axles.

The requirements for base and surfacing thicknesses are shown in Figure 2.

THE FUNCTION OF CEMENT

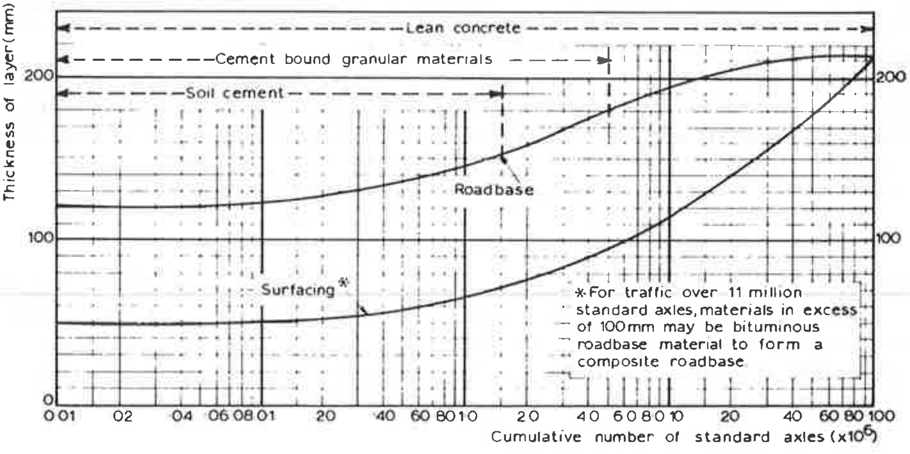
The purpose of adding cement to any material being stabilized is to modify that material in such a way that it is not disrupted by external forces arising from traffic loading or weather. Some materials possess a high level of natural stability when compacted and can be only marginally improved by the addition of cement. Others, such as single-size gravels and highly organic soils, are so poor that to raise them to an

Table 1. Grading requirements for cement-stabilized material (cumulative percent passing).

B.S. Sieve Size	Soil-Cement	Cement-Bound Granular Material	Lean Concrete 37.5-mm Nominal Max. Size	Lean Concrete 20-mm Nominal Max. Size
75 mm	—	—	100	—
50 mm	100	100	—	—
37.5 mm	95	95-100	95-100	100
20 mm	45	45-100	45-80	80-100
10 mm	35	35-100	—	—
4.75 mm	25	25-100	30-40	35-45
600μm	8	8-65	8-30	10-35
300μm	5	5-40	—	—
150μm	—	—	0-6	0-6
75μm	0	0-10	—	—

Figure 1. Modified bituminous paver laying cement-stabilized material.

Figure 2. Minimum thickness of surfacing and of cement-stabilized base in terms of cumulative number of strength axles (1).



*For traffic over 11 million standard axles, materials in excess of 100mm may be bituminous roadbase material to form a composite roadbase acceptable level demands the addition of an uneconomic proportion of cement. (Evaluation of the economic proportion of cement depends on the availability of alternative road-building materials.) Between the two extremes of materials is a wide range of usable soils, low-grade stone, and industrial wastes that can be economically and successfully treated.

The modus operandi of cement when added to widely differing materials will itself vary depending on that material, although the end product may be designed to serve the same function in terms of chosen parameters.

Lilley (5) has suggested that cohesive soils are broken down to small nodules that are coated with cement, and these, when compacted, form a skeletal structure of the type shown in Figure 3. To provide stability, this structure must be strong enough to prevent damage by weathering stresses, the strength and durability being improved by increasing the cement content or by reducing the nodule size. It is also claimed that free lime liberated by the cement during hydration modifies the moisture susceptibility of clays. The existence of some air voids within the whole structure is considered necessary to minimize stresses arising from freezing, and therefore care must be taken to keep stabilized cohesive materials from becoming saturated.

Granular materials, with their relatively large grain size compared with cement, are bonded by cementing at the points of contact between grains. Their strength and stability are increased by increasing the cement content, by selection of a good material grading to maximize the number of points of contact, and by compaction to orient the material particles into the most intimate contact.

In Great Britain, all materials within 450 mm (18 in.) of the road surface are required to be frost-resistant as defined by the Transport and Road Research Laboratory frost-heave test (6). In the test, specimens are subjected for 250 hours to a temperature of -17 C (+1 F) at their upper face while the lower face is in contact with water at +4 C (39 F). The heave that occurs is compared with limits based on the known performance, in Great Britain, of a number of subgrade soils. Although developed for evaluating soils, the test has subsequently been applied to subbase and base materials, including cement-stabilized materials. Some materials, such as certain burnt colliery shales, would be acceptable as granular subbase materials except for their frost susceptibility and are often stabilized with cement solely for this reason. It is commonly assumed that the frost resistance will be adequate if the current compressive strength requirements are met; Sherwood (7) showed this to be the case when chalk, a particularly frost-susceptible material, is stabilized with cement.

Compressive strength is primarily influenced by cement content and density, factors that also influence durability. This does not imply a correlation between durability and compressive strength. It is more likely, in the opinion of the authors, that there is a relation between durability and tensile strength.

In countries using durability tests alone for mix-design purposes, site supervision is limited to the monitoring of cement distribution, mixing, and compaction, requiring a "method" specification. The adoption of strength criteria in mix design has encouraged the use in Great Britain of strength tests for site control purposes, resulting in an "end product" form of specification.

In the United Kingdom, the main specification items relating to material quality are strength and density. In the case of lean concrete, these requirements have to be separately satisfied. If the strength requirements are not met, the contractor may be required to use different materials or mix proportions; if the density measurements indicate an air-void content in excess of 5 percent, the contractor may be required to remove and replace the defective material.

With cement-bound granular material and soil-cement, the specified strength must be met with specimens made to a density similar to the in situ value. Work failing to meet the strength requirements is removed and made good by the contractor.

The use of this form of "end product" specification relies on test results that are not immediately available, and thus the need for remedial work may not be known until large quantities of material have been laid. This potential risk is reflected in the unfavorable attitude of many contractors (8), particularly toward soil-cement.

STRUCTURAL PROPERTIES

Much information has been acquired regarding the factors influencing the compressive strength of cement-stabilized material, but for bases designed for heavy traffic there is a growing awareness among research workers of the need to examine the structural properties that influence behavior in service. This interest is prompted by theoretical studies showing that the use of a stiff base material, such as lean concrete, that has a high value of modulus of elasticity compared with that of an unbound material greatly reduces the vertical pressure transmitted to the subgrade but at the same time causes tensile stresses to be developed at the underside of the base. Therefore, so far as stresses induced by wheel loading are concerned, there is a need for information regarding the modulus and tensile strength of cement-stabilized materials, especially under the repeated loading conditions that apply to highway pavements. Information regarding tensile properties is also needed because they control the incidence of cracks due to restrained thermal and drying shrinkage movements.

Tensile Strength

Measurement of the tensile strength of concrete has presented considerable difficulty over the years, and the evaluation of this property for cement-stabilized materials has proved equally challenging to the research worker. In consequence, the available information is relatively limited in extent and is largely based on indirect tests.

Flexure Tests—The flexural test (9), carried out on beams loaded at the third point, has found favor in some research studies because of its semi-simulative nature where wheel loading stresses are concerned. The test, however, suffers from the limitation that the calculation of strength involves assumptions regarding the elastic properties of the material. In Figure 4, values of flexural strength for lean concrete and for cement-bound granular material are shown plotted against cube strength. This relationship is based on values obtained in laboratory studies (11, 12, 13, 14) and on specimens tested by the Transport and Road Research Laboratory during the construction of experimental roads (15, 16, 17, 18). The correlation is considered reasonable in view of the number of sources from which the results are drawn, and it may be inferred that, in general, the use of a compressive strength criterion is likely to ensure a corresponding flexural strength.

Results for soil-cement are more limited in number, but it is intersting to note that Sherwood (7) concluded that as a first approximation the relation between compressive strength and flexural strength was independent of the type of material processed. These conclusions are in broad agreement with the results published in 1957 by Felt and Abrams (19).

Cylinder Splitting Tests—Cylinder splitting tests have been used by Williams (11) for lean concrete and by Sherwood (7) for soil-cement, but doubts have been expressed (20) regarding the test and especially the influence of the maximum size of aggregate.

Direct Tension Tests—Very recently, attention has been paid to the measurement of uniaxial tensile strength, such tests imposing a state of stress that allows the tensile strength to be calculated directly, providing that the method of gripping and loading does not induce local stresses. Kolias (21) uses a double-scissor friction grip system based on a design by Johnston and Sidwell (22); Figure 5 shows a specimen, in this instance with LVDTs in position for strain measurement.

Bofinger (23) also uses direct tension tests because he considers that estimates of tensile strength from cylinder splitting or flexural tests are uncertain because of the complex behavior of soil-cement under stress.

Modulus of Elasticity

Relatively little information has been published as yet in Great Britain regarding the modulus of elasticity of cement-stabilized materials, and the majority of the available data relates to electrodynamic values.

In Figure 6, values of electrodynamic modulus are shown plotted against flexural strength for lean concrete and cement-bound granular materials; the results published

Figure 3. Suggested skeletal structure for soil-cement (5).

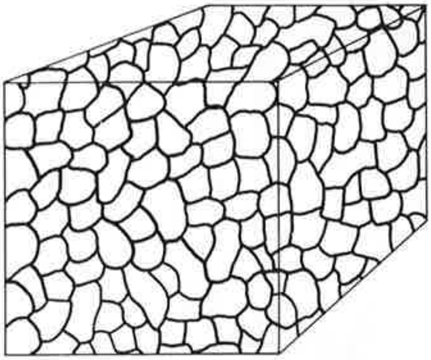


Figure 4. Flexural strength plotted against cube strength for lean concrete and cement-bound granular material (10).

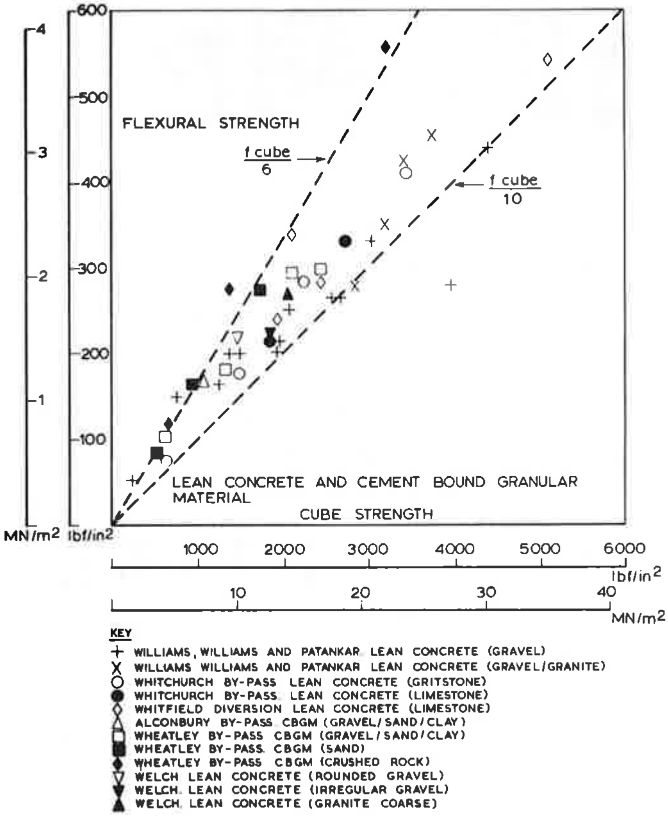


Figure 5. Uniaxial tension test on lean concrete to measure strength and modulus of elasticity (21).

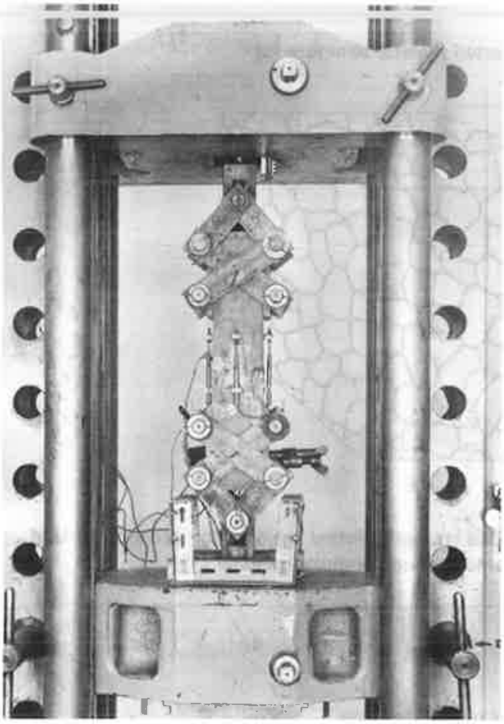
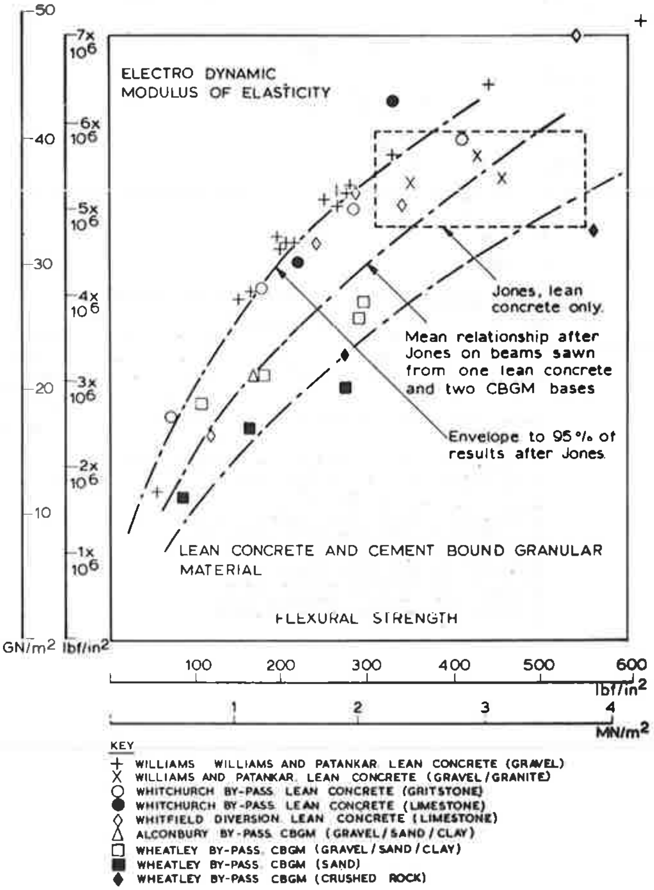


Figure 6. Modulus of elasticity plotted against flexural strength for lean concrete and cement-bound granular material (10).



by Jones (24) are regarded as the main data because they relate to material compacted in the field. Against this background are superimposed the results obtained from laboratory studies and from specimens made during the construction of experimental roads. There is reasonable agreement in the results, especially in view of the range of materials involved, with modulus increasing with increasing flexural strength. For a given flexural strength and, by inference from Figure 4, for a given compressive strength, the lean concrete specimens possess a higher modulus than do the specimens of cement-bound granular material. A further study of these results together with other results, including those published by Felt and Abrams (19) and by Nussbaum and Larsen (25), has led to the plotting of Figure 7.

The results show a reasonably well-defined pattern, with the values falling into three bands rather than following the single relationship implied in Figure 6. It appears that the nearer the material processed approaches a concreting aggregate, the higher the modulus at a given strength. This suggests that with a clean aggregate even a low cement content will produce a material with a relatively high modulus, whereas with a fine-grained plastic soil only a relatively low modulus will be developed even with high cement contents. This finding suggests that the use of a strength criterion alone has severe limitations so far as rational pavement design is concerned.

Few papers in Great Britain have given modulus of elasticity values determined from strain measurements. Bofinger (23) in tests on a soil-cement found that the modulus in tension is much lower than in compression. In contrast, Kolias (21) finds for lean concrete that the modulus is of the same order in both tension and compression. For example, a lean concrete with a cement content of 6.7 percent has a value of 35 GN/m^2 (5 x 10^6 lbf/in.^{2}) at 28 days on specimens compacted to refusal. It is intersting to note that Bonnot (26) has reported a direct tension modulus of 26 GN/m^2 (3.75 x 10^6 lbf/in.^{2}) at 28 days on a gravel stabilized with 3.5 percent cement.

Analysis of Pavements

In 1963, Whiffin and Lister (27) summarized analytical work at the Transport and Road Research Laboratory and showed that the tensile stresses caused by heavy traffic could lead to extensive cracking of weak cement-stabilized bases. Subsequently, Lister and Jones (28) reported that, due to cracking, the effective modulus of weak or thin stabilized bases, determined from surface wave propagation tests, approached that of a crushed-stone base and could be about 50 times smaller than that of the original sound material (29). This observation prompted Pell and Brown (30) in 1972 to question the relevance of laboratory tests on uncracked specimens of lean concrete. However, Lister (31) has analyzed stresses due to the combined effects of traffic loading and temperature warping in pavements having cement-stabilized bases and has compared the stresses with the strength of the materials; an example taken from Lister's paper is shown in Figure 8. From comparisons of this type Lister concluded that it is desirable to design pavements carrying very heavy traffic so as to delay structural cracking and stated that the current design recommendations (1) relating to lean concrete bases conform to this requirement.

Support to this view is given in a paper by Thompson et al. (32), which includes a structural analysis of the tensile stresses induced in the lean concrete bases laid in 1957 at Alconbury Hill. Fatigue data obtained from a similar material show that the performance of the 75 mm (3 in.), 150 mm (6 in.), and 225 mm (9 in.) bases under 100 mm (4 in.) of rolled asphalt is consistent with the calculated tensile stresses. The performance of the 225-mm (9-in.) thick bases after 15 years is described as excellent, and it is interesting to note that practice at the time would have required a 250-mm (10-in.) base thickness. However, the authors comment on the rigid nature of lean concrete in general and emphasize that the high potential life of this type of base is only realized when the asphalt surfacing is thick enough to keep the thermal stresses to an acceptable level and that, once the lean concrete is cracked, a more rapid deterioration develops than with other materials.

Figure 7. Modulus of elasticity plotted against flexural strength for lean concrete, cement-bound granular material, and soil-cement (10).

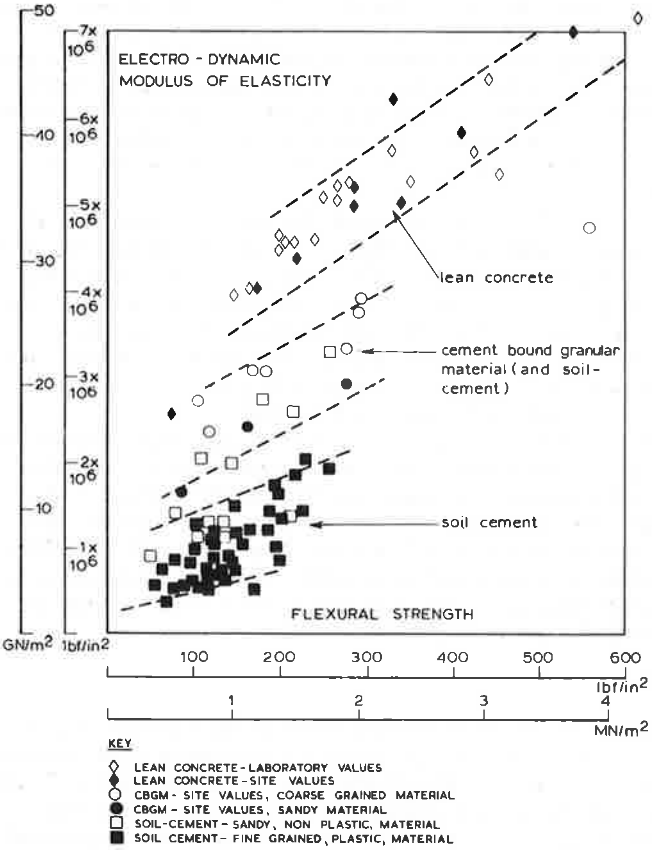
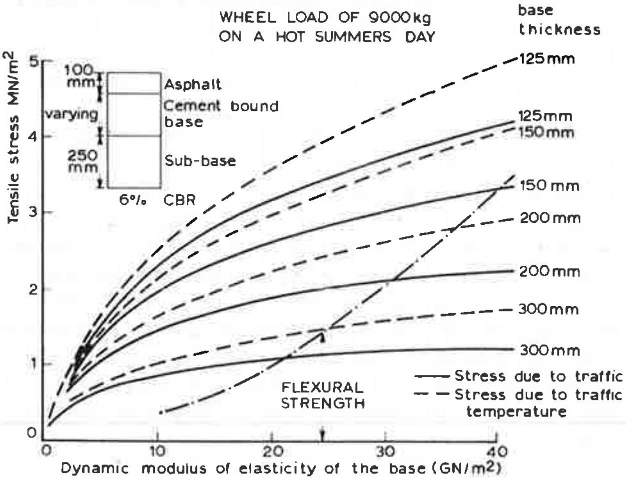


Figure 8. Maximum likely combined stresses due to traffic and temperature in pavements with cement-bound bases and varying stiffness and thickness (31).



EXPERIMENTAL ROADS

The Transport and Road Research Laboratory has been conducting full-scale road experiments since its founding in 1932, and the findings from these experiments have been incorporated in the various design recommendations issued over the years. In addition, trials such as the Cromwell slip-form paver experiment (3) and the development work on lean concrete at Crawley (33) have been organized by other authorities.

The most comprehensive experiment and one that has been reported (32, 34) in detail is the full-scale pavement design experiment at Alconbury Hill. This was a combined rigid and flexible experiment, the flexible part of the experiment examining the relative performance of 5 base materials (wet-mix slag, soil-cement, lean concrete, open-textured tarmacadam, and rolled asphalt) to be compared when laid in thicknesses of 75 mm (3 in.), 150 mm (6 in.), and 225 mm (9 in.) under a 100-mm (4-in.) rolled asphalt surfacing on a subbase of low-quality material. Surfacing type and thickness were also variables, and findings from this experiment, especially those relating to the relative performance of the various base materials, have greatly influenced design recommendations.

The main conclusions regarding lean concrete have been mentioned in the section of this paper dealing with structural properties. The soil-cement used in this experiment was a single-sized fine sand mixed with 8 percent cement and a moisture content of 14 percent, preliminary tests having indicated that this would give a 7-day cylinder crushing strength of 1.75 MN/m^2 (250 lbf/in.^{2}), the value associated with soil-cement at that time. Because of difficulty in compacting the soil-cement on site, the mean 7-day strength achieved was only 0.95 MN/m^2 (140 lbf/in.^{2}). During the first 6 years in the life of the road, 6 of the 7 sections with soil-cement bases failed in the slow lane, whereas by contrast none of the sections with either tarmacadam or asphalt bases required replacing. Croney and Loe (34) stressed that the poor performance of the particular soil-cement did not necessarily apply to stronger soil-cements or to soil-cemen made from better graded materials, and recently Thompson et al. (32) have stated that low-strength soil-cements employing well-graded aggregates are performing well in other experimental roads. Nevertheless, the attitude of practicing engineers toward soil-cement has probably been unfavorably influenced by the Alconbury Hill experiment.

Detailed information has not yet been published on other experimental roads involving cement-stabilized bases. Several further years' traffic is considered necessary before reliable conclusions may be drawn. The variables being examined include cement content, aggregate type and grading, base thickness, and surfacing type and thickness.

ATTITUDES TOWARD CRACKING

Sparkes and Smith (35) in 1945 viewed cement stabilization as an alternative to mechanical stabilization, and in 1953 Maclean and Robinson (36), discussing the use of soil-cement for airfield pavements, stated that it should be considered as a flexible material because it cracked under load into a series of small, closely interlocked blocks comparable with a stone base. This view received wide acceptance in Great Britain and is still held today by many highway engineers. The soil-cement that Maclean and Robinson were discussing was in the strength order of 1.75 MN/m^2 (250 lbf/in.^{2}) at 7 days, with a flexural strength on the order of 0.35 MN/m^2 (50 lbf/in.^{2}).

Experience with lean concrete does not support the view of Maclean and Robinson because it has been found to crack at fairly widely spaced intervals comparable to that of conventional concrete. Wartime experience in Germany (37) also shows that materials comparable with lean concrete, at least in strength, but mixed in situ cracked infrequently, but the cracks were wide. Concern has been felt in Great Britain over cracking that reflects into bituminous surfacings because of the potential weakening of the subgrade due to ingress of water and of fretting of materials in the vicinity of the cracks, problems that have also been reported from both Australia and Germany (38).

In an attempt to minimize the problem of cracking of lean concrete, cement contents have been reduced, on the theory that weaker material will crack more frequently and the cracks will therefore be narrower. However, doubts of the ability to batch and mix very small quantities of cement have limited the cement content to 4 percent, except in a very few instances where cement contents of 2 to 3 percent have been tried. The cement content currently specified is a compromise between minimizing the cracking problem and avoiding low-strength areas. Other methods that have been tried, with only marginal success, include the use of fabric reinforcement, adding bitumen emulsion to impart ductility, and the use of rubberized bituminous surfacings. The most favored technique has been to increase the overall thickness of bituminous surfacing, although Blake (39) suggested that this technique could lead to rutting. A survey of lean concrete bases by Brewer and Williams (40) suggests that cracking was not regarded by practicing highway engineers in Britain as a serious defect, but the onset of local failure caused concern.

A survey by Lewis and Broad (41) of 9 major roads with bases of cement-bound granular material and an average age of $5^1/_2$ years showed that the roads had all performed well despite being underdesigned for thickness. Although their report refers to cracking, it does not appear to have been a problem on any of these roads.

Soil-cement bases for lightly trafficked roads in the United Kingdom have performed well, according to a survey by Wright (42) in 1968 of 164 roads that were 8 to 23 years old. He claimed that simple cracking in the surfacing was a defect not likely to worsen with time, but he did not find evidence to indicate that the load spreading of soil-cement was better than that of unbound materials.

The authors believe that cracks develop in all forms of cement-stabilized material, usually within a few days of construction, and the presence of these cracks confirms that the cement is hydrating normally. With fine-grained materials such as silts and clays, the cracks will usually be very fine, often so fine that they are difficult to see, and closely spaced, but with lean concrete types of materials the cracks will be less frequent and more liable to reflect into a bituminous surfacing.

Movement of cement-stabilized materials is normally first apparent at daywork joints, the only joints considered necessary in road construction. If the joints are not vertical or if the standard of compaction in the vicinity of the joints is lower than elsewhere, they are a potential source of weakness. Thermal expansion can cause crushing or local buckling in the vicinity of these joints although, fortunately, instances of this form of defect are not common.

CONCLUSIONS

Lean concrete bases have been widely used in Great Britain and are giving good service. The construction method has proved popular with contractors, and performance over the last 20 years has given practicing engineers considerable confidence. However, the incidence of cracking has in recent years encouraged the use of thick bituminous layers. Wet lean concrete laid by slip-form paver as a subbase to concrete paving has also proved effective, both during and subsequent to construction.

Cement-bound granular material is regarded principally as a subbase material and, as such, has proved both practical and economic on many major road schemes. Soil-cement, on the other hand, is used less frequently, although it is likely with the growing shortage of traditional materials that this situation may change, leading especially to the wider use of industrial waste materials.

The authors believe that in Great Britain wider use should be made of cement-stabilized materials at the upper subbase level in order to provide a sound "working platform" to both facilitate and improve subsequent construction. Some change in the form of specification, however, is considered to be necessary.

A better understanding of the structural properties of cement-stabilized materials is considered desirable in order to allow the performance of roads under changing traffic conditions to be predicted with greater certainty from the results obtained on experimental roads.

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