Effect of Moisture on the Structural Performance of a Crushed-Limestone Road Base

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A series of repeated load triaxial tests on a crushed-rock aggregate is described, including variations in grading and degree of compaction as well as moisture content. The effects of these variables are discussed and it is found that elastic stiffness tends to decrease slightly with increased moisture content for broadly graded materials. The influence of density is negligible, and that of grading minor, which results in some stiffness reduction as the fines content increases. The accumulation of permanent strain under multicyclic loading is found to be strongly dependent on density; denser material performs better. Grading has a minor effect. Increased moisture content results in substantially increased straining. The value of suction, which could exist in a granular material, is then explored indirectly by means of unconfined compression tests, and its effect on drainage is noted. Permeability measurements are given and their possible effect on drainage considered. Finally, computations are presented that illustrate the influence of partial and full saturation of a base layer of a pavement structure.

The need to avoid excessive water accumulating in a granular road base material has been experientially proved many times in post mortem analyses of failures. Generations of practical engineers have insisted that drainage is of first importance in road design though it is often not effective in the long term. There is uncertainty about how much water is permissible and how this relates to variables such as grading, density, and loading frequency.

To provide some information on these points, a series of triaxial tests was performed on a particular crushed-rock material (dolomitic limestone) at different gradings and densities. The tests were aimed at exploring both elastic behavior, which controls the load-spreading ability of the granular layer, and development of permanent deformation under repeated loading. Further tests were performed to measure permeability, determine approximate suction values, and establish compaction characteristics.

REPEATED LOAD TRIAXIAL APPARATUS

All tests were performed on specimens 75 mm in diameter and 150 mm in height. The triaxial loading arrangement involved air pressure to generate confining stress. Deviator stress was applied by a servo-hydraulic actuator operating on feedback from a load cell. A signal generator, giving sinusoidal output at frequencies up to 10 kHz, provided the repeated loading facility. Three hertz was the maximum frequency used because of the constraints of the servo-hydraulic system.

Deformations were measured between studs embedded in the sides of the specimen using the technique developed by Boyce and Brown *(1)*. These were arranged in diametrically opposite pairs at approximately the $^1/_4$ and $^3/_4$ height points. A pair of linear variable differential transformers (LVDTs) gave the axial deformation of either side of the specimen. Strain-gauged epoxy hoops gave the radial deformation at two levels. Facilities to introduce or extract water from the specimen were provided through the loading platens. The whole arrangement is shown diagrammatically in Figure 1.

MATERIAL AND SPECIMEN PREPARATION

The material chosen was dolomitic limestone, commonly used in road construction in England. The gradings investigated are shown in Figure 2 and range from nearly uniform to very broadly graded, but all had a maximum particle size of 10 mm, dictated by the test specimen diameter.

All specimens were made by tamping the material into a mold of the appropriate size. The membrane, with studs attached, was held against the wall of the mold by vacuum. Compaction was generally carried out in 5 layers, although, where extremely heavy tamping was required, this was increased to 10 layers.

TEST PROGRAM

Initially, a full series of tests was carried out on the material in a dry state. Three specimens were made at each grading, each at a different level of compaction. Various stress paths were used to determine elastic behavior, and repeated loading on a single stress path (the same for all specimens) was applied to study permanent deformation. Finally, each specimen was brought "close" to failure in order to determine the failure stress state. On completion of this test sequence, water was passed through the specimen to measure permeability and then allowed to drain, which gave an "equilibrium" moisture content.

Compaction curves were obtained on all but the two most uniform gradings. To be of direct relevance to the triaxial testing, compaction was carried out in the same mold, and with a number of blows per layer in the middle of the range used in specimen preparation. Clearly, a higher level of compaction

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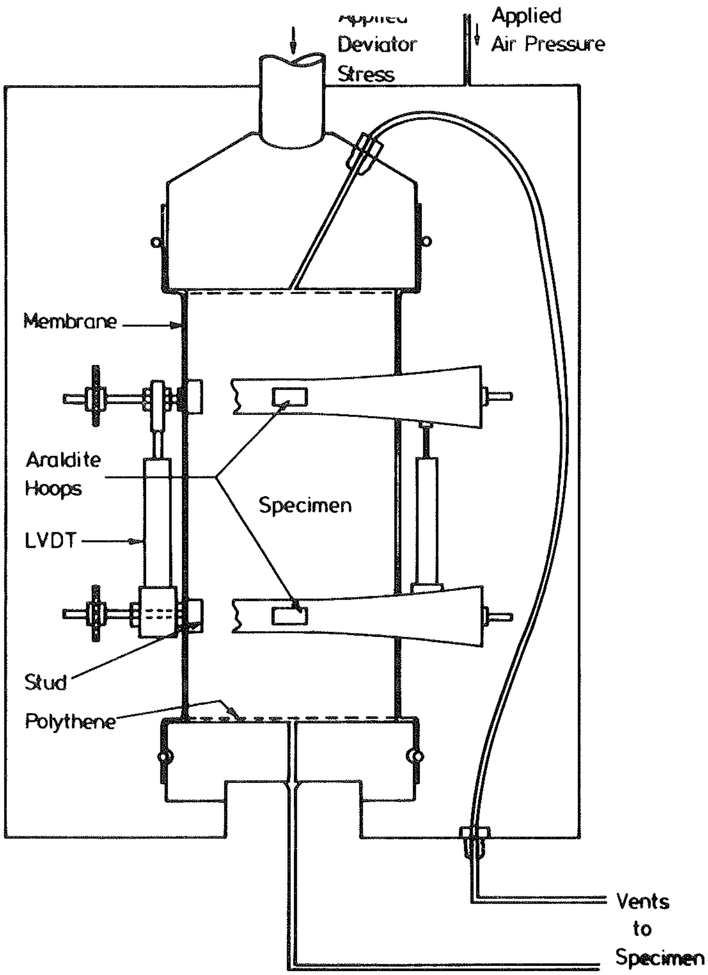


FIGURE 1 Triaxial specimen arrangement.

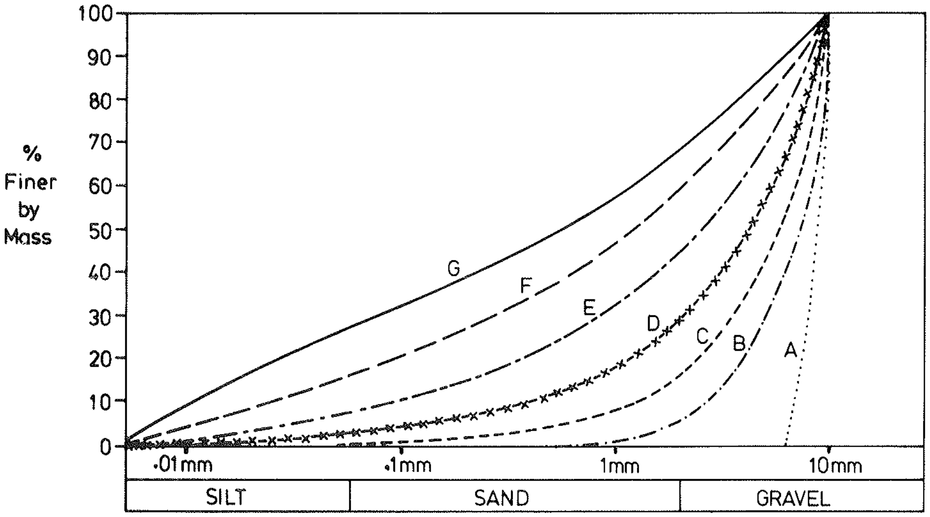


FIGURE 2 Particle size distribution chart.

would reduce the optimum moisture content and probably also the pessimum on the compaction curve. The results obtained are shown in Figure 3.

A series of drained repeated load triaxial tests was performed on material from Gradings D, E, and F (Figure 2). At least two specimens were made for each grading. Moisture content was varied during testing and results for both elastic behavior and permanent deformation were obtained for each moisture level. The stress paths used are shown in Figure 4. Moisture content was determined by monitoring the weight of the whole apparatus together with the specimen.

Finally, a series of unconfined compression tests was performed on dry specimens of all gradings and wet specimens of Gradings D, E, and F, at similar densities, and at moisture

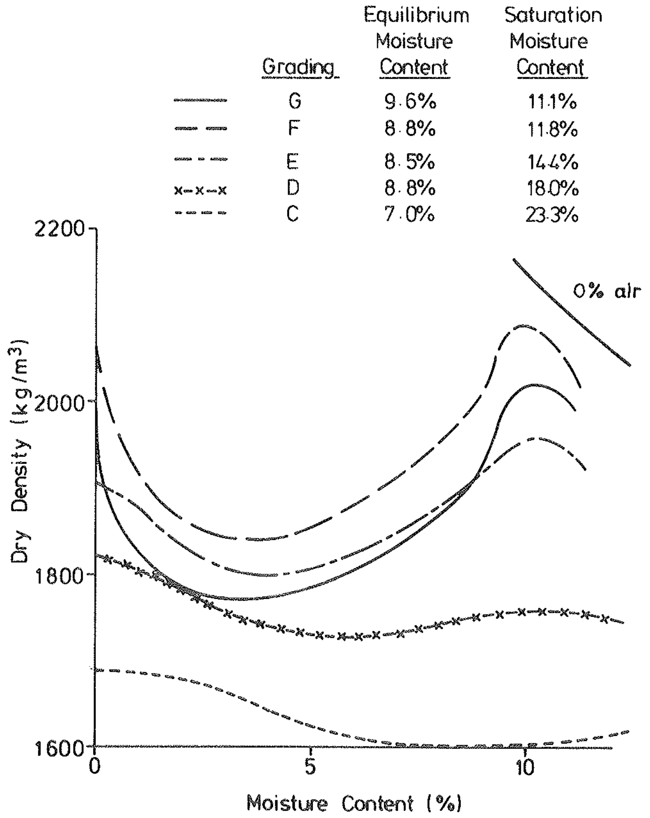


FIGURE 3 Compaction curves.

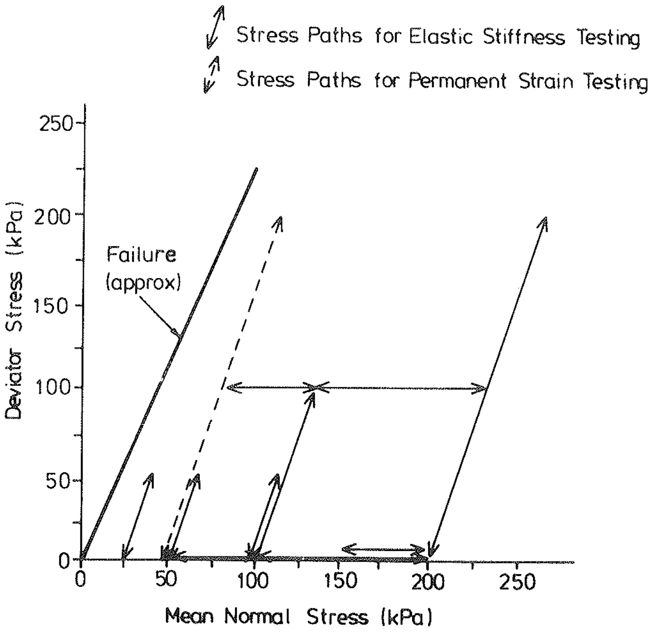


FIGURE 4 Stress paths used.

contents likely to correspond to the maximum suction value. The difference between the wet and the dry results gives a strong indication of the value of suction.

COMPACTION CHARACTERISTICS

The results of compaction tests on materials at Gradings C to G are shown in Figure 3. The general shape is a familiar one, with a pessimum at a relatively low moisture content and an optimum at a higher one. The shape is lost on the more uniform materials because of their inability to retain large quantities of moisture and because the effects are much smaller.

Other important moisture contents are also shown in Figure 3, those at saturation and equilibrium. Equilibrium is defined here as the moisture content that remains when a saturated specimen has been allowed to drain under gravity until no further moisture emerges. Suction can be expected to exist at moisture contents below equilibrium. It is considered that the maximum suction will, approximately, coincide with the pessimum on the compaction curve because suction is likely to impede compaction by increasing interparticle forces.

ELASTIC CHARACTERISTICS

It is not the purpose of this paper to discuss in any detail the real nonlinear behavior of a granular material, which has been done previously *(2)*. The purpose of this paper is to compare behavior at different gradings, moisture contents, densities, and frequencies. Elastic stiffness will, therefore, be expressed here simply as the value of resilient modulus (repeated deviator stress divided by resilient axial strain) averaged over the five stress paths used involving cyclic deviation stress (Figure 4). These stress levels would be at the upper end of the expected range for a road base layer.

Figure 5 is a plot of elastic stiffness from drained tests on three specimens at Grading E, chosen because it approximates to a one-third scale British Type 1 subbase material *(3)*. Specimens 1 and 2 were compacted dry, and Specimen 3 at or near optimum moisture content. Dry densities were 2000, 1995, and 2006 kg/m³, respectively. Specimen 2 had water added before

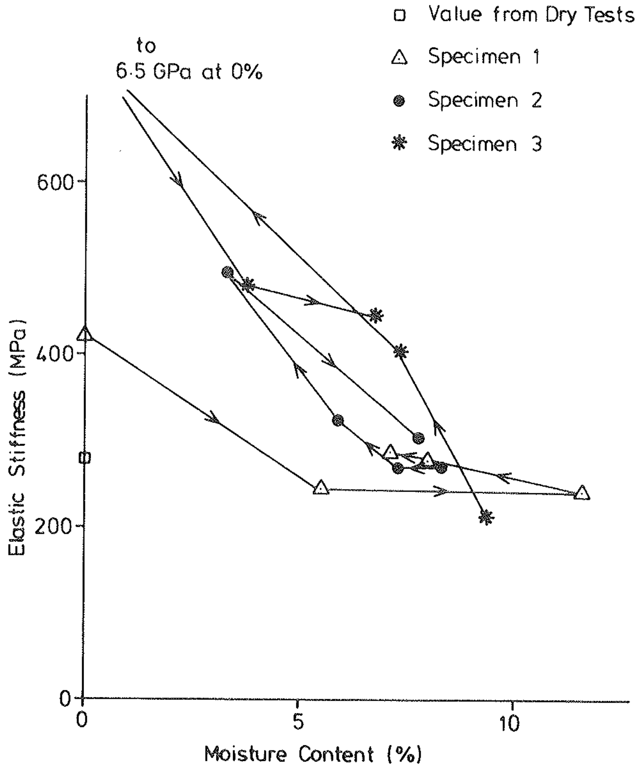


FIGURE 5 Elastic stiffness variation, Grading E.

any testing was done. The progression of wetting and drying may be seen by the direction of the arrows in Figure 5. For comparison, the elastic stiffness obtained during the series of dry tests (299 MPa) is also shown.

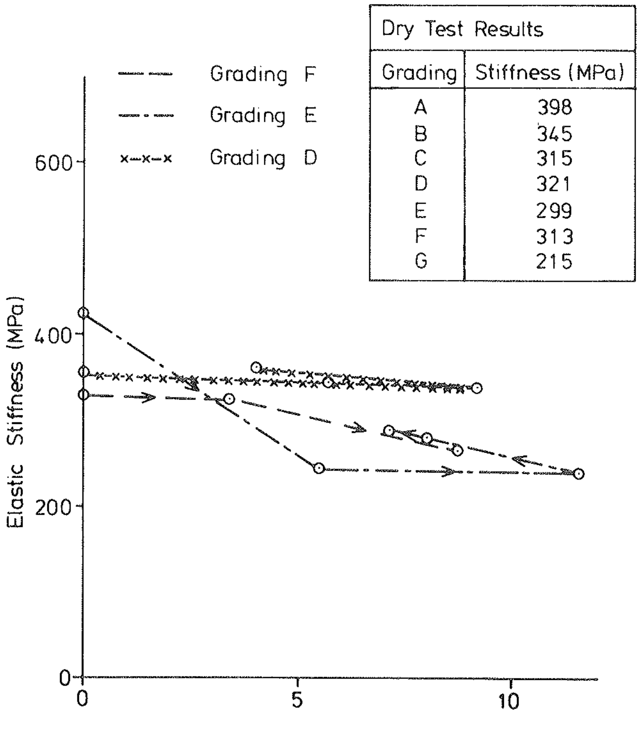
The amount of variability among specimens is quite considerable, but a trend of decreasing stiffness with increasing moisture content is clearly apparent.

It can also be seen that stiffness increases to a far greater value after drying than before initial wetting. This may be attributed to cementation between the limestone particles.

The decrease in stiffness with increased moisture content agrees with results from Smith and Nair *(4)*, who attributed it to pore pressure increases. However, for the tests described here, which were drained, frequency of sinusoidal load pulsing was varied over a range of 0.1 to 3 Hz with no discernible differences in stiffness. This indicates that, at the degrees of saturation used (up to 85 percent), no pore pressures developed, which confirms earlier work by Brown *(5)*.

The different effects of moisture on different gradings are shown in Figure 6 for Gradings D, E, and F. The elastic stiffnesses from initial dry testing are also included for all gradings. All specimens were compacted dry using identical compactive efforts. The same trends in behavior can be seen for the three gradings, but variations are evidently quite slight for Grading D. It is logical to expect that the effect of moisture increases with the amount of fine material present and that material at the more open gradings (A, B, and C) will show little stiffness variation in the partly saturated state.

Results for the dry state over the whole range of gradings indicate no substantial variation but a general trend of decreasing stiffness with increasing fines content. Not shown here are the stiffnesses obtained on dry materials at levels of compaction different from that used for the wet material. Interestingly, elastic stiffness was found to vary only slightly (± 10 to 15 percent) over a large range of compactive efforts. This was true of all seven gradings.



Dry Test Results	
Grading	Stiffness (MPa)
A	398
B	345
C	315
D	321
E	299
F	313
G	215

FIGURE 6 Elastic stiffness for different gradings.

As indicated previously, over the range of moisture contents covered, no noticeable pore pressures were developed. The moisture effect may, therefore, be some form of lubrication. However, if the material is close to saturation, pore pressures will clearly develop and the effective stresses decrease, as was recognized by Smith and Nair *(4)*. Research has shown [e.g., Pappin *(6)*], and the present work confirms it, that the effective stress principle is still broadly applicable. The knowledge that is required, therefore, in order to predict pore pressures, involves permeability (discussed later), loading time, and drainage path length as well as degree of saturation. It is an almost incalculable problem, but a worst possible case can be obtained by assuming completely undrained saturated conditions and this is included in the computations in a section of this paper.

PERMANENT DEFORMATION BEHAVIOR

The method of presenting permanent strain results is in a plot of strain rate (permanent shear strain per cycle) against shear strain, and the measure of permanent shear strain used is the difference between the axial and radial strains at the end of a loading cycle. Experience has shown that a decrease of strain rate is the usual result, which gives a straight line if a logarithmic scale is used for strain rate. Figure 7 shows the results of three specimens at Gradings D, E, and F, which had moisture added during testing. The stress path used was a cell pressure of 50 kPa and a deviator stress cycling between zero and 200 kPa (Figure 4).

The major feature of Figure 7 is the considerable increase in strain rate resulting from the addition of water. The effect of moisture addition is slightly greater when the fines content is higher but is still quite significant for Grading D. It appears that a relatively small moisture content is required to trigger the strain rate increase and that addition of further water has little effect. The exception is Grading F the strain rate of which increased in two stages. Loading frequency had a minor effect; higher frequency gave a slightly lower strain rate.

The implication of the dramatic increase in strain rate on wetting is clearly that the rutting potential of the granular layer will increase by a significant factor. This has been noted in tests using the Heavy Vehicle Simulator in South Africa *(7)*. Because no recognizable pore pressures are involved, it appears that the water merely acts as a lubricant on the particles.

It is of interest to summarize here the pattern of permanent deformation results from dry material over all of the gradings and covering a large range of compactive efforts. The different gradings produced similar results at high compactive efforts, but, at lower levels, the more open gradings performed better. For any one grading, density variation (due to different compactive efforts) had a dramatic effect; denser specimens performed far better. This was particularly true for the more broadly graded materials.

This gives rise to a dilemma. Because the highest densities are achieved at optimum moisture content and density is so important for permanent deformation resistance, it is logical to use material at that moisture content. However, once the material is placed, the water is a problem that can lead to increased

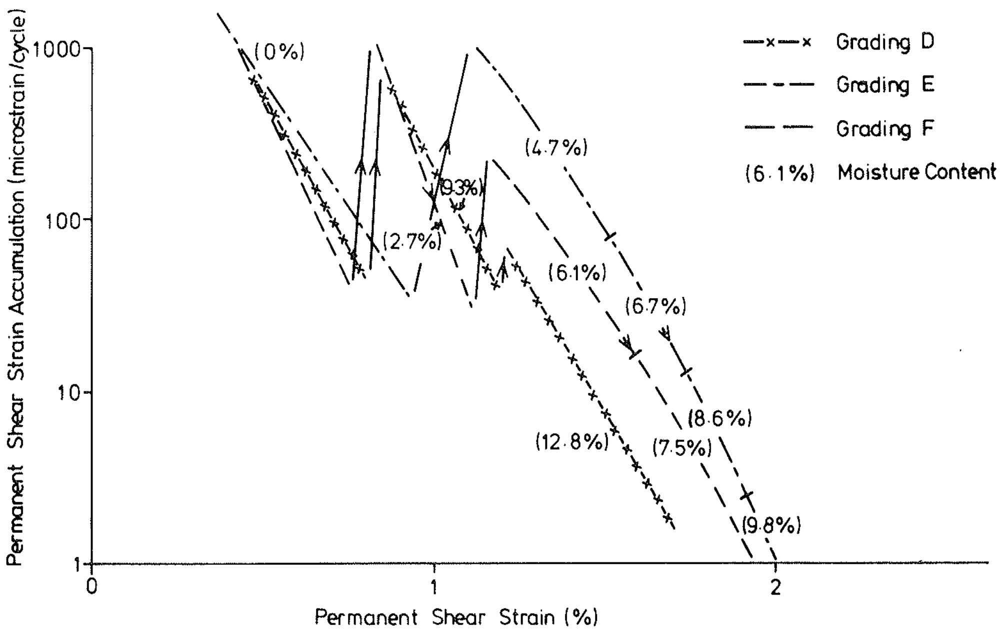


FIGURE 7 Accumulation of permanent strain.

permanent deformation and, if saturation occurs, the problems could multiply.

SUCTION CHARACTERISTICS

Suction measurement is notoriously difficult, particularly for granular materials the values of which are low. For this reason it was decided not to measure suction directly but to deduce it using the effective stress principle.

It was noticed that compacted dry graded aggregates tend to display an unconfined compression strength that is typically 20 to 30 kPa and a failure envelope at low confining stress, as shown in Figure 8, for material at Grading D. Unconfined means zero cell pressure and the membrane hanging loosely around the specimen. Thus, if any suction were operating, the unconfined strength would increase because, as well as aggregate interlock, the suction would act in the same way as confining stress. The suction value is therefore given by the difference between wet and dry strengths divided by the slope of the failure line. The only requirement is to achieve a wet specimen at the same dry density that is used in dry testing. This was done, at pessimum moisture contents, for materials at Gradings D to G and the deduced suction values are plotted in Figure 9. Different densities would undoubtedly affect these values.

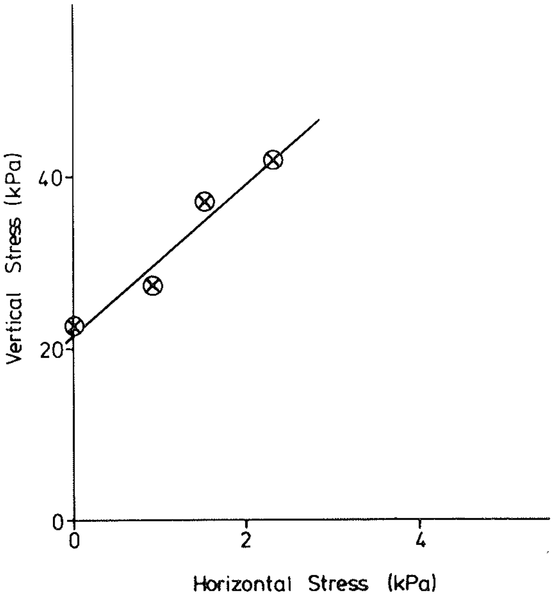


FIGURE 8 Failure envelope at low stresses.

As may be seen, the numbers are relatively small and would probably not have any great effect on the elastic performance of a road base, but they are quite significant for drainage. For example, 3.1 kPa for Grading F represents a head of 300 mm of water. Thus a drain less than 300 mm below the bottom of the subbase layer would be relatively ineffective for such a material. A drain level with the bottom of the subbase would hardly allow better than equilibrium conditions to prevail.

PERMEABILITY

The coefficient of permeability is also a difficult parameter to measure consistently, but it has obvious application to drainage problems. It could also have significance in determining pore pressure development if the base material ever approached saturation. Permeability values are shown in Figure 10 for the gradings investigated. They were obtained using ordinary tap water through a small specimen with a scaled-down aggregate grading. The values may therefore be lower than expected on site, but relative permeabilities are probably correct.

As an example of the effect of low permeability, a 5-m-wide, 200-mm-thick layer of material at Grading F, with a coefficient of about 2×10^{-6} m/sec, draining along the length of one side under a head of 200 mm could pass about 100 mL of water per hour per meter length of road. Over the same meter length, moderate rain may give rise to 20,000 mL of water per hour. Thus it may readily be seen how easily such a layer could become saturated if the surface were not adequately sealed.

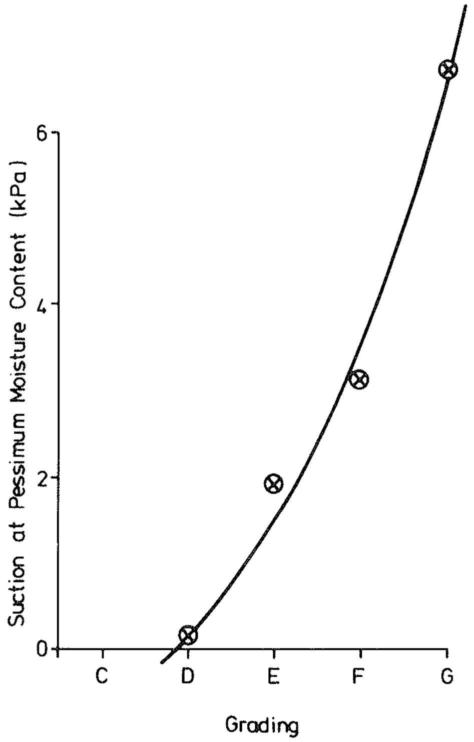


FIGURE 9 Deduced maximum suction values.

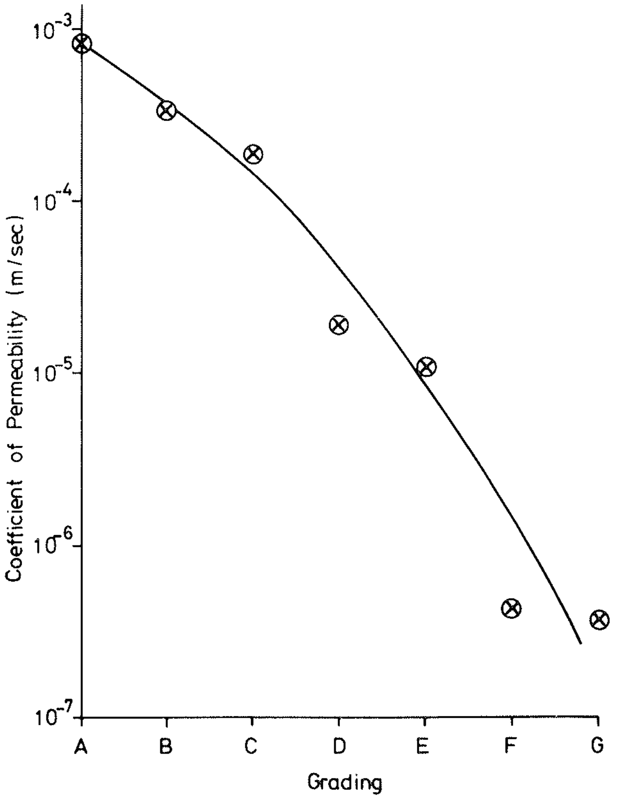


FIGURE 10 Coefficient of permeability for all gradings.

PAVEMENT ANALYSIS

The changes in elastic stiffness that occur because of changes in moisture content have been described. In this section the results of pavement analysis using these data are given. A standard pavement, incorporating material at Grading E in the dry state, was selected for analysis. The parameters were then adjusted to allow for material at optimum moisture content (about 10.5 percent). Finally, the pavement was analyzed using the parameters for optimum moisture content but assuming full saturation and no drainage. The pavement details and analysis results are given in Tables 1 and 2.

TABLE 1 PAVEMENT DETAILS USED IN ANALYSIS

Layer	Thickness (mm)	Stiffness (MPa)	Density (kg/m^3)
Asphalt	50	5000	2500
Base	200	150 (dry) 120 (wet)	2200
Subgrade	3000	100	2000
Bedrock	-	∞	-

Two programs for pavement analysis were used. BISTRO *(8)* deals with linear elastic layered systems and allows analysis of the first two situations. GRANMAT is a new program that incorporates nonlinear behavior in the subbase and is still under development at Nottingham. It allows the saturated undrained situation to be modeled.

The significant quantities emerging are tensile strain at the bottom of the asphalt layer (controls cracking) and vertical strain at the top of the subgrade (indicates rutting potential). Surface deflections under the load are also included.

It can be seen from both BISTRO and GRANMAT that the effect of using optimum moisture content parameters rather than dry ones is small. The difference between the two programs is probably due to the difficulty in selecting the appropriate single value of elastic stiffness of a granular layer for use in BISTRO. However, the saturated undrained results from GRANMAT demonstrate the immense weakening that is theoretically possible if a pavement becomes saturated. Both strains have increased enormously, giving a manyfold decrease in expected pavement life; the order of magnitude may be found using a design method such as that described by Brown et al. *(9)*.

CONCLUSIONS

The presence of moisture in an aggregate "lubricates" the particles and increases both elastic and, particularly, permanent deformation. This takes place with no apparent pore pressures being generated. The permanent deformation accumulation rate can increase tenfold on wetting.

Subsequent drying out of a limestone aggregate can allow cementation and greatly increased stiffness.

TABLE 2 RESULTS OF PAVEMENT ANALYSIS

Run	Asphalt Tensile Strain (microstrain)	Subgrade Strain (microstrain)	Surface Deflection (microns)
BISTRO (dry)	332	832	530
BISTRO (wet)	372	842	579
GRANMAT (dry)	510	945	1037
GRANMAT (wet)	615	720	1082
GRANMAT (sat.)	1320	4515	2459

Loading frequency has a negligible effect on strains at degrees of saturation up to 85 percent.

Suction values have been deduced that would affect drainage properties of an aggregate layer but have little effect on stress-strain relationships.

The magnitudes of permeability that were measured underline the danger of excessive fines in a road base; they lead to poor drainage and subsequent saturation.

Analysis of a typical pavement structure has indicated that moderate levels of moisture have only a minor effect on overall elastic behavior but that saturation of a poorly drained base layer has a drastic effect.

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