Laboratory Testing for Use in the Prediction of Rutting in Asphalt Pavements

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Increasing interest in methods for the quantitative prediction of rutting in asphalt pavements requires that particular attention be given to relevant laboratory materials testing. The major tools for such testing are the repeated load triaxial test and the creep test. This paper discusses experimental aspects of the repeated load triaxial test in some detail. Particular attention is given to stress application systems and the measurement of load and deformation. Where appropriate, the particular requirements of different materials are considered. In addition to the test techniques described in the literature, several novel features of recent research at the University of Nottingham are described.

The emphasis of recent research concerned with the problem of rutting in flexible pavements has moved from methods related to prevention to the development of methods for prediction (1, 2, 3, and a paper by van de Loo in this Record). The most promising of these are based on the so-called engineering approach, which is outlined in detail in a paper by Monismith in this Record. One of the most important aspects of the proposed design procedure is that of materials testing. Not only are the relations between the applied stress and the resulting permanent strain required, but the elastic stress-strain parameters are also needed for the initial theoretical analysis of the pavement. Recommended procedures for evaluating the elastic response of pavement materials have been published by the Transportation Research Board (4).

The overall objective of laboratory materials testing is to reproduce the in situ pavement conditions of stress, temperature or moisture, and sample condition under circumstances that permit the accurate measurement of deformation, so that reliable stress-strain relations can be obtained.

The difficulties involved in meeting this overall criterion have been discussed (5, 6, 7). The major concerns of these are the various conditions, but there are also problems in the preparation of representative samples when cores from the pavement are inadequate or unobtainable.

The repeated load triaxial test is the best practical method for the testing of pavement materials and soils in the context of design against rutting. It allows the determination of both resilient and permanent strains so that both of the types of stress-strain relations required for design may be established. This paper, therefore, concentrates on the use of the repeated load triaxial test, attempting to show how it can best be used for the various materials and situations involved in the design problem.

REPEATED LOAD TRIAXIAL TEST

Stress Conditions

The major limitation of the triaxial test is that only principal stresses can be applied to a test specimen. Furthermore, as shown in Figure 1, two of these are necessarily equal because of the axial symmetry of the arrangement. Also, although in the testing of soils and unbound aggregates only compressive stresses can be applied, in the testing of bound material it is possible to apply tension and a further limitation of the triaxial test is that this can be done in only one direction.

The stress distribution in a pavement is considerably more complex than that in the axisymmetric triaxial test. Figure 2 shows the stresses acting on a general, vertically oriented element as a result of a single, circular, uniformly distributed surface load. In addition to the three normal stresses in the vertical, radial, and tangential directions, since only one of them (σ_θ) is a principal stress, shear stresses act on the other two planes. Even if the element is reoriented, the three principal stresses are all different, and the situation is therefore at variance with the triaxial test.

If, however, an element on the axis of the load is being considered, then two simplifications will bring the conditions in line with those occurring in the triaxial test. The principal stresses will become vertical and horizontal, and the two stresses acting horizontally will be equal.

Hence, for points on the axis of symmetry of the load, the triaxial test can reproduce the in situ conditions except near the bottom of an asphalt layer, where the hori-

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zontal tension becomes relevant. For this latter situation, Brown (8) has suggested an approach to laboratory stress simulation that is based on the use of stress invariants. A similar approach can also be used to deal with off-axis locations as illustrated in Figure 2. In view of the important influence of shear stress on permanent strain, the shear components shown in Figure 2 should not be ignored, as is generally the case (2, and in a paper by Snaith and Kirwan in this Record). The invariant approach avoids the necessity for this.

Stress Application Systems

The basic triaxial test developed for use in soil mechanics (9) has been adapted in two different ways for use in repeated loading tests for the pavement design problem. The original concept (Figure 1) of a cylindrical sample subjected to an equal, all-around pressure, the confining stress, on which an additional axial stress, the deviator stress, is added, has been modified in some cases so that the vertical and lateral stresses are independently applied (Figure 3). Whichever system is used, it is necessary to apply a vertical load that varies with time in a manner representative of the pavement situation. Various pulse shapes—sinusoidal, square, triangular, and trapezoidal—have been used for this purpose. In many cases the shape chosen is a function of the test equipment available, but an analysis of the in situ stress pulses (10) has indicated that sinusoidal or triangular shapes are the most appropriate for direct simulation.

Since the identical variation of stress conditions with time of an in situ element is not possible in the triaxial test, the actual pulse shape is relatively unimportant, at least for the determination of the elastic parameters. For accuracy in load control and the measurement of deformation, a system that avoids sudden changes of stress is desirable, and on this basis the sinusoidal pulse is the most attractive, although it usually requires the more complex equipment.

A variety of test systems ranging from relatively simple pneumatic or mechanical systems (11, 12) to rather sophisticated servo-controlled electro-hydraulic systems (13) have been used for the repeated loading of pavement materials. The principles of operation for these systems are shown in Figures 3 to 5. Clearly, the more comprehensive systems can be used for both fundamental research-oriented testing and the more routine design-related tests. Simpler systems may be more useful for the design function if they are properly applied.

A major simplification that some equipment has is to pulse only the vertical stress, while applying a constant confining stress. For granular material, either asphalt-bound or unbound, this restriction can be overcome by ensuring that the constant confining stress is approximately equal to the mean of the desirable cyclic value (14, 15).

A further consideration concerning repeated load application is whether to cycle continuously or with some rest period between pulses. Most research, particularly in the United States, has done the latter by using 20 or 30 repetitions/min of a pulse about 0.1 s in duration for both resilient and permanent strain measurements. Recent investigations at the University of Nottingham (16, 17) have confirmed that rest periods are not significant for permanent strain tests on asphaltic material or cohesive soils. For resilient measurements, however, a short interval between pulses would seem advisable to allow for the delayed elastic recovery in asphaltic materials and cohesive soils, but for granular material continuous cycling would probably be suitable.

Barksdale (10) has presented data with which to determine the length of the pulse corresponding to various vehicle speeds and depths in the pavement. For the permanent deformation of cohesive soils and asphalt, this is not an important parameter as confirmed by the relations between creep testing results and those from repeated load tests (14, 18, 19). For granular materials, where the shear resistance depends mainly on interparticle friction, the number of load cycles is more significant than the pulse time. The correct pulse time is of importance mainly in the determination of resilient response in asphalt materials.

With this background it is now possible to review the various types of loading systems that have been used.

Mechanical Systems

These are of the type that in principle operate either in the way illustrated in Figure 4 or by the use of a conventional screw-driven loading frame with appropriate controls. A system such as that in Figure 4 was developed for testing clays by Grainger and Lister (12). It incorporates an arrangement with which to pulse the confining stress. Most other mechanical systems (e.g., 20, 21) cycle only the deviator stress. Shakel (22) uses a screw-operated machine for slow repeated loading (only 4 cycles/min) with a bellows arrangement beneath the sample to cycle the confining stress in phase with the deviator stress.

Mechanical systems can be used for either stress or strain-controlled testing; arrangements for the latter are usually simpler. Taylor and Bacchus (23), for example, connected the loading ram to an eccentric. Screw-driven machines are well suited to controlled strain testing at low frequencies.

Pneumatic Systems

These are best used for controlled load testing and operate in principle like the arrangement in Figure 3. This system, developed by Seed and Fead (11), has been widely adopted because of its relative simplicity. A compressed air line is connected to an air ram, usually incorporating a Bellofram seal, through a solenoid valve. The electrical signal to the solenoid comes from a timing unit that can be set to provide appropriate pulse times and spacings.

The further development of this type of system by Dehlen (24), which is the one actually shown in Figure 3, is able to pulse both vertical and lateral stresses in phase. Nair and Chang (15) have developed a system in which two rams operate in series, one applying a static load while the other superimposes a cyclic load with double acting ram used for the latter so that tension can be applied to the specimens.

Hydraulic Systems

The introduction of servo-controlled electro-hydraulic systems for materials testing represents a large step forward in accurate and flexible testing capabilities, and also in cost. In addition to the various commercial systems that have been developed in recent years, several laboratories have developed their own.

Figure 5 shows the system developed by Snaith (13, 16) for testing bituminous materials. Two closed-loop systems are used, one to control the vertical load and the other to control the confining stress. The servo-valve controls the flow of oil to the hydraulic actuator. The electrical signal operating the servo-valve is continuously adjusted by comparing the output from the appropriate transducer (a load cell or cell pressure transducer) with the command signal from a waveform generator. The flexibility of this system, together with certain additional components, provides a test facility having many capabilities. Similar systems have been used for testing soil and unbound granular materials (15, 26, 27).

Control of the cell pressure cycling system creates more problems than does the axial load. It is essential that the system being pressurized should be as stiff as possible so as to minimize the required movement of the hydraulic actuator. The confining medium in such cases is usually a silicone oil that does not conduct electricity or attack latex membranes. A system such as Dehlen's (24) (Figure 3), where the actuator (in this case, a Bellofram seal) operates directly onto the confining fluid in the triaxial cell, should provide better control than the remote pressurization system shown in Figure 5. This type of system is also used by Allen and Thompson (28).

Figure 1. Triaxial test.

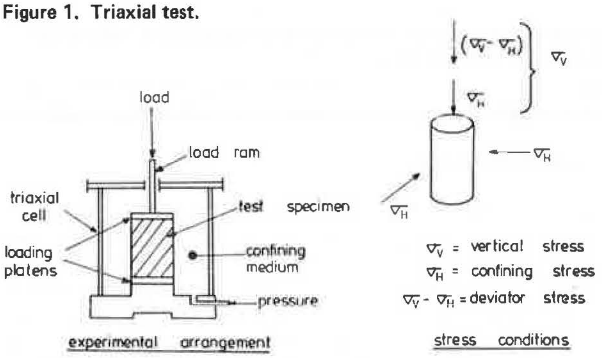


Figure 2. In situ stresses.

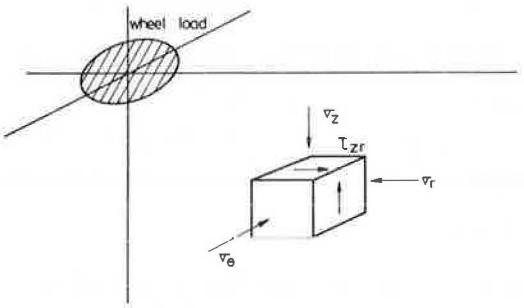
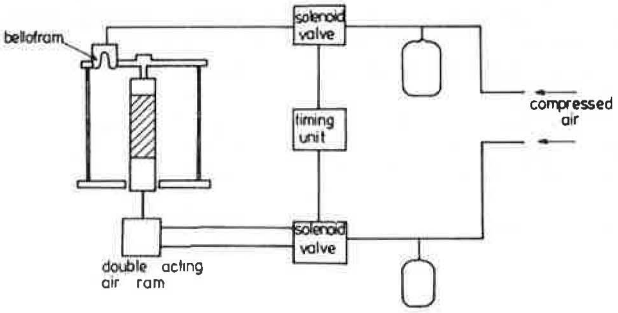


Figure 3. Principle of pneumatic test facility.



Servo-controlled hydraulic systems can provide either load, stress, or deformation control, and many different waveforms can be used. Independent control in terms of pulse amplitude and length can be provided between vertical and confining stresses. The system can be programmed to provide various combinations of load pulse and rest periods.

Load Cells

The vertical load applied to the sample is almost always measured by a load cell of some type that provides an electrical output that can be recorded with the other data of interest.

A common problem with load measurement in the triaxial test has been the error caused by the friction between the loading ram and the hole in the cell top when the load is measured outside the cell. This problem is particularly acute when testing at the low stress levels that are usually appropriate for subgrade soils. Although this ram friction error can be calibrated, it is clearly more desirable to use an internal load cell. These cells may be located either in the pedestal on which the sample is seated, in the top loading platen, or in the loading ram. Care must be taken to ensure that, in tests where the cell pressure is cycled, the output from the load cell is unaffected by these ambient pressure variations.

Deformation Measurement

Accurate deformation measurements can best be obtained

Figure 4. Principles of a mechanical testing system.

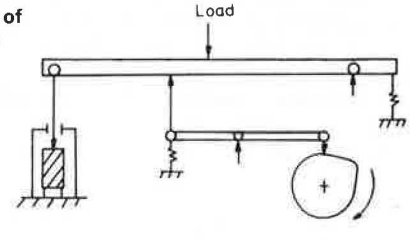


Figure 5. Principles of servo-controlled electro-hydraulic system.

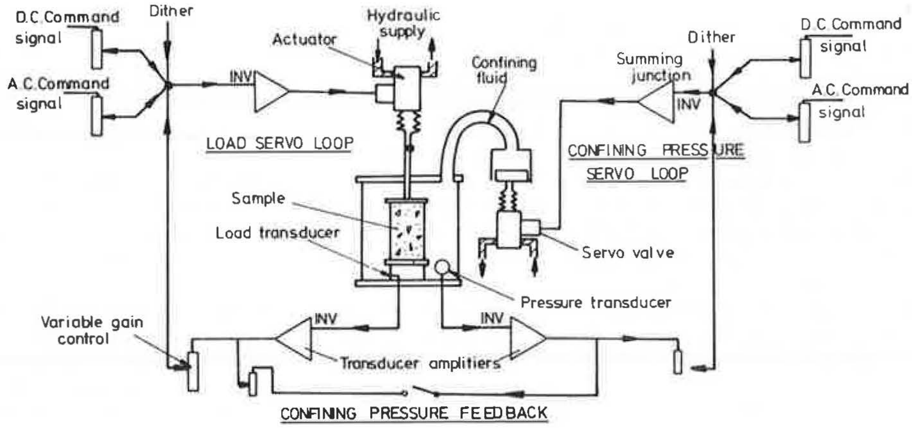


Figure 6. Direct attachment of linear variable differential transformer to asphalt sample.

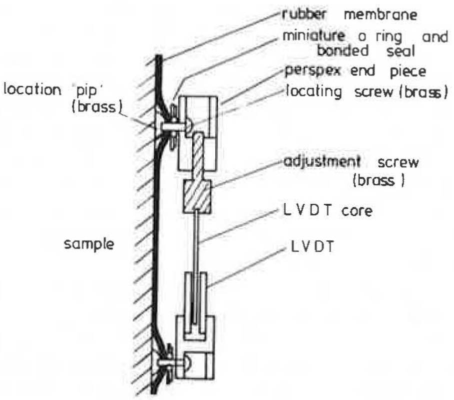


Figure 7. Deformation measuring system for granular material.

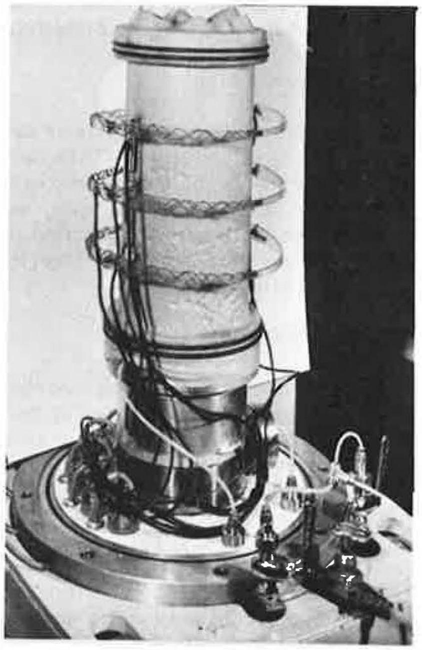
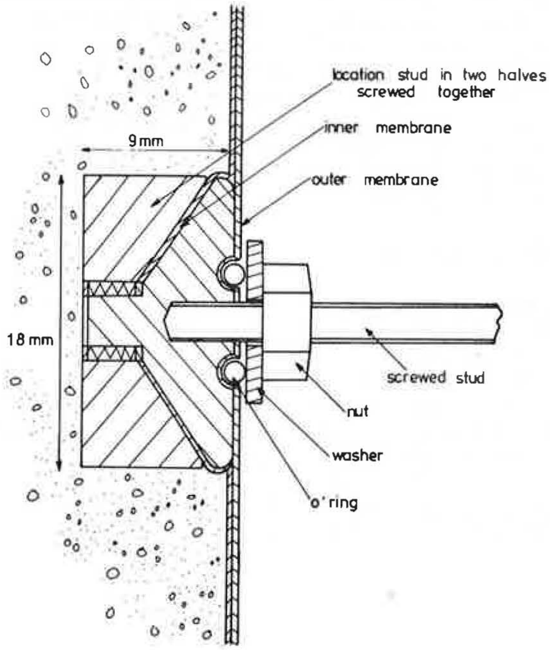


Figure 8. Locating stud for deformation measurements in granular material.



with samples that deform as right cylinders, but this ideal situation is usually prevented by the restraint to lateral movement caused by friction between the sample and the loading platens. This can be minimized in compression tests by using a thin layer of high vacuum silicone grease on the platens and a rubber membrane between this and the sample. Such a system is most effective, at least for soils, when the ratio of the sample height to its diameter is 1:1 (29), although the possibility of end restraint usually requires longer samples to be used. For tension tests, end restraint can obviously not be avoided.

The simplest method of measuring vertical sample deformation is by an external displacement transducer monitoring the movement of the loading ram relative to the triaxial cell. Such a system is subject to many errors due to deformation in the equipment that may be of the same order of magnitude as a typical resilient sample deformation. Tests on the soil testing facility used by Brown and others (26) indicate errors of $10\mu\epsilon/\text{kN/m}^2$ for 100-mm diameter samples. Although careful calibration can eliminate errors, this system is really only suitable for large permanent deformation measurements, and then only in circumstances in which the end platen restraint is small.

Most testing concerned with evaluating resilient strains has, in recent years, used direct on-sample measuring techniques. The use of linear variable differential transformer (LVDT) clamps or strain collars is now formally recommended in an Asphalt Institute design manual (30). These systems can measure strains down to $2\ \mu\epsilon$ (13) [details can be found in the TRB special report dealing with resilient modulus testing (4)]. They have been used for all types of material and for both tension and compression testing.

Further discussion of deformation measuring devices can best be carried out by considering those appropriate to the various types of materials.

Asphaltic Materials

Bonded electrical resistance strain gauges have often been used for testing asphalt samples. They are satisfactory if the temperature is not too high, when the relatively high stiffness of the cement causes errors. Strains in excess of 1 percent also cause problems. An evaluation of strain gauge accuracy by Smith and Nair (31) showed that these gauges can be used at temperatures up to 38°C, but that the largest strain level they recorded was only 0.08 percent.

The use of LVDTs mounted on gauge lengths about the center of the sample is the best method presently available for both resilient and permanent deformation measurement. Either the strain collar idea or a system such as that devised by Cooper (32) and shown in Figure 6, where the collar is eliminated and the LVDT attached directly to a locating point cemented to the sample, may be used. A collar, operating like a caliper, is still required for lateral deformations.

Granular Materials

LVDT clamps have been used for granular materials (33), but there is a possibility of error if the measuring points are separated from the sample by the rubber membrane. The system shown in Figure 7 was developed by Boyce (37) for both resilient and permanent strain evaluation.

Six locating studs are attached to the rubber membrane prior to the compaction of the sample so that they subsequently behave like a particle of aggregate (Figure 8). An arrangement of four LVDTs and three strain-gauged hoops (Figure 7) provides several measurements of deformation from which a reasonable average in the two directions may be obtained. This multiplicity of measurements is important for materials having large particle sizes as there is considerable local variability of strain. The standard deviations for sets of readings on materials having a 38-mm maximum particle size were between 9 and 41 percent (34).

Induction coils have also been used for the measurement of lateral deformation of granular materials (28, 35). The major problem in this instrumentation is the interference caused by metal objects moving relative to the coils while measurements are being made. If large enough coils are used for a pair to operate across a sample diameter, the flux field may be cut by the movement of the end platens during repeated loading.

The use of individual locating points for lateral deformation measurements has been criticized because the measurement is being made on a single diameter. Kennedy (21), following the idea of Lee and Morgan (36), used a thin foil band to surround the sample and monitored changes in the circumference by an LVDT. However, the system of transmitting the movement to the LVDT and the fact that the band is located outside the rubber membrane can also introduce errors, particularly if the test frequencies are higher than approximately 1 Hz.

An optical tracking system was used by Allen and Thompson (28) for vertical deformations. Although extremely expensive, this system is accurate and convenient.

Soil

The methods described for granular materials can also be used, in principle, for soils, provided the sample size is large enough. Direct on-sample measurements are difficult if sample diameters are less than 50 mm, unless an optical technique is used. The attachment of equipment to weak soils is difficult and may introduce larger errors than those associated with external or overall measurement, unless very light equipment can be developed. Hence, when small or weak soil samples are being tested, lubricated ends are essential; deformations can then be measured across the end platens or externally on the loading ram, provided false deformations are quantified.

If saturated samples are being tested, it is more convenient to measure the volume change in a drained test than the lateral deformation. In an undrained test, the volume remains constant and only the vertical deformation need be measured.

Special Requirements for Soil Testing

In testing soils or granular material, the drainage conditions must be appropriate to the in situ situation. For granular materials, this will usually mean that free drainage is allowed because of the high permeability of the material. There may be circumstances, however, where undrained conditions apply. Such a situation may be represented by a saturated dense granular base located beneath an asphalt layer and above a saturated clay subgrade.

For cohesive soils, the undrained test is more appropriate. Grainger and Lister (12) have attempted to introduce a false water table to their testing arrangement so that in situ drainage conditions could be more accurately reproduced.

The importance of the principle of effective stress has been overlooked in much of the laboratory testing of soils and granular materials. Its significance has been discussed by Smith and Nair (31) for granular materials and by Brown and others (26) for clays.

The accuracy with which effective stresses can be determined in undrained tests depends entirely on the ability to measure pore pressures. For repeated load tests this can only be done with saturated samples, and cyclic changes in pore pressure are only likely to be measurable in granular materials at relatively low frequencies ($\leq$1 Hz). For such materials, testing in the dry state is an easier way of evaluating results in terms of effective stresses (34).

The principles of pore pressure measurement in the triaxial test are well documented (9). Electrical pressure transducers of high stiffness are available so that a very low compliance system that requires a minimum flow from the sample can be used. The filter element between the soil and the measuring system must be sufficiently permeable as to allow adequate flow but not so porous that blockage by soil particles can occur.

Sample Preparation

In a design situation it is usually desirable to test material in the as-layed state. This can be done by coring samples of the asphalt or cohesive soil. For other materials and other circumstances, samples must be prepared in the laboratory. Detailed procedures for this have been recommended in connection with resilient modulus testing (4).

CONCLUDING DISCUSSION

This paper has reviewed the considerable expertise that has been developed in the use of the repeated load triaxial test for laboratory testing related to the prediction of rutting in asphalt pavements.

Of the other possible test methods, the creep test offers the most potential for cohesive soils (19) and asphaltic materials (14, 18).

The state of the art is that both long-term, fundamentally oriented research and the testing related to particular design situations can be studied. There is still a need for the development of improved laboratory tests and techniques, but there are sufficiently well-defined procedures now available for the important task of design method validation. This is an urgent problem that should initially be carried out on controlled experiments in which loading and environmental conditions are well-defined. Several experiments of this kind (18, 37) and some full-scale trials (3) have already been reported.

The simplifications to laboratory testing that will be required before analytically based design methods become widely accepted will only emerge as a result of further research. However, the potential of the creep test is already apparent.

ACKNOWLEDGMENTS

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