Instrumentation for the Nottingham Pavement Test Facility

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A description is given of the instrumentation that has been used successfully in the Nottingham pavement test facility to obtain in situ measurements of stress, strain, and permanent deformation in pavements subjected to moving wheel loads. The data from tests of this kind are being used to validate theoretical computations of pavement performance. Diaphragm-type earth pressure cells have been used in asphalt, unbound aggregate, and soils; details are given of installation and calibration techniques. Bison strain coils have proved useful for in situ measurements of both transient and permanent strains. An electronic unit has been developed to linearize the output from these transducers, thus making it easier to use. Electrical foil-strain gauges and post-yield gauges were also used for measurements in asphalt and on fabric inclusions, respectively. An automatic data-acquisition system allows a direct printout to be obtained of peak stresses and strains from the pulses generated by moving wheel loads. A typical layout of instruments is presented, which was designed to obtain maximum information from a short section of pavement.

Data from carefully instrumented pavement test sections are available for the continuing development of analytically based procedures for pavement design. A general review of suitable equipment has been presented by Brown (1). At Nottingham, such installations have been used in a pavement test facility (see our other paper in this Record) and in a few full-scale trials on public roads.

This paper concentrates on the work done with the pavement test facility. We describe the instruments and how they were used to obtain in situ measurements of stress and strain. The materials involved were representative of the three components of a flexible pavement--asphalt, unbound aggregate, and clay.

The instruments that have been used most extensively are the Nottingham pressure cell (2), Bison-strain coils (3), and foil-strain gauges. All these have been calibrated in or on the relevant pavement materials or checked during testing in order to quantify their influence on the local stress and strain fields. This in situ calibration follows the philosophy that the transducer output must be processed to give a measurement that is representative of the stress or strain that would have existed had the transducer not been present. Care with installation is extremely important and, if carried out incorrectly, may result in large errors. Despite the precautions necessary for accuracy, scatter is still inevitable, and the variability in material properties (either inherent or due to compaction) and the complexity of the loading effects all result in the need to take as many replicate measurements as is practical. A data-acquisition system was, therefore, developed to provide direct printout of stress and strain values. This system operates in parallel with an analogue recorder so that the shape of the output pulse can be observed. A linearizer unit was introduced for the strain coil instrument to facilitate easy direct reading of transient signals due to moving wheel loads.

INSTRUMENTS

Only the instruments used in the pavement test facility and site investigations are described. They were chosen because of previous experience in their use and their simplicity of design, which fulfilled the compromise between practicality and ideal characteristics. A stress gauge, for instance, should be robust but have a large diameter-to-thickness ratio, and a strain transducer also needs to be robust but it should not reinforce the pavement material.

Nottingham Pressure Cell

The Nottingham earth-pressure cell (2) consists of a recessed titanium disc that, in effect, is a diaphragm attached rigidly to a guard ring (Figure 1). A four-arm strain-gauge bridge is attached to the diaphragm and physically arranged and connected to reduce cross sensitivity and compensate for temperature. A lid is riveted in place to form a cavity that is partly filled with silicon rubber and a cable entry is sealed into the side of the cell body. The instrument can be either alternating current (AC)- or direct current (DC)-powered and is suitable for transient or short-term stress measurements. Its characteristics have been well documented elsewhere (2,4).

Strain Coils

The development of strain coils for in situ measurements was described by Selig and Grangaard (3) and Selig (5). The technique consists of a pair of wire-wound discs, which can be obtained in various sizes (Figure 2) and installed either in a coaxial or coplanar alignment and are connected to a Bison-soil-strain-gauge instrument. An AC signal is supplied to one coil and an electromagnetic coupling is developed with the other coil. The strength of this coupling is related to the spacing between the coils in a nonlinear way and is converted to a voltage by the Bison instrument. When balanced by means of phase and amplitude potentiometers, a reading is obtained that can be interpreted as the gauge length. Any transient change from this gauge length can be monitored on a suitable recorder and resilient strain can be calculated. Long-term changes in gauge length can be evaluated from a curve that relates coil spacing to amplitude dial reading in order to determine permanent strain values. A calibration and sensitivity control can be used to produce a signal on a recorder of a known strain over the spacing range, which is approximately 1-4 diameters.

Strain Gauges

Strain gauges are simply wire or foil grids on a thin backing that can be attached to any structural component subjected to strains within the range of the gauge. In the pavement field, they are usually limited to use on bituminous materials, particularly in the tensile zone at the bottom of the layer (1). Carrier blocks cut from sections of the asphalt mix may be placed within the layer or a thin sandwich that contains the gauge can also be used. In a situation where high initial strains may be expected during compaction or on fabric inclusions over a soft subgrade, post-yield gauges can be used that remain operational up to a strain of 10 percent.

INSTRUMENT CALIBRATION

The calibration procedures for the pressure cells and strain coils in a subgrade and granular material (maximum particle size 9.5 mm) have been previously described (1,2,4,6) so discussion here is restricted to more recent work in a bituminous material and in a granular material that has a larger maximum particle size. Calibrations of strain gauges have also

Figure 1. Nottingham earth-pressure cell.

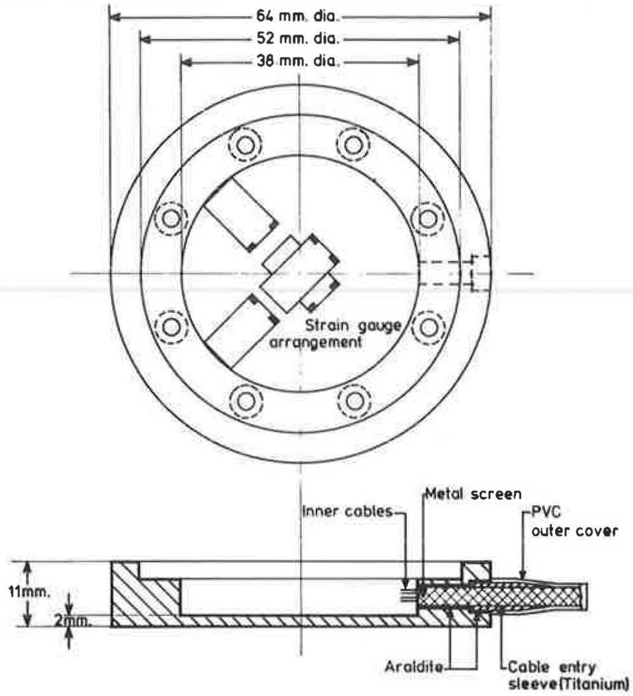
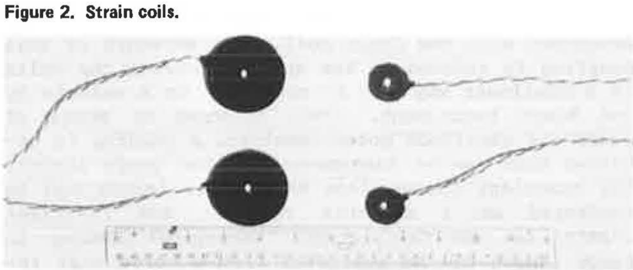


Figure 2. Strain coils.



been carried out on a nonwoven fabric. Strain coils have yet to be calibrated in asphalt, but evidence suggests (6,7) that the coils give an accurate representation of the true strains unless a dense or weak pocket develops during installation or some metal is present that will distort the flux linkage between the coils.

Pressure Cell in Crushed Stone

The material involved was a dry, crushed limestone of 40 mm maximum particle size and well graded to the specification for road bases in the United Kingdom (8). The accepted ratio of diaphragm diameter to maximum particle size for pressure cells is 50:1 (9), so clearly the cell shown in Figure 1 was incompatible with this design parameter. To overcome this, fine material was packed over the diaphragm, to protect it from point loading by large particles of aggregate. Thin plastic film held the fines in position, as shown in Figure 3.

A bench calibration, which involves application of fluid pressure directly to the diaphragm (1), and calibrations in several 230-mm diameter triaxial test specimens were then carried out. A cell-registration factor, which is the measured stress divided by a true stress, was thus obtained. The apparatus for in situ calibration is shown in Figure 4, which is the general arrangement for the calibration of both stress and strain transducers. Specimen preparation involved compaction of two layers of aggregate in a mold on a vibrating table prior to installation of the instrument at midheight.

The specimen was load cycled 10 times before testing to improve repeatability and relevance of subsequent results. Increments of vertical load were then applied at various confining stresses and the output of the pressure cell was monitored. The true stress was calculated from the applied load divided by the specimen cross-sectional area. This procedure was repeated after further load cycling was carried out. As the load could only be applied relatively slowly, this exercise was essentially a static calibration, but time effects were unlikely to be significant in dry granular material.

The results shown in Figure 5 indicate cell registrations just below 1.0 at a confining stress of 48 kPa; lower values were obtained with higher confinement. Further load cycling did not have any significant effect at the lower confining stress, but a large hysteresis curve was noted during unloading. These trends were observed for two other specimens, and it was concluded that the prepacked pressure cell could be used successfully in the pavement experiments that involved relatively low confining stresses.

Pressure Cell in Asphalt

The experimental arrangement for pressure cells in asphalt was similar to that in Figure 4, but a continuously graded dense asphaltic material was used. This calibration work was required in connection with a project that involved full-depth asphalt paving (10). Compaction of the asphaltic specimen was by falling hammer. A servohydraulic load test facility was then used to apply static and repeated uniaxial loads to the specimen. Fine material was again placed around the instrument; both a sand asphalt and fines from the asphalt mix were used.

Specimen testing was carried out at various rates of uniaxial loading and a range of temperatures in order to cover a range of mix stiffnesses. A typical set of results is presented in Figure 6, and this also includes the theoretical relationship predicted by Tory and Sparrow (11). Flexibility factor (F) is the ratio of the soil stiffness to cell stiffness and is defined as

$$F = E_s d^3 / E_c t^3 \quad (1)$$

where

E_s = Young's modulus of the soil,
E_c = Young's modulus of the cell,
d = diaphragm diameter, and
t = diaphragm thickness.

Higher registrations were obtained compared with the predicted curve when sandsheet was used over the cell, and good agreement can be seen when fines from the actual mix were involved.

In practice, it is best to operate in a stiffness range that gives a cell registration of about 1.0, and on the flat (left-hand) part of the theoretical curve. When practical considerations make this impossible, the theoretical curve may be used. In bituminous mixes and crushed-stone materials, an interface of fine materials is required over the cell diaphragm if the cell dimensions are to be practical, but the material actually used has an influence on the results that needs checking by calibration tests. To obtain good data from these high stiffness applications, it is necessary to know the material stiffness with some accuracy.

Figure 3. Pressure cell prepacked for granular material.

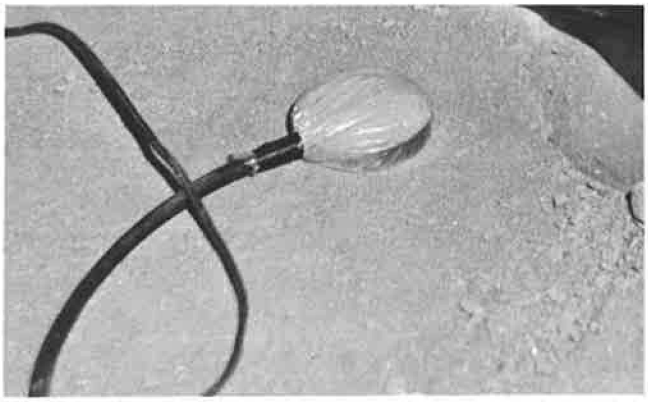
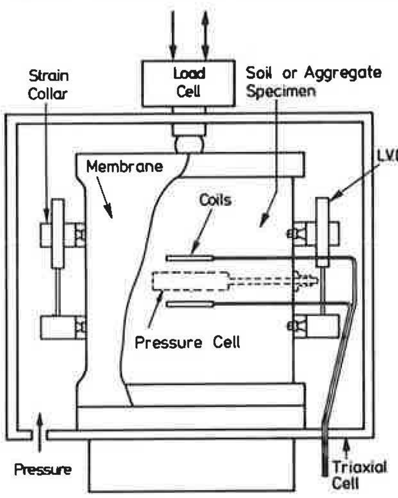


Figure 4. Arrangements for instrumentation calibration.



Strain Gauges on Nonwoven Fabric

A series of pavement tests that incorporate fabric between the subgrade and granular layer of a three-layer system (12) required that strains in the fabric due to wheel loading be measured. Coplanar strain coils were used initially and then supplemented with strain gauges. These were 60-mm gauge length post-yield gauges capable of operating up to 10 percent strain and they were attached to the fabric with cyanoacrylate adhesive. Fabric segments were positioned over the gauges for protection and to present the correct surface texture to the adjacent soil. This technique was even more important with strain coils since they would otherwise tend to lock into the soil, and any relative movement between the soil and fabric would not be accurately measured.

Prior to installation, a calibration test was conducted with the gauge on a 200-mm wide strip of fabric, which was clamped between the jaws of a tensile test apparatus (Figure 7). The true or reference strain about the gauge was measured with strain coils. Increments of load were applied to the fabric and the relation between the outputs from the gauge and strain coils is presented in Figure 7. A calibration figure of 2.15 mV for 0.5 percent strain was obtained for the gauge, but beyond this steady readings were difficult to obtain because the fabric tended to creep.

Figure 5. Calibration of pressure cell in crushed limestone.

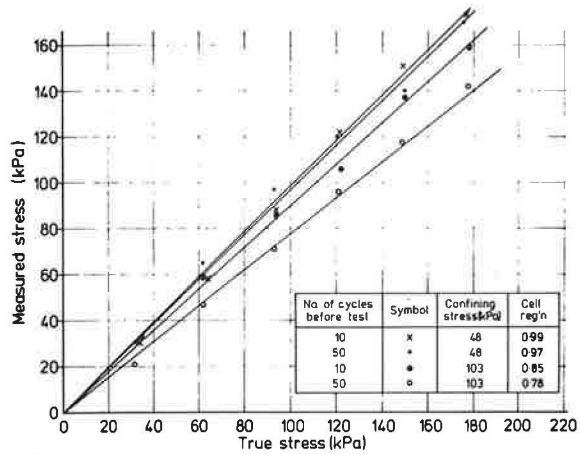


Figure 6. Comparison of theoretical and experimental cell registrations for pressure cell in asphalt.

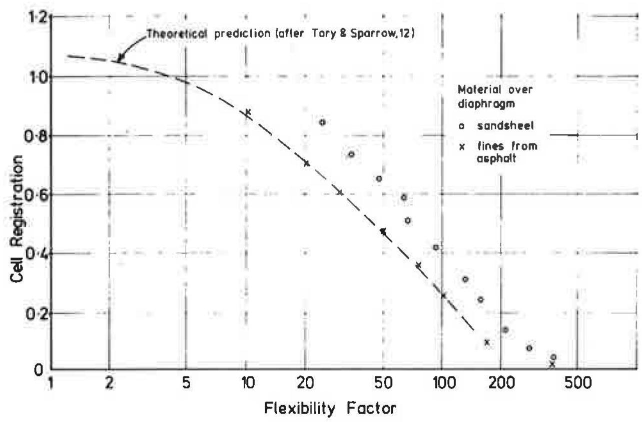
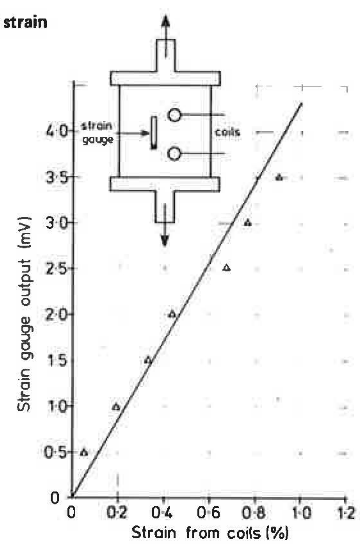


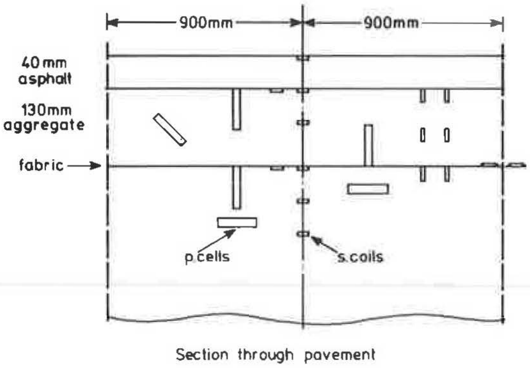
Figure 7. Calibration of strain gauge on fabric.

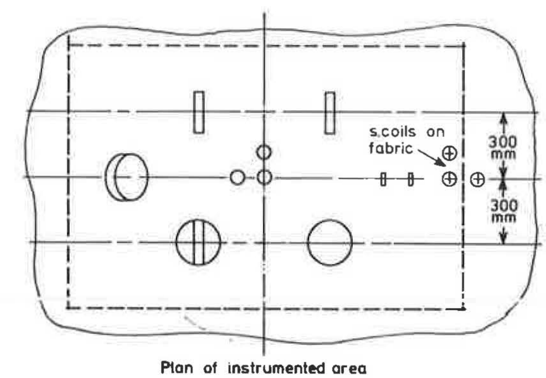


INSTALLATION PROCEDURES

A typical layout of instruments in a three-layer pavement constructed in the pavement test facility (2) is shown in Figure 8. The apparent overcrowding is a function of the reduced horizontal scale since

Figure 8. Typical instrumentation layout in pavement test facility.





all pressure cells are separated from each other and the strain coil stack by at least 200 mm. Interaction between cells only occurs when they are within two to three diameters of each other (13).

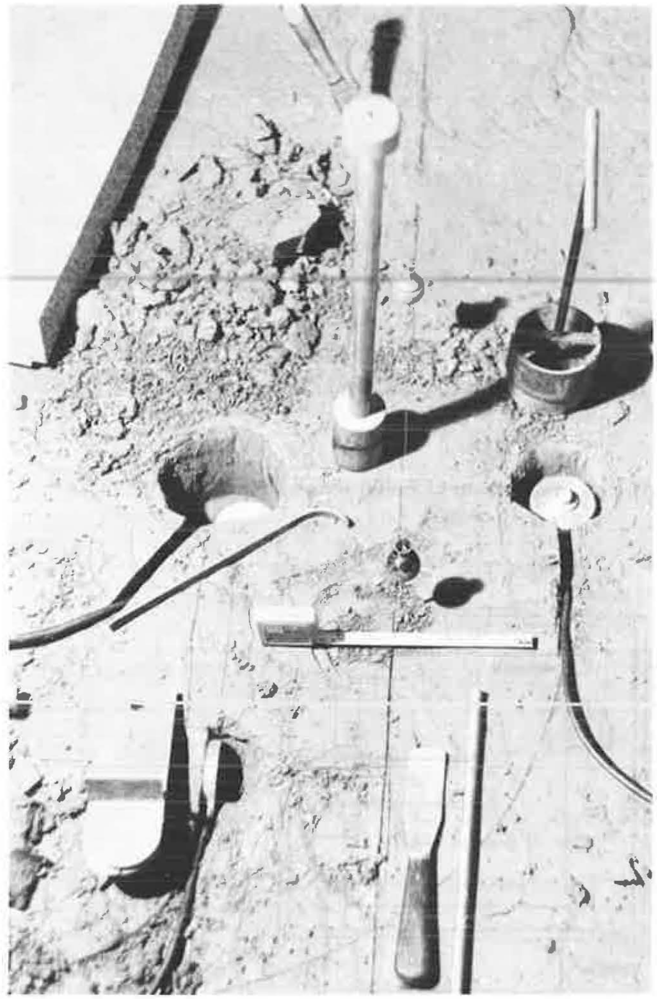
The strain coil stack consists of 25-mm coils separated by approximately 50 mm. Only one pair of coils is energized at a time and the effect of the inactive adjacent coils was found to be negligible during calibration. A set of tools has been developed to bring a measure of consistency to the installation procedure, and these are shown in Figure 9.

Pressure Cells

Because of the destructive nature of the clay subgrade-compaction procedure, the instruments could only be installed on completion of this operation. Holes were then prepared by using special tools (Figure 9) to accept the cell with enough working clearance for backfilling. This is particularly important for the vertically installed cells (for measuring horizontal stresses), as it is necessary to select the soil for placement against the diaphragm. This involves removal of large particles and careful compaction against the diaphragm. The sides of the holes and any backfill layers are scarified to maintain continuity with the undisturbed soil. Attempts were made to achieve the same density in the backfill as in the main soil mass by using the correct amount of soil for the unfilled volume of the hole.

The crushed limestone base was compacted by vibration in layers to a level that only required a shallow hole to accommodate the instrument prepacked with fines held in position over the diaphragm with a thin polythene sheet. Excavations of holes to a specific size are not possible in granular materials and only the minimum amount of material was removed. More fines were used to position the cell in relation to a suspended plumb bob and then the excavated aggregate was carefully placed and hand tamped against these fines before compaction of the next layer of base.

Figure 9. Tools for installation of instruments.



Pressure cells were only used in the asphalt layer for the full-depth tests (10). They were positioned at a layer interface during paving. A hot-hand-compacted sandsheet mix covered the diaphragms for the horizontally placed cells. The vertically oriented cells were positioned in a mound of sandsheet. A quantity of the actual pavement mix was immediately compacted with a ram over the sandsheet in order to integrate the two materials. Paving operations were commenced as soom as possible to establish the satisfactory bond with the interface materials. Calibration tests specifically relating to this installation procedure and the appropriate test conditions yielded a cell registration of 0.97.

Strain Coils

Figure 10 illustrates the installation arrangements for strain coils in various situations. Generally, 25-mm coils were used, but 50-mm coils were occasionally adopted for the coplaner mode since it was felt that they were more likely to resist reorientation during compaction and testing.

A hole was cut in the subgrade with a 37-mm diameter sharpened tube to a depth of 100 mm and then an

Figure 10. Installation of strain coils.

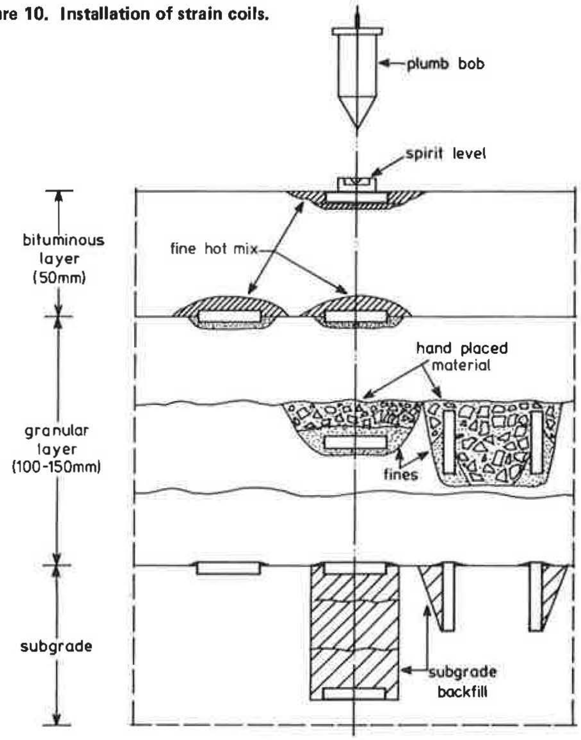


Table 1. In situ performance of instruments.

Instrument	Output	Pavement Layer	Cell Registration	Accuracy
Pressure cells, not amplified	0.5 μV/kPa per V DC	Subgrade Aggregate Asphalt	0.95 0.98 0.97	±10 kPa ±30 kPa ±30 kPa
Strain coils	Typically 1 percent strain = 2V	Subgrade Aggregate Asphalt	1.0 1.0 1.0	±50 $\mu\epsilon$ ±100 $\mu\epsilon$ ±50 $\mu\epsilon$
Strain gauges	0.43 mV/1000 $\mu\epsilon$	Fabric	Direct calibration	±20 $\mu\epsilon$

angled slot that leads to the bottom of this hole was excavated for cable entries. The base of the hole was flattened and a strain coil was gently pressed into this base being positioned by a plumb bob. A circular spirit level was laid on the coil to ensure horizontal placement. Soil from the tube was then tamped in layers over the coil to give 50-mm cover and then the next coil was installed. The sides of the holes and layer interfaces were scarified and an attempt was made to achieve the same backfill compaction, by touch, as the surrounding soil. A third coil was installed level with the subgrade surface and two further coils were placed longitudinally and laterally to provide a coplanar measurement of horizontal strain at the interface. Subgrade material was pressed around the perimeters to lock them into the soil. An alternative to the coplanar arrangement was provided for measuring horizontal strain by placing the coils vertically, in coaxial and parallel alignment (i.e., with the strain coils on edge in slots) (Figure 10).

The strain coils were placed in the granular layer as each lift was completed. It was necessary to set the coils on a bed of fines below the surface of the lift and then add further fines and some larger aggregate as protection from the effects of compaction of the next layer. The final set of coils on the surface of the granular layer was covered with selected fine mix from the hot asphalt just after delivery.

The thickness of the bituminous layer, for the three-layer pavements, was approximately 50 mm, and it was only necessary to glue the top coil of the stack into a recess cut into the surface after the mix had cooled. Grooves for the cables were chiseled out and a fine hot asphalt mix was run in to cover the cables and exposed coils.

Protection of Cables

It is very important to protect instrument cables. They were usually separate or in small groups set in trenches leading to a larger trench away from the test area. Trenches are more difficult to cut in the granular layer and exposed cables can be covered with a mound of fines prior to placement of subsequent material. Braided copper-sheathed cables are normally connected to the instruments and these are inherently robust. Poly-tera-fluoro-ethylene (PTFE)-coated cables are recommended for applications in high temperature. Polyvinylchloride (PVC)-coated cables will melt in hot asphalt but they have been known to survive if protected by a covering of a sandsheet mix that is given time to cool before the next layer is placed.

INSTRUMENT PERFORMANCE

Table 1 summarizes performance data on all the instruments in the pavement test facility. The estimated accuracies were based on work with 11 pavement installations in which the consistency of the readings was examined. Permanent strain accumulated by the strain coils was checked from measurements during pavement excavations (14).

The potential accuracy of these instruments is much greater than the figures indicate in Table 1. The figures in Table 1 take account of the typical scatter obtained from in situ readings obtained in the pavement test facility (1), where stress levels were somewhat higher than may be expected in a full-scale road.

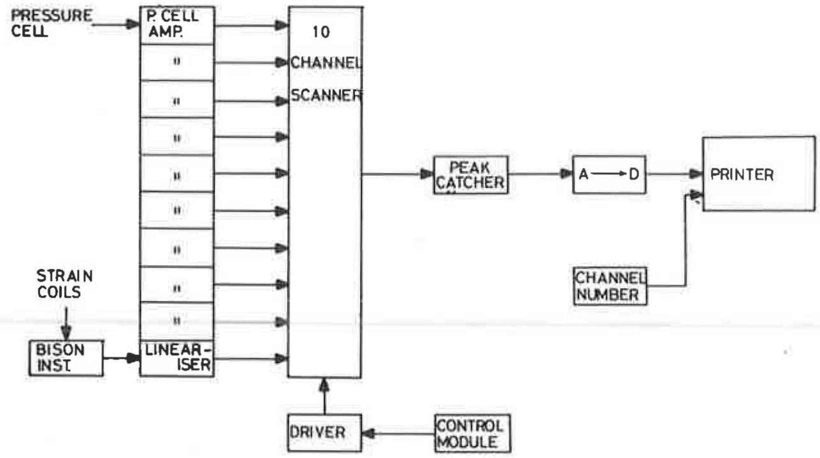
DATA ACQUISITION

To obtain the maximum benefit from pavement instrument installations, a considerable amount of data will be generated. This needs to be converted to stresses, strains, and deformations in a convenient way. The system developed at Nottingham produces results on a printer in appropriate units. Improvements that involve microprocessors or minicomputers could be added later.

Originally, the strain-gauged pressure cells had a DC supply and, because of current limitations, low outputs were obtained. The type of amplifiers that were introduced not only increased these outputs but gave considerable flexibility in terms of the required size of output signal. They were connected to the ultraviolet (UV) recorders by means of galvanometer matching units. The sensitivities of all the pressure cells were then adjusted to an identical level during calibration so that the recorded pulses could be conveniently, quickly, and easily converted to stresses.

Users of the Bison-strain-coil equipment will be familiar with the nonlinear relation between strain and amplitude dial reading. Although this characteristic does not present problems when reading permanent strains, it is a major difficulty for measuring transient values, as the sensitivity varies with the amplitude dial reading. A linearizer unit was developed to overcome this difficulty by providing a constant sensitivity of 1 V for 1 percent strain,

Figure 11. Schematic of data-acquisition system.



although this could be increased to 1 V for 0.1 percent strain if required. Full details of this device are presented elsewhere (12).

This initial processing of signals from pressure cells and strain coils forms the first stage of the data-acquisition systems shown in Figure 11.

The scanner moves automatically or manually from one instrument circuit to the next. In the automatic mode, a pulse from the wheel loading control equipment (1) moves it on so that readings are taken for consecutive wheel passes. Thus, for one pass of the wheel, the output of one transducer will be amplified, caught on a peak catcher, the peak voltage will be converted to a digital signal, and then printed as a stress or strain. It is for this last operation that scale factor controls are necessary to produce a convenient reading such as 600 mV for 600 kPa. Calibration can be carried out through the system and adjustments made to compensate for installation effects. In the tests that we have performed, transient stresses and strains reached reasonably uniform values after about the first 5000 wheel passes and so did not change significantly over the 10 or 20 passes required during scanning by the instrumentation.

CONCLUSIONS

Pressure cells for transient stress measurements in pavements can be used in cohesive soils, crushed rock, and asphalt when suitable techniques are adopted. Pressure cell diaphragms should be protected from the action of large aggregate particles. In crushed rock, this may be done by prepacking the instrument with fine material held in position by a thin plastic film. In asphalt, a fine mix may be compacted over the diaphragm.

The Nottingham pressure cell had a registration close to unity at low confining stresses (48 kPa) but underregistered under greater confinement. The response of the pressure cell placed in asphalt was very similar to that predicted theoretically by Tory and Sparrow (11).

Post-yield electrical resistance strain gauges may be used on fabrics to determine in situ strains. This arrangement was shown to operate successfully up to 1 percent strain and should be capable of measuring higher values up to 10 percent.

Techniques have been developed for the installation of pressure cells, strain coils, and strain gauges in various layers of test pavements by using special tools that cause a minimum of disturbance to the material. Measurement accuracies have been estimated for the various instruments. These depend on the material in which the instrument is to be placed. An electronic unit has been developed to linearize the output from Bison strain coils, thus data acquisition is made easier. A peak hold, scanning, and printing facility has been used to determine transient stresses and strains in pavement experiments.

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