A REPETITIVE TRIAXIAL LOADING APPARATUS FOR LARGE DIAMETER SPECIMENS OF GRANULAR MATERIALS

By

Wayne A. Dunlap
Assistant Research Engineer

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Distribution of Stress in Layered Systems
Composed of Granular Materials
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ACKNOWLEDGMENTS

The repetitive testing apparatus described in this report was developed in 1960-61 during the conduct of Research Project 23, "A Study of Factors Influencing the Performance of Flexible Bases," sponsored by the Texas Highway Department. The objectives of this project were later incorporated into Research Project 2-8-62-27, "Distribution of Stress in Layered Systems Composed of Granular Materials," sponsored by the Texas Highway Department in cooperation with the Department of Commerce, Bureau of Public Roads. During the latter project, additional equipment was added to the apparatus to increase its capability, and this report was prepared.

The design of the apparatus was accomplished by Mr. Lyle A. Wolfskill, formerly Research Assistant, and Mr. Wayne A. Dunlap, Assistant Research Engineer. Mr. Frank Smith, President, and Mr. Carl Poling, Engineer, of Hydraquip, Inc., Houston, Texas, contributed many valuable suggestions concerning the design and equipment of the hydraulic portion of the apparatus. Mr. Lionel Milberger, Laboratory Assistant, fabricated the repetitive testing apparatus.

Mr. Conrad Derdeyn, Senior Engineering Assistant, and later Mr. W. R. Hudson, Supervising Designing Research Engineer, D-8, Texas Highway Department, were the project contact members.

Engineers and graduate research assistants who were actually concerned with the report phases of the project were Messrs. F. H. Scrivner, L. E. Stark, W. A. Dunlap, A. M. Koehler, R. E. Bigham and J. W. Burke.

SYNOPSIS

In recent years the need to study the performance of roadway materials under repeated loading has been recognized. However, the laboratory studies of granular materials used for base and subbase courses have been neglected largely due to the lack of equipment capable of simulating the traffic-induced stresses. Therefore the initial phase of research studies on these materials was the design of necessary equipment. The results of this design effort are the subject of this report.

The apparatus consists of a number of related systems. The primary element is a hydraulically operated loading system capable of applying repetitive loads up to 14,000 pounds to large diameter triaxial compression specimens. Related controls permit setting of the magnitude of the load, duration of load application and interval between load applications. Test conditions are maintained constant with a minimum of operator attention. Instrumentation is included to measure the applied load and the deformation of the specimen.

Design criteria and operating procedures are reported.

INTRODUCTION

Design procedures for flexible pavements are severely hampered by the lack of knowledge of the physical behavior of roadway materials under repeated loadings. Recent repetitive triaxial research on clayey soils has done much to expand knowledge of their behavior, but the physical behavior of granular materials under repeated loading has been largely ignored. While the desirability of testing triaxial compression specimens of granular roadway materials under repeated loading conditions may be evident, the development of necessary equipment for this task is rather formidable. The objective of this publication is to report on the design and performance of equipment for this purpose.

The following requirements were established for a triaxial repetitive loading apparatus: (1) it should be able to apply loads rapidly and without impact on large diameter triaxial specimens; (2) it should have suitable controls to regulate the magnitude of load and the duration and frequency of load application; and (3) it should be able to operate continuously for long periods of time with a minimum of operator attention. Repetitive loading machines meeting some of these requirements have been reported (Havers and Yoder 1957; Seed and Fead 1959), but they were developed for testing small diameter specimens and the designs were not suitable for this research.

DESIGN AND CONSTRUCTION OF APPARATUS

1. Design Considerations

The primary design consideration of the repetitive loading apparatus was the size of the specimen to be tested. A diameter of 6 inches was considered especially desirable as it is used in the Texas triaxial test and because equipment for molding this diameter is generally available throughout the State. According to recent research by the Bureau of Reclamation (Holtz and Gibbs 1956), 6-inch diameter specimens are suitable for materials having a maximum particle size up to 1-1/2 inches. Since the Texas Highway Department (1962) specifies a maximum particle size of 1-3/4 inches for granular base course materials (excluding iron ore gravel and sand shell) this would allow most materials to be tested without eliminating larger particle sizes. Based on generally accepted criteria for compression specimens (Lambe 1951 p. 104) the minimum length of the specimen was set at 12 inches.

To determine the magnitude of load that the apparatus must apply, the results of several Texas triaxial tests on base course materials were examined. This survey indicated that an average failure stress of 250 psi could be expected for good base course materials subjected to a confining pressure of 20 psi. However, under rapid loading rates, the failure stresses could approximately double in magnitude (Whitman 1957). Therefore, the apparatus was designed to apply a vertical stress of approximately 500 psi or 14,000 pounds of force on a 6-inch diameter specimen.

The rate at which the apparatus should be able to apply a single load repetition was another important design consideration, but one which was difficult to assess due to the lack of information on this subject. At a depth of 27-inches at the Stockton Test Track (Corps of Engineers 1948), significant stresses were measured approximately 5 feet on either side of the centerline of the wheel or a total stressed length of about 10 feet. It might be expected that stress attenuation would reduce the total stressed length to approximately 5 feet in the near surface base course materials. This means that the material would be stressed approximately 0.06 seconds for a single wheel moving 60 miles per hour. On this basis the minimum period of load application for the repetitive loading apparatus was set at 0.05 seconds. The longest frequency of load application was set at several minutes.

It was also deemed desirable to construct several similar loading units so several specimens could be tested simultaneously.

2. Vertical Loading System

The design requirements cited above were presented to several manufacturers of scientific testing equipment and industrial equipment, and they were invited to bid on the design and construction of the repetitive loading apparatus. Most of these firms declined and the two bids received were well in excess of the funds allotted for the construction of apparatus. Thus the decision was made to design and construct the equipment locally.

In the preliminary design stages, pneumatic, hydraulic, and pneumatic-hydraulic combinations were considered for the loading system. Estimates of equipment costs indicated that only hydraulic systems were economically feasible for large diameter specimens. While discussing the equipment with various hydraulic equipment suppliers, the firm of Hydraquip, Inc., of Houston, Texas, offered to assist in the design. The apparatus, as finally constructed, incorporated most of the design features recommended by them and also utilized the equipment they suggested.

The unit (shown in Figures 1 and 2) is basically a hydraulic testing machine capable of applying repetitive loads to four specimens simultaneously through interchangeable hydraulic cylinders. A Racine-Seco Model Q pump power unit supplies the hydraulic fluid. With a one-horsepower electric motor, the pump supplies 1.5 gpm at a pressure of 800 psi; a maximum flow of 5.0 gpm can be obtained if more powerful motors are used. The Model Q pump is a variable volume type; the built-in volume control adjusts the pump displacement for exact circuit requirements.

A 5-gallon accumulator is installed in the circuit to supply the high rate of flow (about 10-30gpm) needed by the hydraulic cylinders during their short loading period. A check valve installed between the accumulator and the pump prevents the accumulator from dumping its fluid back into the pump when the pump motor is stopped. In addition, a pressure cutoff switch is mounted in the pressure line to disconnect the pump motor if the line pressure falls below 600 psi. This is a safety feature which prevents damage to the pump if there should be a leak in the hydraulic lines during an unattended period.

The fluid passes from the accumulator through a manifold and thence to each separate testing station. Each of the four testing stations has a shutoff (globe) valve followed by an adjustable pressure regulator to control the line pressure desired for each individual cylinder. The globe valves also regulate to a degree the volume of fluid going to each cylinder. The pressure regulators are standard hydraulic regulators, and although they have been generally satisfactory, they require frequent adjustments during the

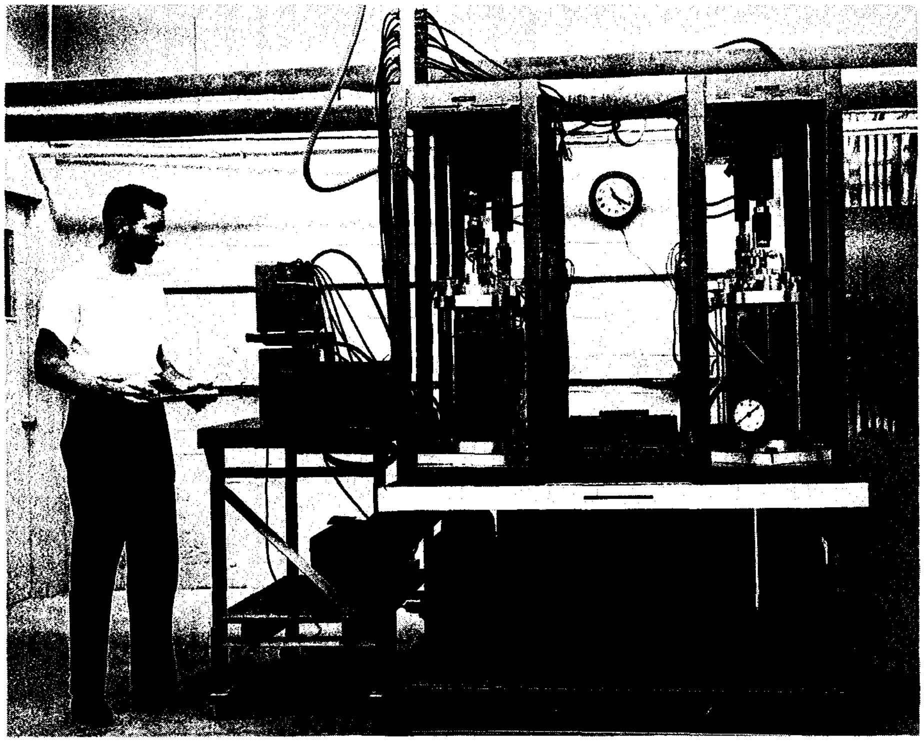

Figure 1. Front view of repetitive loading apparatus.

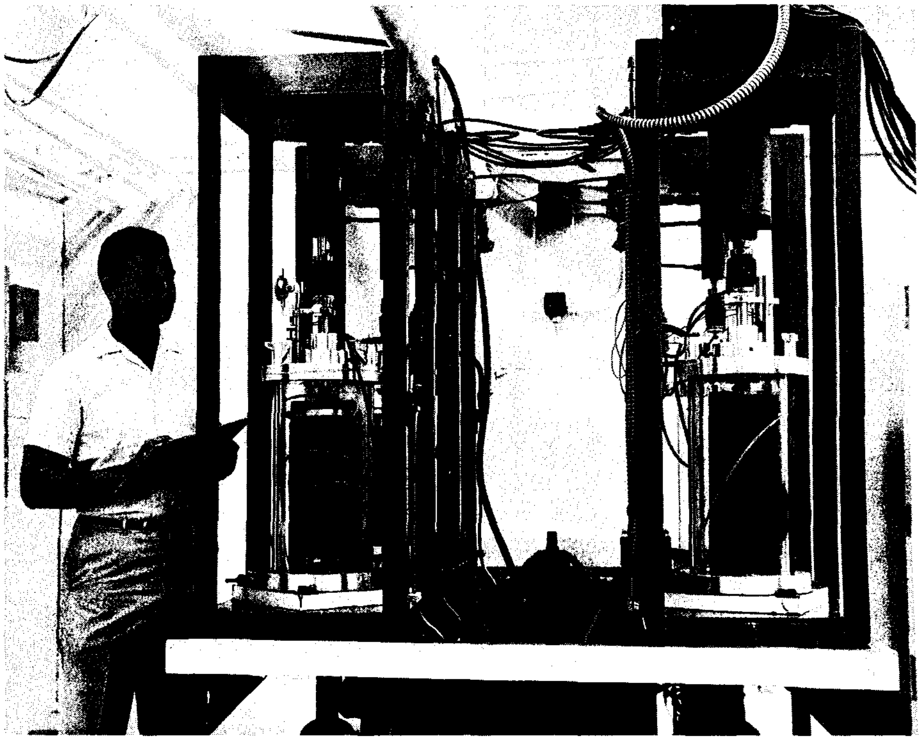

Figure 2. End view of repetitive loading apparatus.

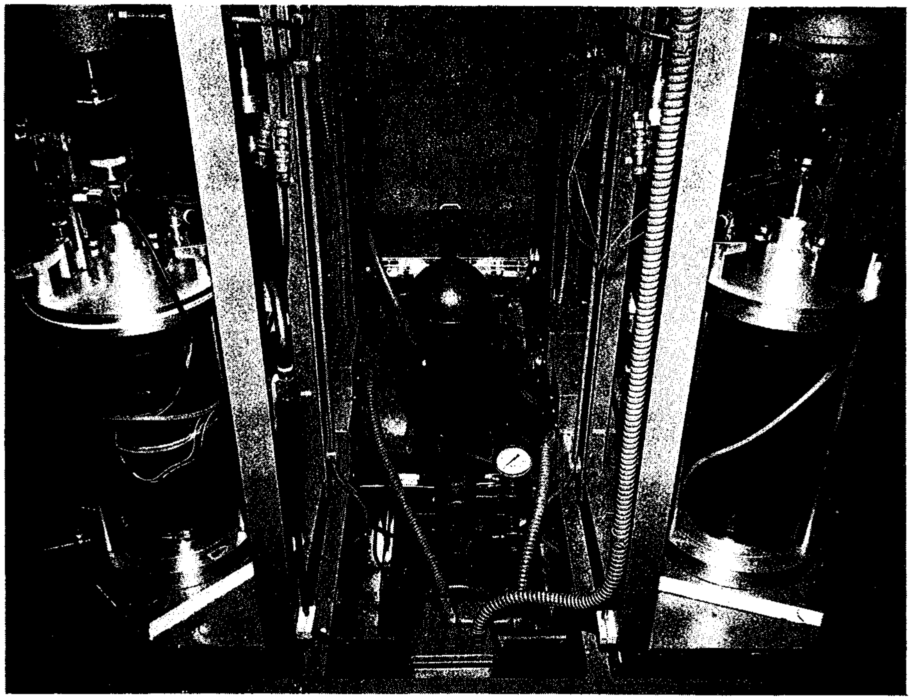

Figure 3. Elevated close-up end view of repetitive loading apparatus. Accumulator shown in center background and pump power unit in center foreground.

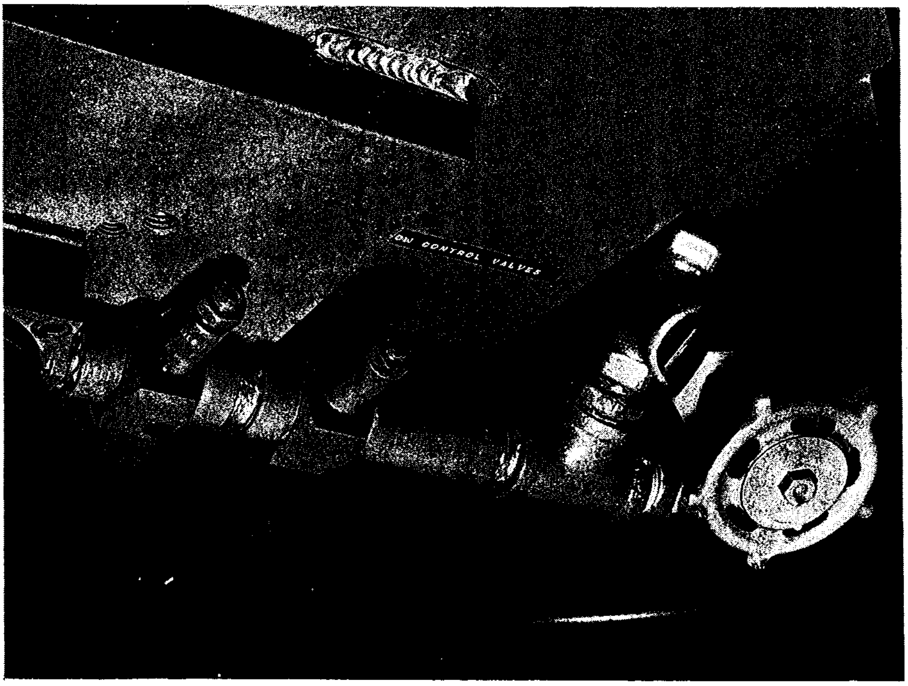

Figure 4. Needle valves for controlling rate of flow to hydraulic loading cylinders.

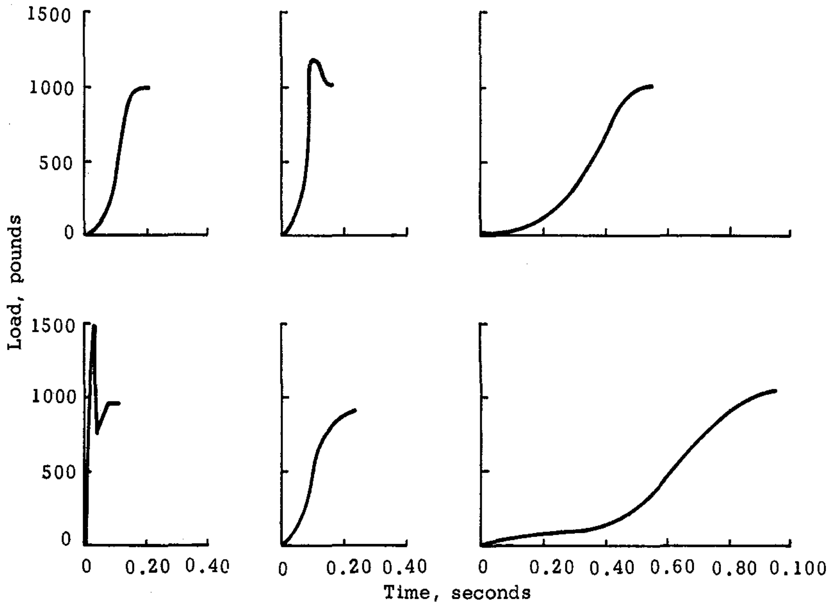

Figure 5. Typical loading patterns.

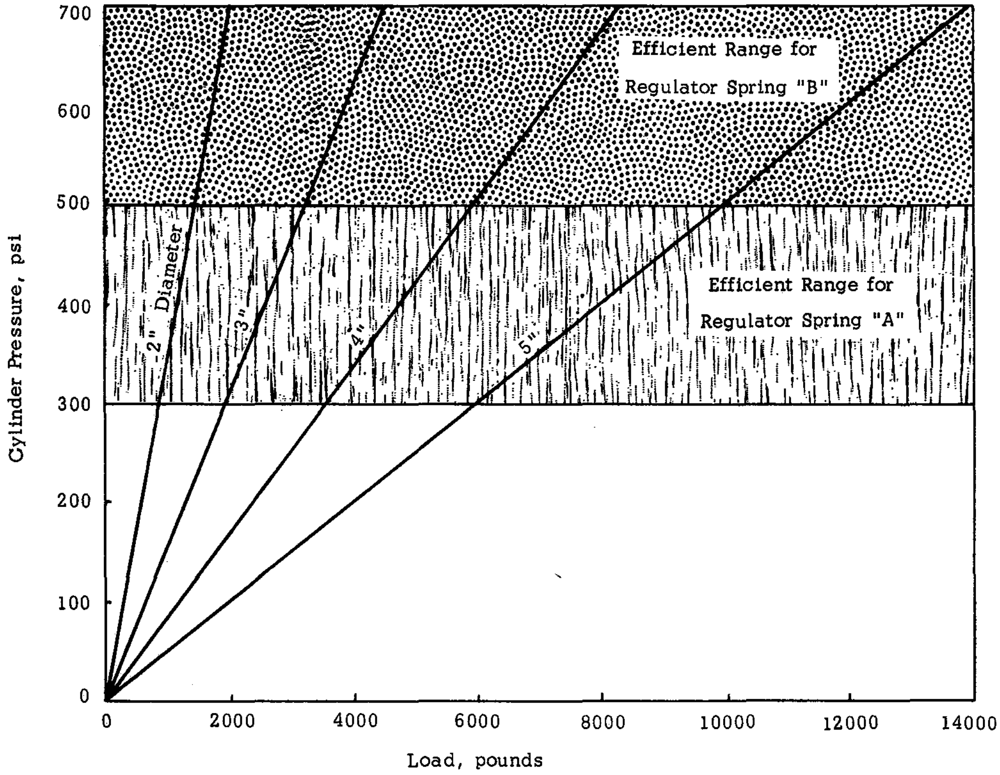

Figure 6. Efficient loading range for hydraulic loading pistons.

initial stages of loading a specimen. Even after the initial adjustments are completed, load variations of ± 25 pounds are often noted. This problem has been minimized by the use of special springs supplied by the manufacturer for use in the lower pressure ranges. More sensitive pilot-operated pressure regulators are available, but the cost of such regulators is approximately five times that of the ones presently being used.

Flow to and from the hydraulic cylinders is controlled by four-way solenoid valves actuated by automatic electric timers. The solenoid valves have two coils to afford quick and positive operation. When the timer energizes one coil, the valve allows the pressurized fluid to enter the hydraulic cylinder; when the other coil is energized, the valve allows the cylinder to exhaust. The fourth port on the solenoid valve is plugged but is available if double-acting cylinders are ever needed. The solenoid valves have proven to be entirely satisfactory and relatively maintenance-free under several million cycles of applications. However, the coils can be damaged if hydraulic fluid leaks into the coil housing; this may be eliminated by drilling a small drain hole in the bottom of the coil housing.

Initially it was planned to use the globe valve preceding the regulator to control the shape of the loading curve. This proved to be impracticable, because impact loads could not be eliminated. To accomplish the desired regulation two needle valves were placed in the pressure line immediately preceding the hydraulic cylinders (Figure 4). One of these has an integral check valve so that it only controls the fluid flowing to the cylinder. The other controls flow in both directions, but it is opened so much wider than the one-way valve that it actually controls only the exhaust flow. Through a combination of settings on the globe valve and the one-way needle valve, the "load" side of the curve can be controlled to obtain almost any pattern desired (see Figure 5). Control of the "unload" side of the curve is more difficult regardless of the flow control device used. Apparently this difficulty arises from the fact that release of the pressure allows decompression of the fluid without significant flow for the valves to control.

The hydraulic cylinders used are Tomkins-Johnson low pressure type suitable for use with air or hydraulic supplies to pressures not exceeding 750 psi. This type was selected over high pressure cylinders due to the smaller amount of friction in the packing glands. In the original design of the apparatus double-acting cylinders were selected because it was difficult to anticipate the rebound behavior of the deformed specimen against the piston friction. (This was also the reason for using a four-way solenoid valve.) Subsequent operation has shown that the specimens are able to completely rebound against the slight friction in the cylinders, and consequently, they have been used entirely as single-acting devices.

The availability of several sizes of interchangeable hydraulic cylinders makes it possible to apply a wide range of loads without significantly altering the hydraulic pressures. Two-inch cylinders are suitable for loads up to 2000 pounds, three-inch cylinders up to 4000 pounds, four-inch cylinders up to 8000 pounds, and five-inch cylinders for loads up to 14,000 pounds (Figure 6).

All pressure lines in the apparatus are Bundy seamless tubing connected with Parker Ferulok fittings. From the pump unit to the globe valves 5/8-inch tubing is used; the remainder is 3/8-inch diameter tubing. Drain lines are connected to all valves, regulators and cylinders. These lines are 3/8-inch diameter dead soft copper refrigeration tubing connected with Parker Intrulok fittings.

3. Electrical Circuit

The most important aspect of the electrical system is the Model MC-1 Industrial Timer Corporation timer which is used to control the solenoid valves. Each timer is basically a series of micro-switches actuated by synchronous motor driven cams. Synchronous motors with varying speeds plus a wide range of low-cost reduction gears are available so that widely varying cam speeds can be obtained. The cams can also be adjusted to vary the off-on time of the micro-switches.

The contacts on each micro-switch are connected to opposite coils on the solenoid valves. In this manner, the micro-switch first energizes the "load" coil in the solenoid and then the "exhaust" coil. In most of the repetitive loading research to date, synchronous motor and gear combinations have been selected to turn the timing cam 30 rpm. The cam has been adjusted so that it has an off-on ratio of approximately 90-10 which allows the load coil in the solenoid valve to be energized for 10 percent of two seconds (0.2 seconds) and the exhaust coil to be energized for the remainder of the cycle or 1.8 seconds. The exact off-on ratio of the cam for any desired loading pattern must be found experimentally. It should be noted that each timer contains an extra micro-switch which is available to control a solenoid in the lateral pressure line, if repeated lateral pressures are desired.

Switches for energizing the synchronous motors and micro-switches are included in the circuit. The electrical connection between the micro-switch and the load coil on the solenoid valve contains a safety switch which is mounted on the triaxial cell in such a manner that the solenoid load coil is disconnected when the deformation of the specimen reaches a predetermined

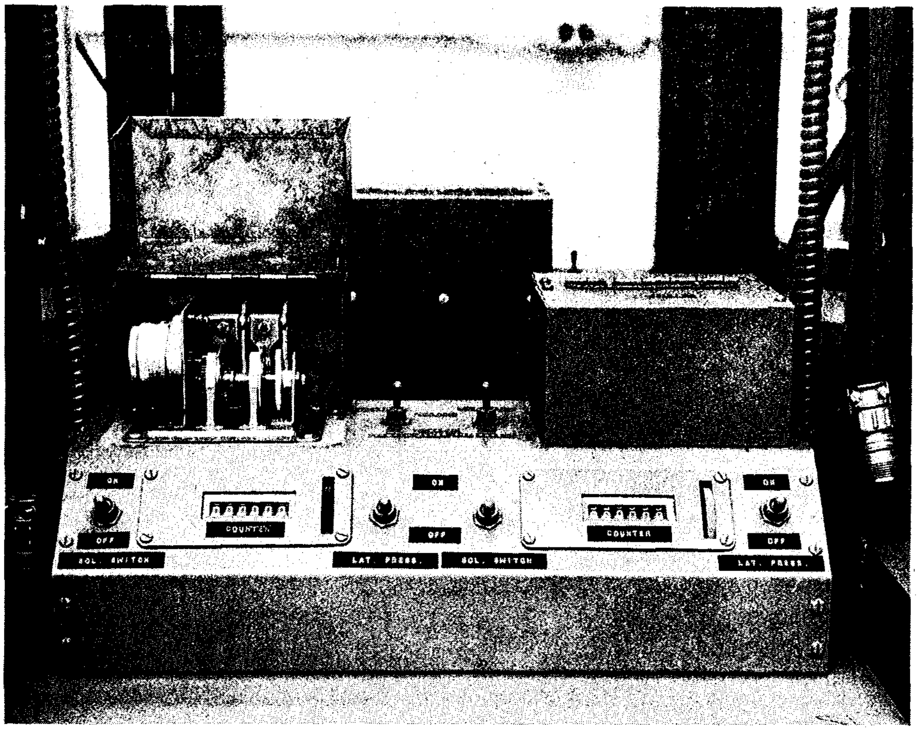

Figure 7. Housing for timers, counters, and control switches.

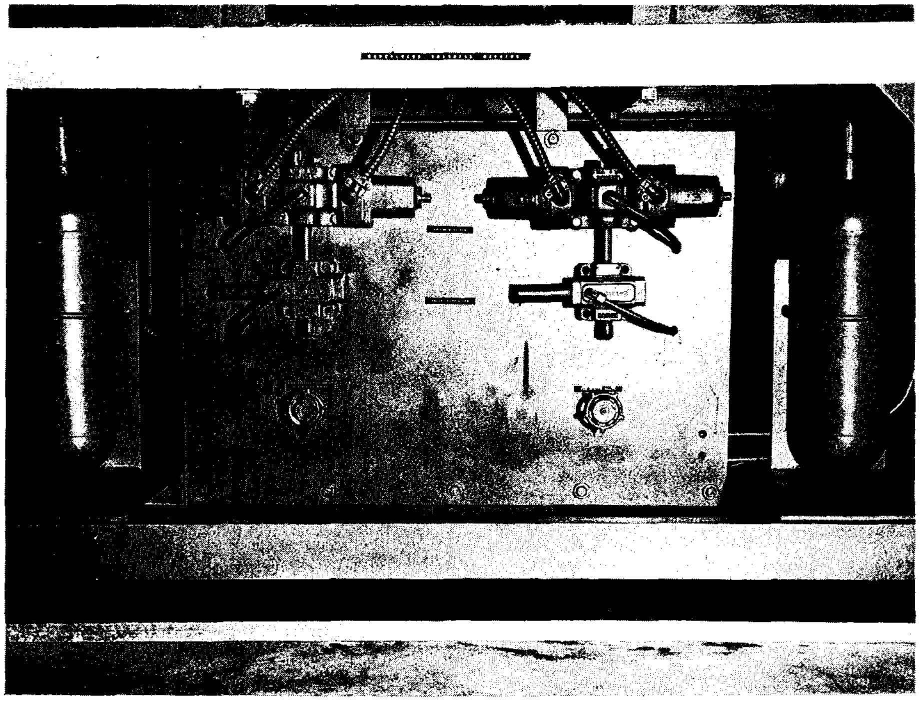

Figure 8. Front view of accessory base unit. Note lateral pressure accumulators on either side of valve board.

value. This feature prevents damage to the equipment which might occur should the specimen deform excessively while the operator is absent. This line also contains a 6-digit resettable counter which automatically records the number of load applications. Figure 7 shows the housing which contains the timers, counter, and switches.

The timers and solenoid valves operate on 115 VAC current. The motor on the pump power unit operates on 230 VAC three-phase current. A push-button switch which starts the pump is interconnected with the safety pressure switch.

4. Structural Frame

The frame for the repetitive loading apparatus is fabricated principally of structural grade angles, plates, and channels; most connections are welded. It consists of two basic units -- the accessory base and four identical loading frames.

The accessory base contains most of the piping and the valve mounting plates (Figure 8) which hold the globe valves, pressure regulators, and solenoid valves. The pump power unit is placed on the floor rather than attached to the accessory base unit. A flexible hose connects the pump to the hydraulic system on the accessory base, thus preventing transmission of pump and motor vibrations to the structural frame.

Fabrication of the loading frame is particularly critical. It must be constructed perfectly square and plumb to eliminate any forces due to eccentric loading. The top and bottom plates on the loading frame contain heavy web reinforcement, but the frame still lacks the desired rigidity when heavily loaded. This has been minimized by installing thick plates at both locations. The top plate, which is 5/8-inch thick, is also drilled and tapped to match the mounting plates of the various cylinders which may be used. The bottom plate is 1-1/2 inches thick and it is connected to the loading frame by four bolts. It has been machined to leave a slightly raised 6-inch diameter boss in the center which fits snugly into a recess on the base of the triaxial compression cell. This facilitates positioning of the triaxial cell directly under the hydraulic cylinder and also prevents movement of the triaxial cell during loading.

5. Lateral Pressure System

The supply system for the lateral pressure to the triaxial cells is not considered unusual for this type of testing operation and is reported herein only as a matter of completeness.

The triaxial specimens are surrounded by water but air is used to apply the pressure. From the air supply a line extends to each of the four testing stations, and each has a separate pressure regulator. A one-gallon accumulator or reservoir is connected to the regulated pressure line. A short section of flexible hose with a rapid disconnect fitting completes the system to the triaxial cell. Provision has been made to include solenoid valves in the air lines, in case repeated lateral pressures are desired.

6. Triaxial Compression Cells

Four triaxial compression cells for 6-inch diameter by 12-inch high specimens were designed and constructed locally. Most of the metal parts in the triaxial cells are made of aluminum to reduce weight. Clear lucite chambers with 0.375-inch wall thickness allow lateral pressures up to 90 psi.

The triaxial cells were initially constructed with 7/8-inch diameter stainless steel loading pistons running in an aluminum bushing. This arrangement was satisfactory for conventional triaxial tests, but after short periods of repetitive loading, the pistons began to bind and in some cases actually froze in the aluminum bushing. To eliminate this problem, two Thomson one-inch diameter linear ball bushings were installed in place of the aluminum bushing. A precision ground one-inch diameter loading piston, also obtained from Thomson Industries, runs through the ball bushings. This piston is case hardened Type 440C stainless steel. A rubber 0-ring is placed in the bushing housing below the ball bushings to prevent loss of lateral pressure around the loading piston. At the top of the housing a Thomson seal is installed to prevent the entry of foreign matter into the bushing.

The ball bushings appear to have eliminated or at least minimized the piston friction. Comparison of the deformation versus repetition curves for identically prepared specimens tested before and after the installation of the ball bushings definitely shows that in the earlier arrangement much of the applied load was lost in piston friction. In the present arrangement, the 0-rings cause some initial or "breakout" friction each time the piston moves, but this is believed to be generally insignificant. If necessary, the breakout friction can be virtually eliminated by the use of a Teflon boot installed over the 0-ring. Known as Kim-rings, these boots are available from the Minnesota

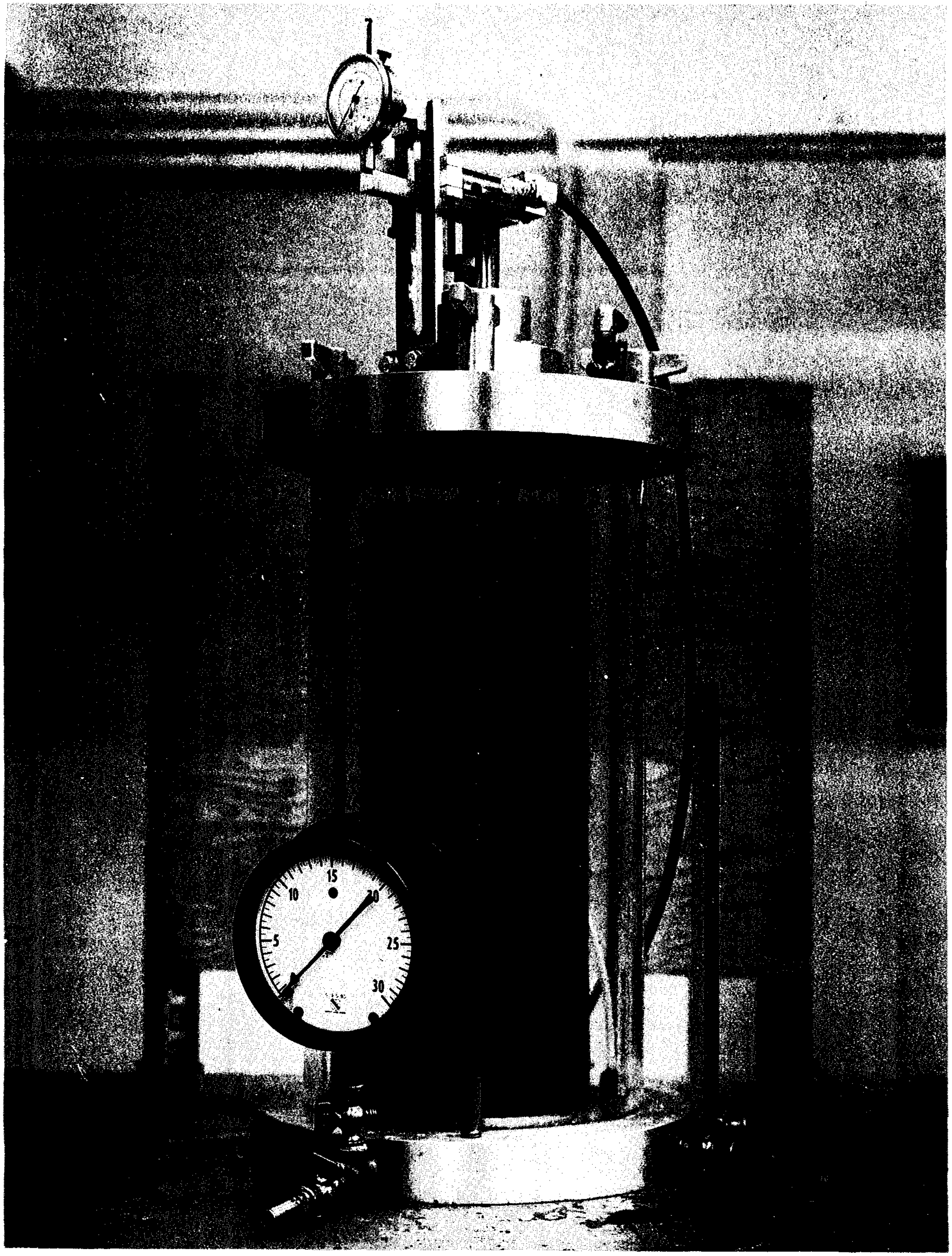

Figure 9. Assembled triaxial cell.

Rubber Company.

Accessories on the triaxial cell include a clamp which is firmly affixed to the piston and a guide for this clamp. A dial gage is attached to the guide and rests on the clamp to measure the deformation of the specimen under repeated loading. For fast loading rates this arrangement is only suitable for obtaining the total specimen deformation; to obtain the shape of the deformation curve, an electronic deformation transducer must be used (see next section). Each triaxial cell also contains a pressure gage for measuring the lateral pressure. Either Imperial-Eastman Poly-Flo or Swagelok tube fittings are used in the triaxial cells. For the valves, simple stopcocks were initially used, but recently it has been found that Circle Seal 9500 series plug shut-off valves are more desirable. These valves are leak-proof and produce no volume change when turned from full off to full on.

Figure 9 illustrates an assembled triaxial cell.

7. Instrumentation

An important part of the repetitive loading apparatus is the related instrumentation. Of particular interest is the measurement of the applied load and the specimen deformation during rapid loading.

Force transducers for obtaining the load characteristics are attached directly to the piston of the hydraulic cylinder and bear on the loading piston of the triaxial cell. They are hollow cylinders machined from Type 6061 T-6 seamless aluminum tubing and instrumented with four temperature compensated strain gages in a full bridge arrangement. The hollow cylindrical cross-section was selected because of its high natural frequency of vibration (Timoshenko 1937). The force transducers designed for this research are suitable for loads up to 8500 pounds; for larger loads thicker wall sections can be used. For loads smaller than about 1500 pounds, the transducer output signal is rather small, but reduction of the present wall thickness may result in undesirable structural stability of the transducer. A possible solution may be the use of a metal which has a more desirable ratio of yield strength to modulus of elasticity than aluminum. Titanium is such a metal, but it is rather difficult to machine due to its work-hardening properties.

The transducers used to measure specimen deformation consist of double cantilever blades with strain gages mounted on both sides of the two blades to form a four-arm bridge. This particular geometry also has a high natural frequency. The blades are made from Berylco 25, quarter-hard beryllium copper, which was heat treated after machining to obtain optimum mechanical properties. The long-term stability of beryllium copper renders it particularly desirable for this application.

Figure 10 illustrates the mounting of the deformation and load transducers in relation to the loading frame and the triaxial cell.

Pressure transducers are also available for measuring either confining pressures on the specimen or the pore pressures within the specimens during repetitive loading. Consolidated Electrodynamics Corporation Type 3-112 pressure transducers with a range of 0-100 psi (abs.) are presently being used.

A 24-channel Model 1508 Honeywell Visicorder oscillograph is used to record transducer output signals. This is an optical oscillograph that utilizes ultraviolet light to develop photographic recording paper. The traces become visible after a few seconds of exposure to ordinary room light. Its design permits the substitution of galvanometers with a wide variety of sensitivities and frequency responses. By designing transducers to fit a particular galvanometer a wide range of sensitivities may be obtained without amplification of the transducer signals.

Transducer bridge voltage is supplied by a Consolidated Electrodynamics Corporation Type 3-132 power supply. Two Model 82-6 Honeywell Bridge Balance units are used to balance and calibrate the transducers.

The complete recording system is shown in Figure 11. Provision is also made to include an oscilloscope in the transducer circuit for instantaneous viewing of the transducer signals. By using a suitable high gain oscilloscope with identical horizontal and vertical amplifiers, such as the Hewlett-Packard Model 130C, and connecting the Y-axis to a force transducer and X-axis to the corresponding deformation transducer, an instantaneous load-deformation curve can be produced on the oscilloscope screen.

8. Design Drawings

Not included in this report are eleven design drawings, a bill of materials, a parts list and addresses of component manufacturers for the repetitive loading apparatus, triaxial cells, and transducers. This information is available to interested parties on request.

Requests should be directed to: Texas Transportation Institute, Pavement Design Department, Texas A&M University, College Station, Texas.

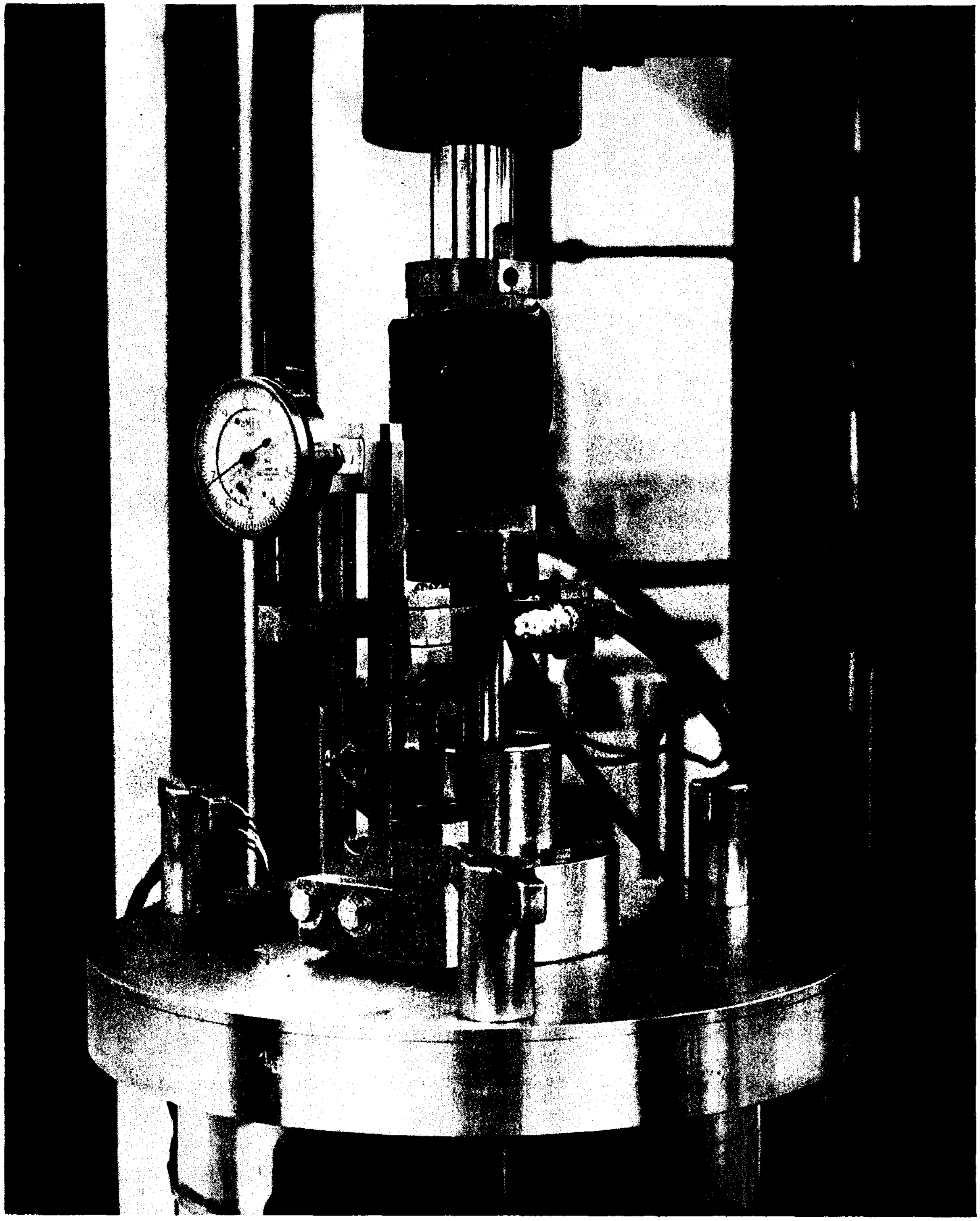

Figure 10. Close-up of head of triaxial cell showing mounting arrangement of dial indicator, force and deformation transducers. Note position of safety switch on piston clamp guide.

TESTING AND OPERATING TECHNIQUES

1. Specimen Preparation

To date all of the investigations with the repetitive loading apparatus have been conducted on laboratory compacted specimens. These specimens are compacted in a 6- by 12-inch mold with a Rainhart automatic compactor. The compacted specimens are extruded from the mold, immediately covered on both ends with 6-inch diameter by 1/2-inch thick porous stones, and then covered with rubber membranes. Initially, two thin (0.012 inch) latex membranes were used, but due to the angular nature of the material being tested, these membranes were often punctured. This proved to be such a problem that research was conducted to find a new type of membrane. The most satisfactory material found so far has been butyl rubber. Carlisle Tire and Rubber Company supplied several 6-inch diameter tubular membranes of 0.03125-inch thick butyl especially for this research. While it is possible to produce seamless membranes on a production basis, these special membranes, which were made from sheet stock, have lapped joints. Great care must be taken to prevent leakage around these joints when mounting the specimen in the triaxial cell. This has been done successfully by first placing a narrow strip of latex membrane over the pedestal and loading cap of the triaxial cell. The butyl membrane is then placed over the latex strip and held in place with two rubber 0-rings. As further protection against leakage, a liberal coating of silicone rubber compound is applied at all joints.

Another advantage of the butyl rubber over the latex membrane is that it is much less permeable to air which might be dissolved in the confining fluid used in the triaxial cell. This is particularly important when performing tests of long duration.

The restraint offered to the specimen by the relatively thick butyl membrane is manifested in increased resistance of the specimen to applied vertical stresses. A correction to the compressive stress due to membrane restraint has been computed using a method suggested by Bishop and Henkel (1957). This method is valid for specimens which deform by symmetrical bulging, which is the general mode of deformation for the granular materials tested in this research. The extension modulus of the butyl membrane, which is necessary in the correction method, was found to average 16.12 lbs./in. for three separate determinations. As shown in Figure 12, the correction to the compression stress amounts to about 0.5 psi for a specimen strain of 5 percent, which is the maximum strain to which the repetitively stressed specimens are carried. This amount is negligible compared to the stresses imposed on these specimens.

2. Repetitive Testing Techniques

Prior to placing the triaxial cell in the repetitive testing apparatus, a "dummy" triaxial cell constructed of metal pipe is placed on the loading frame to be occupied by the cell and the vertical loading mechanism is started. The purpose of this step is to remove air which may have become entrapped in the hydraulic cylinder and to adjust the pressure regulator and needle valves to obtain the desired loading pattern. A thin piece of rubber gasketing is placed between the force transducer and the dummy cell to simulate the deformation of the specimen. Experience has shown that the hydraulic cylinder should be allowed to "pump down" about 15-30 minutes before the actual triaxial cell is placed in the testing station. If this procedure is followed, initial loads applied to the specimen will usually be correct; otherwise, it may take 100-200 load application before the correct load is reached.

After the "pump down" procedure the triaxial cell is quickly placed in the testing station and centered under the hydraulic cylinder. The counter is reset to zero and the repetitive loading is started. Typically, the loading pattern is recorded for the first 25-50 repetitions and if necessary, the pressure regulator is adjusted. After this, occasional checks are made to insure that the correct load is being applied to the specimen.

Long-term deformation of the specimen is measured with the dial gage which is attached to the triaxial cell. In the usual test where the deviator stress is repeated applied and removed, the deformation is obtained at suitable intervals when the specimen is fully loaded and just after the load is removed. If the entire deformation curve for any particular repetition is desired, the deformation transducer is used.

3. Use of Repetitive Test Results

It is not the purpose of this report to present the results of repetitive load tests; however, a typical example of the results obtained is presented in Figure 13. The progressive increase in <u>total</u> deformation and the residual or <u>nonrecoverable</u> deformation is plotted as a function of the number of load repetitions. The difference between the total and nonrecoverable deformation is the <u>recoverable</u> deformation.

The use of repetitive load tests on granular materials, especially base course materials, should be an invaluable aid in design and selection of materials. For example, the recoverable deformations should be related to the elastic deflections in the roadway under transient wheel loads. The

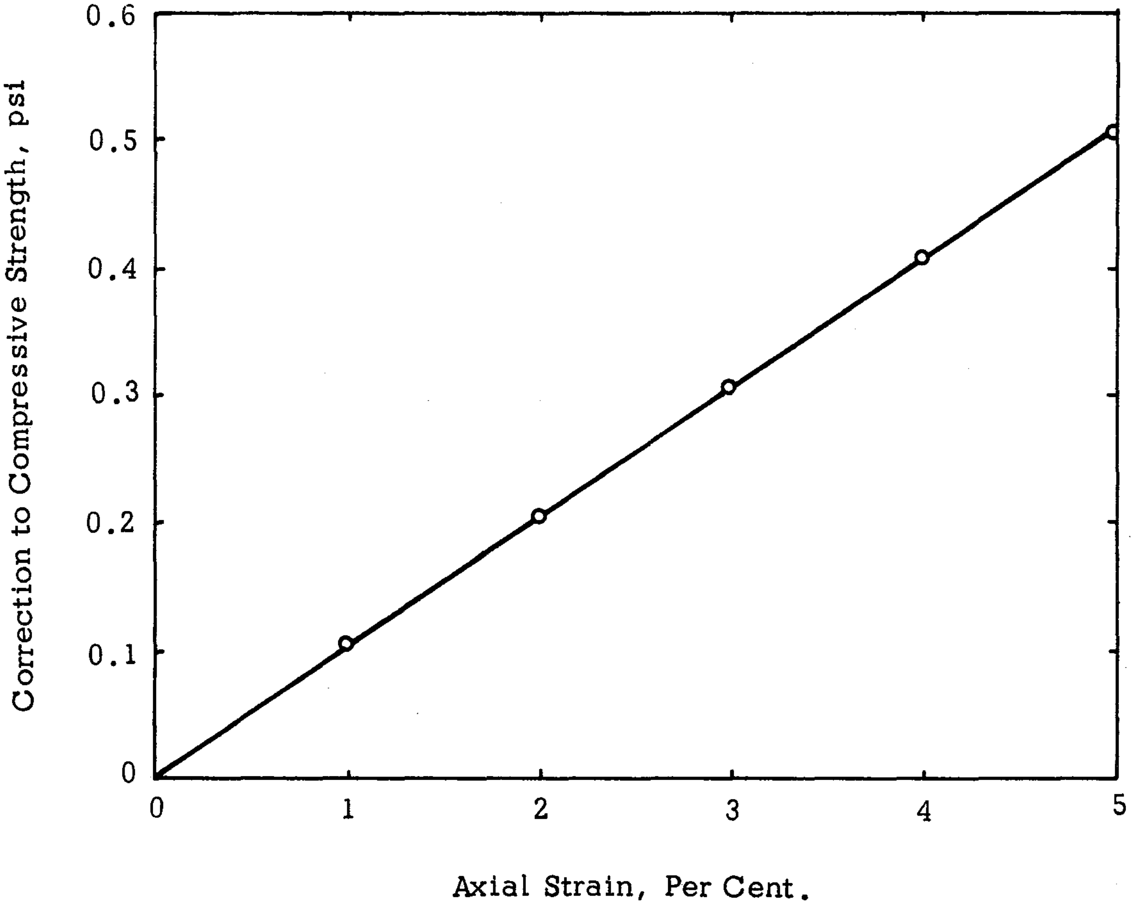

Figure 12. Correction to compression strength for 6-inch diameter butyl membrane. Extension modulus of butyl = 16.12 lbs./in.

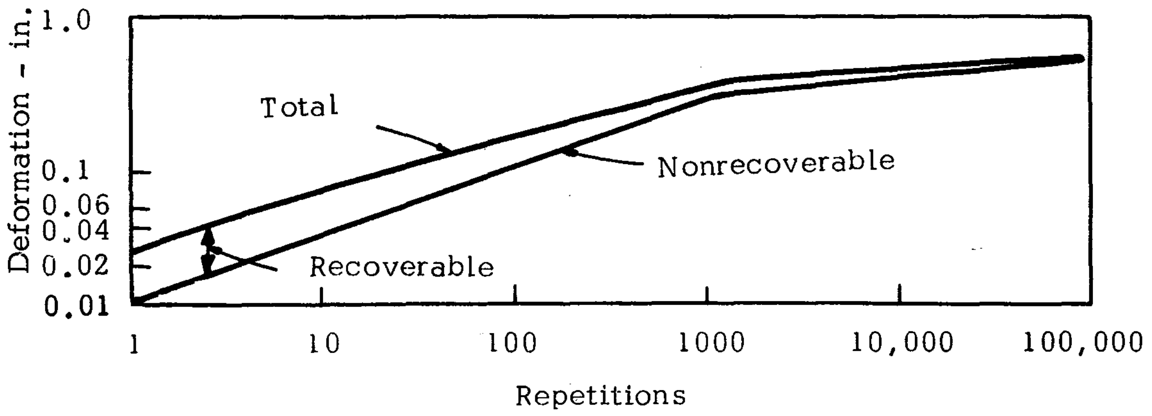

Figure 13. Typical deformation - repetition curve.

nonrecoverable deformations should be related to the permanent ruts formed in roadways. Repetitive triaxial tests may also be an excellent way of distinguishing those materials which appear to be satisfactory under static laboratory triaxial tests but which subsequently degrade in use. This and other information should lead to a fundamental knowledge of the behavior of granular soils in the roadway.

SUMMARY

The repetitive loading apparatus described in this report has been in use approximately 2-1/2 years. During this time, operation has been relatively trouble-free. The one component of the system where redesign seems desirable is the loading frame. The adjustments required to eliminate eccentric loads on the test specimens have proved to be difficult and time consuming. Improved rigidity would result if heavy castings, similar to those employed in commercial testing machines, were used instead of rolled steel sections. An adjustable upper platen head would be particularly advantageous.

The use of more sensitive pressure regulators in the hydraulic system would also be desirable. This is not a technical problem since suitable regulators are already commercially available, but the cost is disproportionate.

The use of the repetitive loading apparatus should provide considerable insight into the stress-deformation characteristics of granular base course and subbase materials. Since the equipment was designed to achieve one specific objective, its use for other purposes may be limited. Those persons contemplating the construction of similar equipment are cautioned to review the design considerations and the limitations of this apparatus before using it as a basis of design.

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