DETERMINING THE RESILIENT MODULUS AND DYNAMIC POISSON'S RATIO OF ASPHALTIC CONCRETE

DETERMINING THE RESILIENT MODULUS AND DYNAMIC POISSON'S RATIO OF ASPHALTIC CONCRETE

by:

STANISLAUS E. MICHAEL GONSALVES, B. ENG.

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

MASTER OF ENGINEERING

McMASTER UNIVERSITY

HAMILTON, ONTARIO

CANADA

1978

MASTER OF ENGINEERING (1978)
(CIVIL ENGINEERING)

McMaster University
HAMILTON, ONTARIO

TITLE: DETERMINING THE RESILIENT MODULUS AND DYNAMIC POISSON'S RATIO OF ASPHALTIC CONCRETE

AUTHOR: STANISLAUS E. MICHAEL GONSALVES, B. ENG.
(McMASTER UNIVERSITY)

SUPERVISOR: DR. JOHN J. EMERY

NUMBER OF PAGES: viii, 82

ABSTRACT

A theoretically sound and practical method of flexible pavement design remains one of the most needed, though widely unappreciated, aspects of transportation engineering. Papers presented at The Third International Conference on the Structural Design of Asphalt Pavements in 1972 greatly increased the awareness of design engineers of the testing problems involved in this field. The generated interest in rational, as opposed to empirical, flexible pavement design approaches brought about a pressing need for material characteristics for use in available theoretical models.

This study involved the development of laboratory equipment capable of providing values of resilient modulus, M_R, and Poisson's ratio, ν, of asphaltic concrete specimens. These properties are required as input for elastic layer analyses of flexible pavement systems. It was recognized that the developed equipment must be capable of providing reliable results at similar costs to conventional Marshall or Hveem tests, and should be adaptable to realistically simulate site conditions. It is considered that the equipment described herein satisfies these conditions.

Test results on polymeric calibration samples compare favourably to those obtained during previous work on the resilient modulus of asphalt mixes. The testing program identified temperature, asphalt content and aggregate type as parameters that affect the resilient modulus. A future phase of this study involves a more comprehensive testing program in these areas, in addition to studying the effects of confining pressure and stress levels on material properties using equipment suggested from this initial testing program.

Comparative design studies using available theoretical methods and generated stiffness parameters indicate possible cost savings as a result of reduced thickness requirements for pavement systems comprised of mixes with higher M_R values. Conventional empirical approaches do not permit similar thickness reductions for higher quality (strength) mixes.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Dr. John Emery for his guidance and encouragement throughout the course of this research.

Special thanks go to Messrs. W. Sheriff and K. Chin for their help in constructing the equipment. The careful preparation of this text by the secretarial staff of The Trow Group Limited is also gratefully acknowledged.

This work was completed in January of 1976 and a draft report of the findings prepared. However, due to personal circumstances, the final version was not submitted until March of 1978. In the iterim, significant further developments in the research area were made at McMaster University by M. A. Lee who expanded the investigation conducted during the initial phase reported here.

TABLE OF CONTENTS

TABLE OF CONTENTS - Cont'd

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The development of a rational flexible pavement structural design approach based on fundamental concepts is necessary to deal with design situations differing from those previously experienced. A combination of theoretical methods of analysis, and accurate knowledge of the mechanical properties of component materials, must replace current empirical methods if efficient designs are to be achieved. New materials with better strength characteristics (performance) or heavier, and more numerous vehicles, could lead to over-design or under-design respectively, in the future, if roads are constructed on the basis of past experience alone. Further, the increasing cost of construction materials requires the most efficient utilization of these resources. This study is concerned with the characterization of asphaltic concrete mixes, an essential step in the rational approach to flexible pavement design.

1.1 PAVEMENT STRUCTURES

A pavement structure is a layered system designed to distribute repeated truck axle loadings to the subgrade without permanent deformations. There are basically two types of pavements, rigid and flexible. A rigid pavement structure usually consists of two layers, a portland cement concrete slab, and a base course. Figure 1.1 illustrates the rigid concept in pavement design. Asphaltic concrete (flexible) pavements consist of an asphaltic concrete surface course and one or more asphaltic concrete base courses.

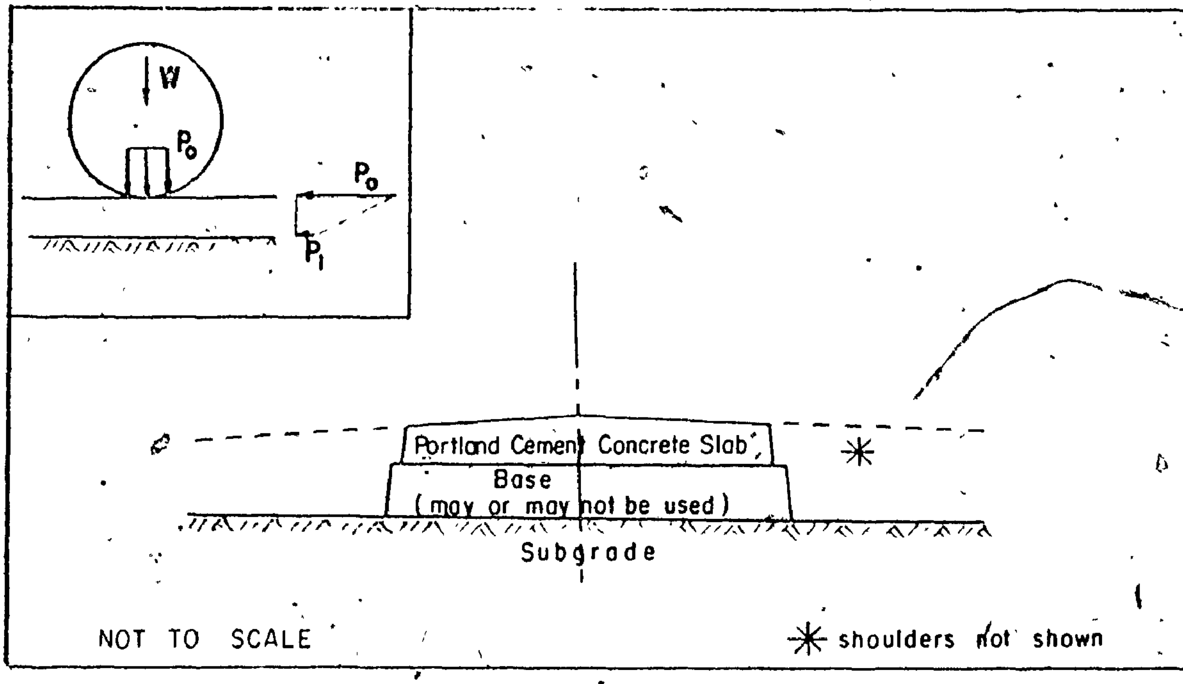


Fig 1.1 - RIGID CONCEPT

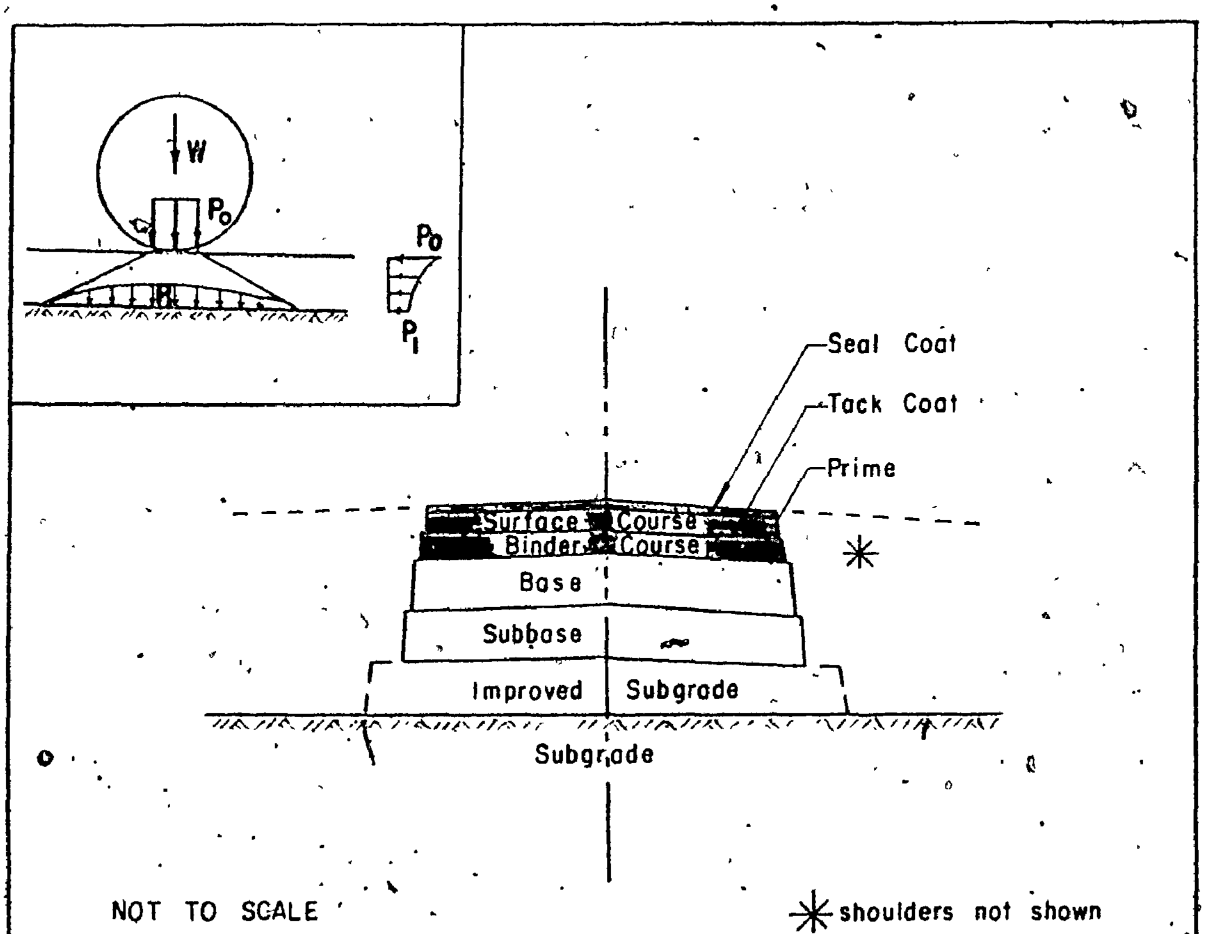


Fig.1.2 - FLEXIBLE CONCEPT

supported by the subgrade. Subbase, or improved subgrade layers, or both, are sometimes included in the structure, as indicated in Figure 1.2. The object of the flexible system is to distribute the applied stresses through layers of decreasing quality with depth. The loading effects are thus reduced to the point where the subgrade will support the load without damage. While not discussed here, research has also indicated the importance of correct shoulder design.

In this study, the stress-strain behaviour of asphaltic concrete mixes is being considered, and hence subsequent discussion will be restricted to flexible pavements. The asphaltic concrete layers of prime interest are shaded in Figure 1.2.

1.2 EXISTING ASPHALTIC CONCRETE PAVEMENT DESIGN METHODS

Developments in pavement design have generally followed two discernible patterns, either the empirical or the theoretical. The empirical methods have sought rationality through statistical treatments designed to fit the measured data to a curve(s), whose equation can then be used as a basis for predicting behaviour under different loading and subgrade conditions. On the other hand, the theoretical methods have sought to validate the resultant design equations through experimental work. Some of these systems and a number of sub-systems are shown in Table 1.1. The method of particular concern in this study is Number 1 (a).

TABLE 1.1

BRIEF REVIEW OF SOME EXISTING METHODS OF PAVEMENT DESIGN[1]

1. <u>Elasticity Methods</u> -Consider the behaviour of pavements under working stress conditions when deflections by definition remain proportional to applied loads. Design criteria consist of limiting stresses or strains to values established by observations to be "safe". Methods in this group include: (a) Shell Oil Company Method (i) The horizontal (radial) tensile strain at the bottom of the lowest asphalt bound layer must be sufficiently small to prevent fatigue cracking in the asphalt layer. (ii) The vertical compressive strain at the surface of the subgrade must be maintained sufficiently small to prevent permanent deformation. (b) Kansas Highway Department Method The surface deflection is the criterion for determining the adequacy of the design. The effect of the relative stiffness of pavement and subgrade materials is accounted for by replacing the pavement with an "equivalent" thickness of subgrade material.
2. <u>Empirical and Environmental Methods</u> -Relate the pavement thickness to some particular soil and environmental conditions. (a) Michigan Method This method is based on experience, with the design criterion being that the pavement section be similar to one which has been successful under similar traffic and subgrade conditions. (b) Canadian Good Roads Association (RTAC) Method Based on observing the performance of many existing pavements. Deflections of the surface must not exceed a value which is a function of the particular area in which the pavement is constructed.

TABLE 1.1 Continued

3. Semi-Empirical and Statistical Methods

– Based on information concerning conditions under which pavements of certain composition and strength have experienced performance failures. They include no theoretical consideration of pavement mechanics yet the thicknesses are determined from properties of materials as determined by some empirical "strength" test.

(a) CBR Method.

Thickness of each overlying layer is empirically related to the strength of the material as indicated by CBR tests. Relationships between thickness required and CBR have been established from practical experience. Extensions and modifications to permit treatment of traffic volume, minimum subgrade strengths, etc. vary greatly between organizations.

(b) State of California Method

Pavement thickness is determined by the requirement that permanent deformation in each layer of the pavement system be prevented. The thickness required to accomplish this is a function of traffic, and tensile and shear strength (stabilometer) characteristics of paving materials.

(c) Other Methods in this Group Include:

The Canadian Department of Transport Method, The AASHO Interim Guides and The Asphalt Institute Full Depth Asphalt Pavement Design Procedures.

1.3 THEORETICAL (RATIONAL) METHOD

An essential step in any rational flexible pavement design approach is the computation of the deformations (strains) and stresses at key points in the pavement structure resulting from any anticipated wheel loadings. (There are a number of methods currently available for estimating equivalent axle loads for variable truck loadings.) These values are then compared to maximum acceptable levels that still give satisfactory performance for similar loadings over the given design life. This is essentially an iterative process with the thicknesses and mix compositions (quality and characteristics of asphaltic concrete mixes) being adjusted until a satisfactory design results. Obviously, there are many combinations that will achieve this and the best solution would be that which is most economic from an initial cost, maintenance and salvage viewpoint.

1.3.1. DISTRESS MECHANISMS

Once the pavement is constructed, the factors that govern its actual performance are closely tied to loadings and environment. Traffic loadings generate pavement distress through fatigue and plastic deformation of materials, and result in cracking and permanent deformation. The environment causes deterioration of pavements mainly through differential settlements of the subgrade resulting in roughness and cracking of the surface. Obviously, while the anticipated loadings have been considered during the design stage, changes, particularly a trend to heavier axle loadings, will be quickly reflected in poor pavement performance. The rational method can be used to study the effects of such changes and allow for remedial measures. It is difficult to incorporate environmental effects (temperature, moisture and water table position) in the rational procedure, except to allow for a range of material behaviour during the analyses.

A failure in the pavement system is simple to define since the user has a keen perception of poor riding quality. However, for pavement design purposes these perceptions must be related to actual distress indicators.

1.3.2. DISTRESS INDICATORS

Experience in various countries has indicated that there are three principal failure indicators: permanent deformations; load induced cracking; and thermal cracking. In Great Britain, permanent deformation seems to be the one of major concern, but the potential also exists for load associated (fatigue) cracking. [2] Fatigue cracking is the most prevalent indicator of distress in the United States. [3] By using results from the AASHO road test and analysing successful Ontario designs, Jung and Phang [4] found that the vertical deflection at the top of the subgrade was the most important indicator of flexible pavement performance for this area.

It is convenient to consider the design computations in two parts: fatigue cracking; and permanent deformation. Design methods to prevent failure due to fatigue cracking have been fairly well established, especially for conditions existing in the United States. The object is to limit the strain at the bottom of the asphaltic concrete layer to a value determined from a fatique curve relating tensile strain to service life. Finn et al [3] have given a comprehensive summary of this "fatigue sub-system".

The determination of permanent deformation is more complex and the procedure less well defined than for fatigue cracking. An interim method for dealing with permanent deformation is to limit the vertical strain at the top of the subgrade.

1.3.3. AVAILABLE THEORETICAL METHODS OF ANALYSIS

Based on the distress indicators discussed previously, the two critical parameters that need to be calculated in the analysis of the flexible pavement structure are the horizontal strain at the bottom of the lowest asphalt bound layer and the vertical strain at the top of the subgrade, as shown in Figure 1.3. The use of elastic layer theory for predicting these values has gained wide acceptance. (For instance, Finn and Hicks [5] have shown that strains measured in the field are reasonably close to those computed by the elastic layer analysis). This is the general concept adopted by the Shell Oil Company, Chevron Oil Company, Peattie, Jones [6,7,8,9] and various other agencies and researchers. The initial step involves

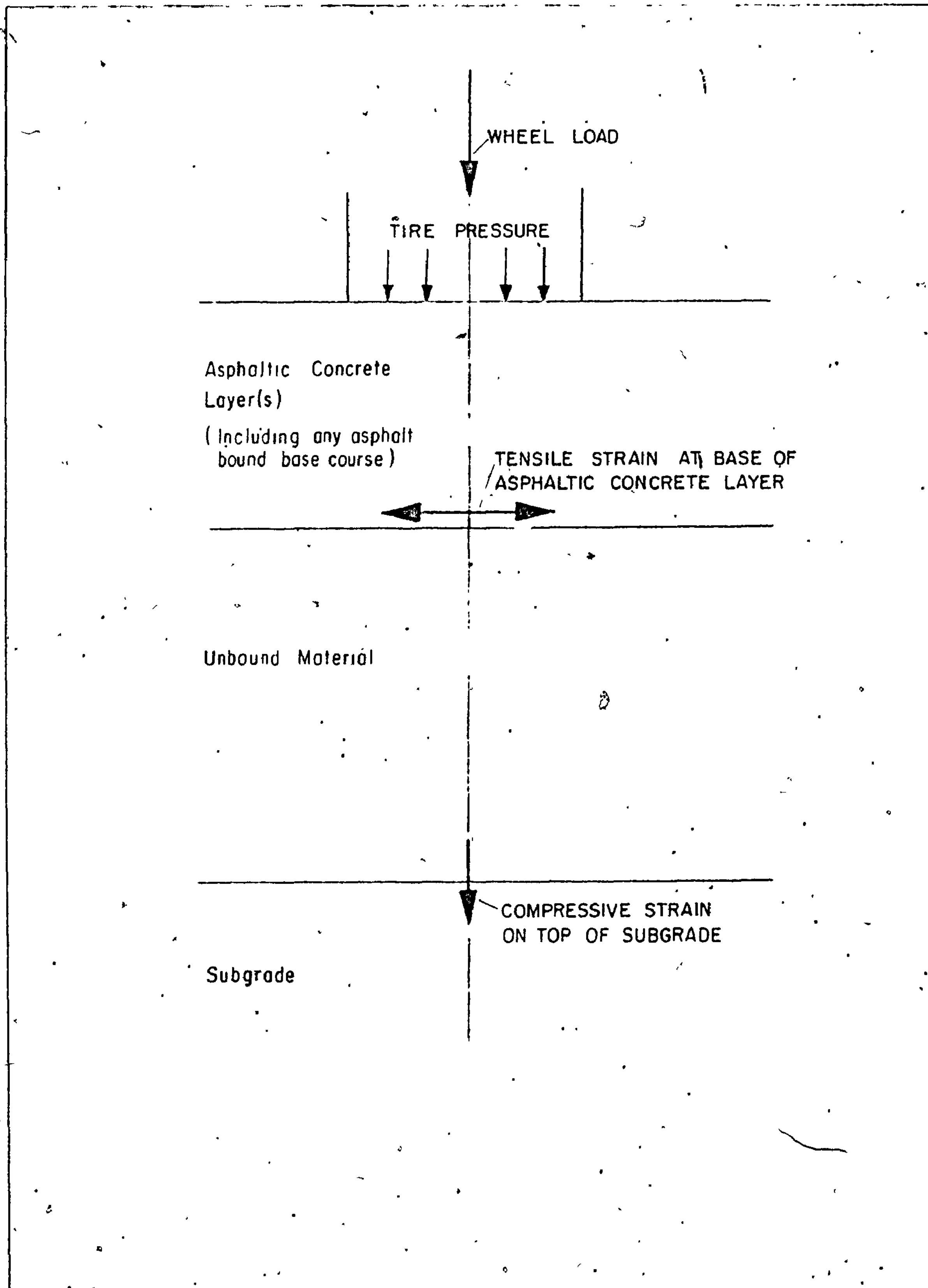


FIG. 1.3 - CRITICAL REGIONS OF STRESS AND STRAIN

representing the real pavement structure and loadings in a simpler form suitable for currently available methods of computer-based analysis. The representation of a typical flexible pavement is given in Figure 1.4. A summary of the available methods for the elastic analysis of flexible pavements, and their requirements and limitations are given in Table 1.2. While the CHEVRON, Shell BISTRO and Shell BISAR computer programs have been obtained and developed for use on the McMaster CDC6400, for reasons given later, only the BISTRO program has been used in this study.

1.3.4. MATERIAL PROPERTIES

It is clear from Table 1.2 that the material properties of the various layers of a pavement structure must be known if a theoretical analysis using any of the elastic methods described earlier is to be undertaken. Some of the currently available methods for highway materials characterization are outlined in following sections. The property of prime concern in this investigation is the resilient modulus of asphaltic concrete mixes.

Resilient Modulus of Asphaltic Concrete Mixes

The stiffness (resilient modulus) of asphaltic concrete mixes has been shown to be dependent on loading time, temperature and void content, as well as volume concentration of aggregate in the mix.[2] A semi-graphical method that has been widely used to predict mix stiffness in the past is the Shell Oil Nomograph[10].

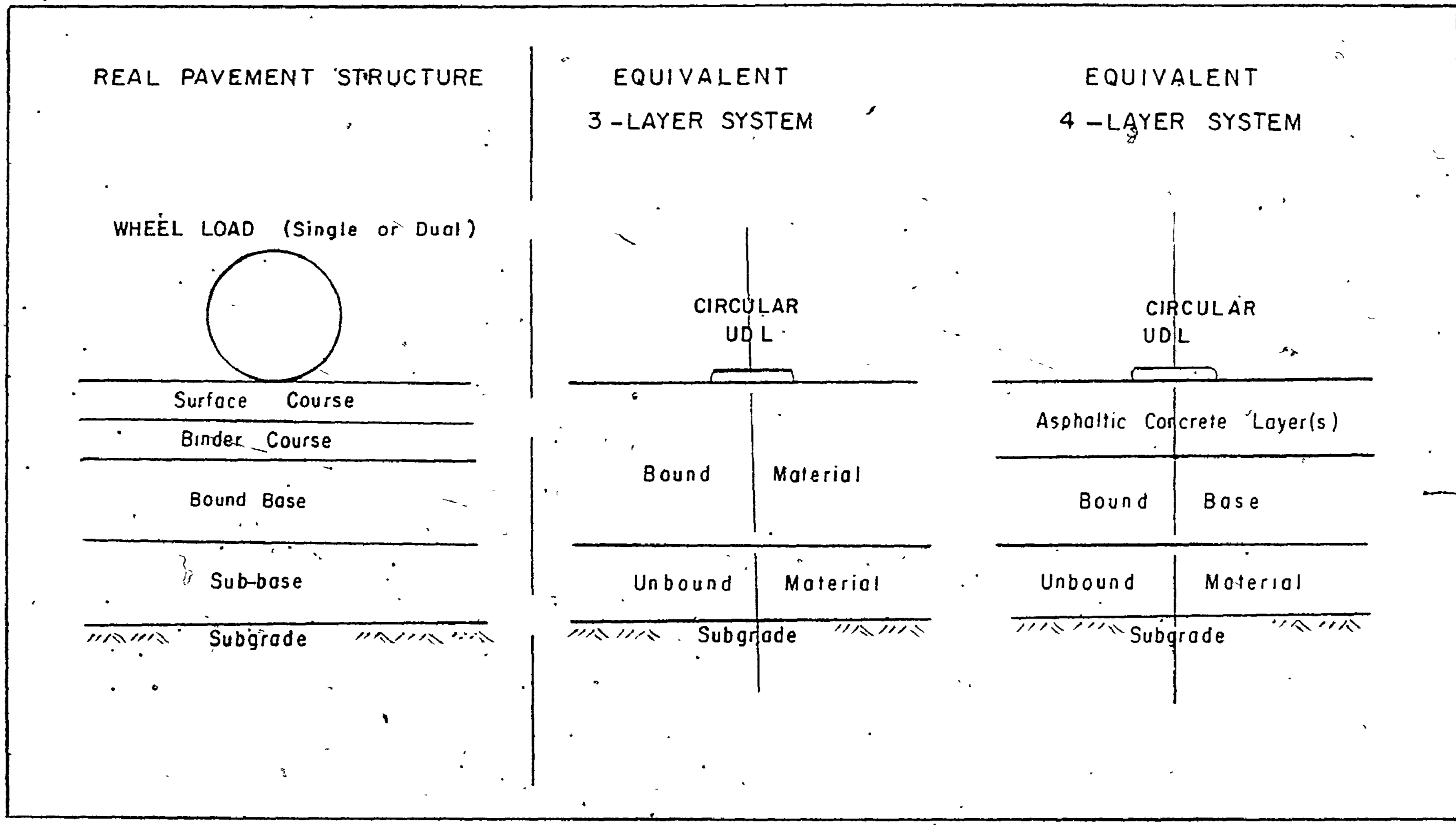


FIG. 1.4 EQUIVALENT LAYERED SYSTEMS TO ACTUAL PAVEMENT STRUCTURE

TABLE 1.2

METHODS FOR STRESS-STRAIN ANALYSIS (2)

OF ASPHALTIC CONCRETE PAVEMENTS

(a) Data required for analysis of flexible pavement structures using linear elastic theory.

LOAD DETAILS	Radius of loaded area Contact pressure or total load
LAYER DETAILS	*Modulus of Elasticity, E *Poisson's Ratio, ν Thickness (not required for subgrade)

(b) Summary of major methods available for flexible pavement analysis.

METHOD	FORMAT	LIMITATIONS
Jones	Tables and Charts	Three layer systems; $\nu = 0.5$
Peattie		Stresses and strains only at interfaces on ℄ of load Interpolation difficult
Peattie and Jones	Tables	Three layer systems; $\nu = 0.35$ Surface deflections only Interpolation difficult
"Interpolation"	Computer Program	Based on Jones' tables
"CHEVRON"	Computer Program	Requires fairly large computer
"BISTRO/BISAR"	Computer Program	Requires fairly large computer

* or similar properties such as M_R and Dynamic ν

This involves the use of a nomograph to first determine the asphalt cement stiffness and then an equation to determine the asphaltic concrete mix stiffness. A correction factor is applied to mixes with high voids content. This procedure reflects the importance of asphalt cement characteristics, but does not adequately handle the total mix properties.

Clearly, the use of laboratory tests on the actual asphaltic concrete mix is the most realistic method for obtaining its stiffness. Anticipated loading and environmental conditions at the site should be reproduced during such tests if the resulting parameters are to be useful in design. Schmidt,[11] while working for Chevron Oil in California, developed a method for determining the resilient modulus of asphalt treated mixes that is now used for a range of asphaltic mixes. The equipment while expensive, is commercially available, but for reasons outlined later was not used in its original form in this study.

Resilient Modulus of the Other Constituent Layers

Though not of direct concern here, the properties of soil and granular materials as well as asphalt treated bases are required for most pavement analyses. Investigations have indicated that dynamic repeated loading triaxial tests can provide the necessary design parameters for soils and unbound materials. An approximate relationship[2] that has been extensively used to determine the dynamic modulus of soils and unbound materials is:

$$M_R = 10 \times CBR\ MN/M^2$$

where: the CBR (California Bearing Ration) is in per cent.

Terrel and Monismith (12) have investigated the resilient and stress-strain properties of asphalt treated base materials. Various other investigations have also focused on this problem.

Poisson's Ratio

Reference to the experimental determination of Poisson's ratio for asphalt mixes in the literature is scant. Although, a range of values for Poisson's ratio between 0.3 and 0.5 may be assumed without introducing large errors in the computed stresses and strains, on a more fundamental level, a knowledge of the mixes Poisson's ratio gives some indication of potential rutting and lateral deformation. A simple system for Poisson's ratio determination is presented in this study.

1.4 PURPOSE AND SCOPE

It would seem that the currently available techniques for rational pavement analysis have progressed further than the ability of conventional test methods to provide the required material properties. Parameters such as resilient modulus, creep modulus, Poisson's ratio, etc., are needed to describe the elastic and visco-elastic properties of asphaltic concrete mixes. Test methods must be simple and sufficiently accurate if a theoretically sound approach integrating a complete stress and strain analysis with appropriate constitutive properties is to replace the present "recipe" solutions in routine control and mix designs.

This thesis presents methods for the rapid and accurate determination of the resilient modulus M_R and Poisson's ratio ν of asphalt mixes. The resilient modulus device developed is an extension of the system suggested by Schmidt. A simple apparatus for obtaining Poisson's ratio has also been developed, but was not used in the current study. The effect of asphalt content, aggregate type and temperature on the resilient modulus of asphaltic concrete mixes was investigated. Comparative studies between thickness designs based on multilayer elastic theory using the BISTRO computer program and stress-strain parameters obtained in this study were made.

CHAPTER 2

THEORETICAL CONSIDERATIONS AND EQUIPMENT DEVELOPMENT

2.1 RESILIENT MODULUS TEST

2.1.1 HISTORY

In 1953, an indirect test for measuring the tensile strength of portland cement concrete was described by Carneiro and Barcellus[13] in Brazil, and independently by Akazawa[14] in Japan. In this test cylinders of portland cement concrete are crushed by applying uniformly distributed loads across a diameter which results in tension along the connecting diametral plane. This test (split-cylinder test) is now widely used to determine the tensile strength of a number of construction materials (ASTM C496-71)(CSA A.23.2.25). A schematic illustration of the test is given in Figure 2.1.

2.1.2 THEORETICAL BASIS

An analysis of the indirect tensile test for a number of simplifications has been presented by various researchers.[15,16] It has been demonstrated that a uniform compressive load applied along the vertical diameter of a thin disc (assuming plane stress) results in a constant horizontal tension across the vertical central section (i.e., along the line of the load). Below the yield point, the elastic modulus of a material may be determined if the deformation across the horizontal diameter is measured.

Frocht[16] gives expressions for the stress components σ_x and σ_y (Figure 2.2) along the horizontal section of symmetry for a disc under diametral compression:

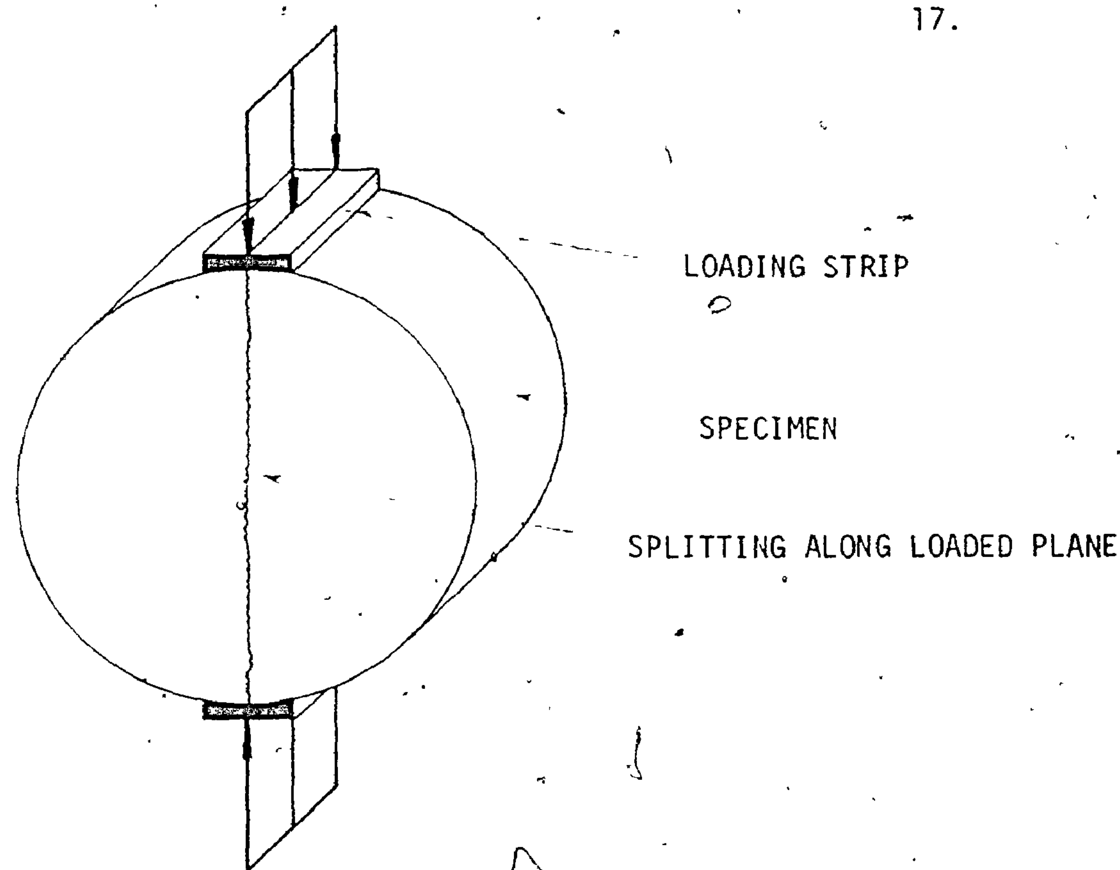


FIGURE 2.1: THE INDIRECT TENSILE TEST

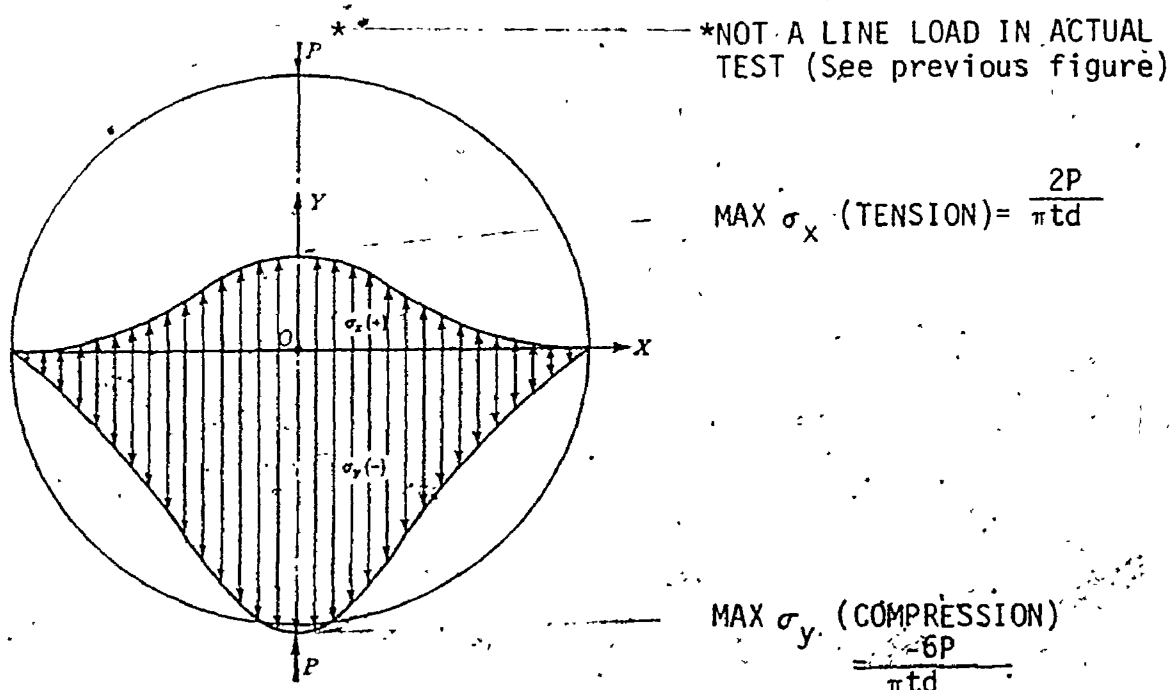


FIGURE 2.2: STRESS DISTRIBUTIONS ON X AXIS

$$\sigma_x = \frac{2P}{\pi td}\left(\frac{d^2 - 4x^2}{d^2 + 4x^2}\right)^2 \qquad (2.1)$$

$$\sigma_y = -\frac{2P}{\pi td}\left(\frac{4d^4}{(d^2 + 4x^2)^2} - 1\right) \qquad (2.2)$$

where σ_x, σ_y = stresses perpendicular and parallel to direction of loading, respectively;

P = applied load;

t = thickness of cylindrical disc;

d = diameter of disc; and

x = distance along horizontal diameter from centre of disc.

Assuming plane stress and elastic behaviour, the strain across the horizontal diameter is:

$$\varepsilon_x = \frac{1}{E}\left(\sigma_x - \nu\sigma_y\right) \qquad (2.3)$$

where: ε_x = strain across the horizontal diameter;

E = Young's modulus; and

ν = Poisson's ratio.

Substituting equations (2.1) and (2.2) into equation (2.3) gives:

$$\varepsilon_x = \frac{2P}{E\pi td}\left[\frac{(4d^4\nu - 16d^2x^2)}{(d^2 + 4x^2)^2} + (1 - \nu)\right] \qquad (2.4)$$

The total deformation across the horizontal diameter is found by integrating the strain, ε_x, between the limits $\pm$ d/2:

$$\Delta = \int_{-d/2}^{d/2} \varepsilon_x dx \qquad (2.5)$$

where Δ = total deformation across the diameter. Substituting equation (2.4) into equation (2.5) and integrating yields:

$$\Delta = \frac{P}{tE} \{(4/\pi) + \nu - 1\} \qquad (2.6)$$

or in terms of E:

$$E = \frac{P(\nu + 0.2732)}{t\Delta} \qquad (2.7)$$

Thus the modulus of elasticity E can be calculated if values of Poisson's ratio ν, thickness t, and the horizontal deformation Δ across a cylinder for a given vertical load P are known. In the case of purely elastic materials equation (2.7) applies for both static and dynamic loadings. For asphaltic concrete mixes (which are actually non-linear and visco elastic) and short duration loadings, it is usual to adopt the term resilient modulus M_R to describe the "apparent" Young's modulus. The resilient modulus is used interchangeably with Young's modulus in flexible pavement structural design calculations using finite element or multi-layer elastic methods. Thus, for the resilient modulus test:

$$M_R = \frac{P(\nu + 0.2732)}{t\Delta} \qquad (2.8)$$

where Δ is the maximum lateral deflection and is not necessarily in phase with the load pulse. Any phase lag aspects between the load and deflection pulses may be used in a qualitative manner to examine potential fatigue resistance, an area of interest to be considered in future research.

Equations (2.1 to (2.8) represent stress conditions for a point load on a thin disc. In practice, a loading strip of finite width is employed to ensure good load distribution. The stress analysis of a circular element subjected to short strip loadings has been presented by Hondros[17]. However, the simplifying assumptions of line loading and plane stress conditions are generally reasonable for the geometrics involved. (This aspect of the test is being considered in an extension of this study). Experimental modulii values presented in this study are based on the preceeding theoretical considerations.

2.1.3. METHOD ADOPTED

The diametral method for determining resilient modulus proposed by Schmidt [11] was adopted for this investigation. This procedure is attractive because it is non-destructive, relatively simple, cheap (with the equipment developed) and uses samples prepared by the widely used Marshall Method. Consequently, the same samples that were used for resilient modulus determinations can be subjected to Marshall stability and flow tests. This system can also accommodate cores from existing pavements so that the important influences of environment can be considered. It was recognized that there was scope for adopting the system for use in standard 7 inch (178 mm) diameter triaxial cells to study the effects of confining pressure (lateral stress) which is a future phase of this investigation. In addition, results obtained by this procedure correlate well with those using direct tension and compression methods[11].

2.1.4 EQUIPMENT DEVELOPMENT

The resilient modulus device used in this research is based on the assembly developed by Schmidt. Significant modifications have been made to key aspects of the system, particularly for the determination of the lateral deflection where strain gauges mounted on cantilever beams replaced the Stratham UC-3 transducers used by Schmidt. Figures 2.3 and 2.4 show the assembly utilized. Other developments of note included changes to the yoke (floating collar) to facilitate more accurate assembly, and designs for a solid state timing circuit and solid state amplifiers.

The changes presented in the following sections improved the system in terms of ease of assembly, resistance to damage and decreased manufacturing costs. A critical design considerations was the potential miniaturization of the system so that it could be fitted into available triaxial cells for a future phase of this investigation. Also, the proven strain gauge cantilever beams for measuring deformations were utilized during the design and fabrication of a Poisson's ratio determination apparatus.

2.1.4.1 Loading System

The loading system developed used controlled time and pressure air pulses supplied to a diaphragm air cylinder (Bellofram D-12) from an electric solenoid valve (Skinner AE-2)

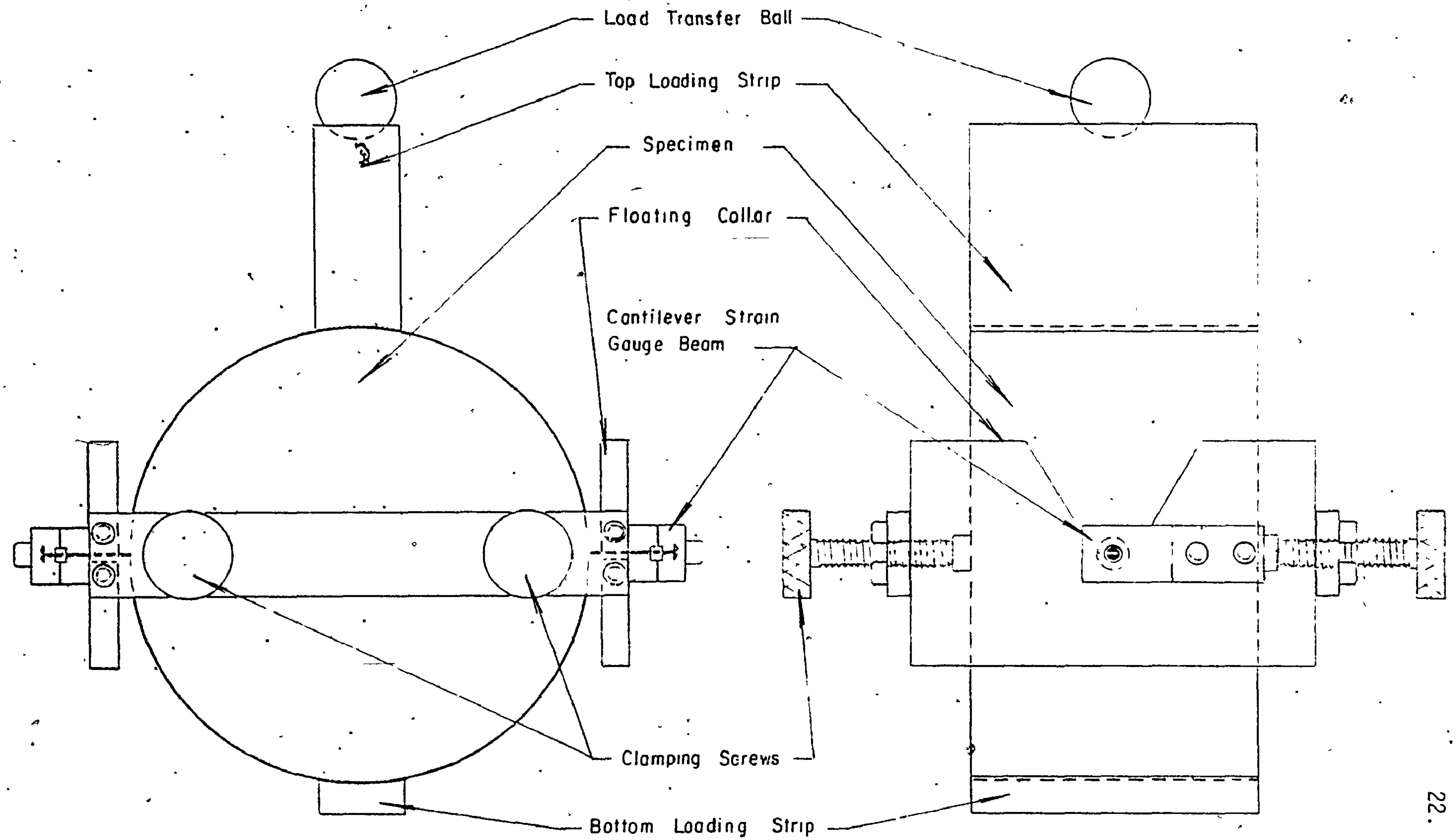


Figure 2.3 RESILIENT MODULUS MEASURING DEVICE

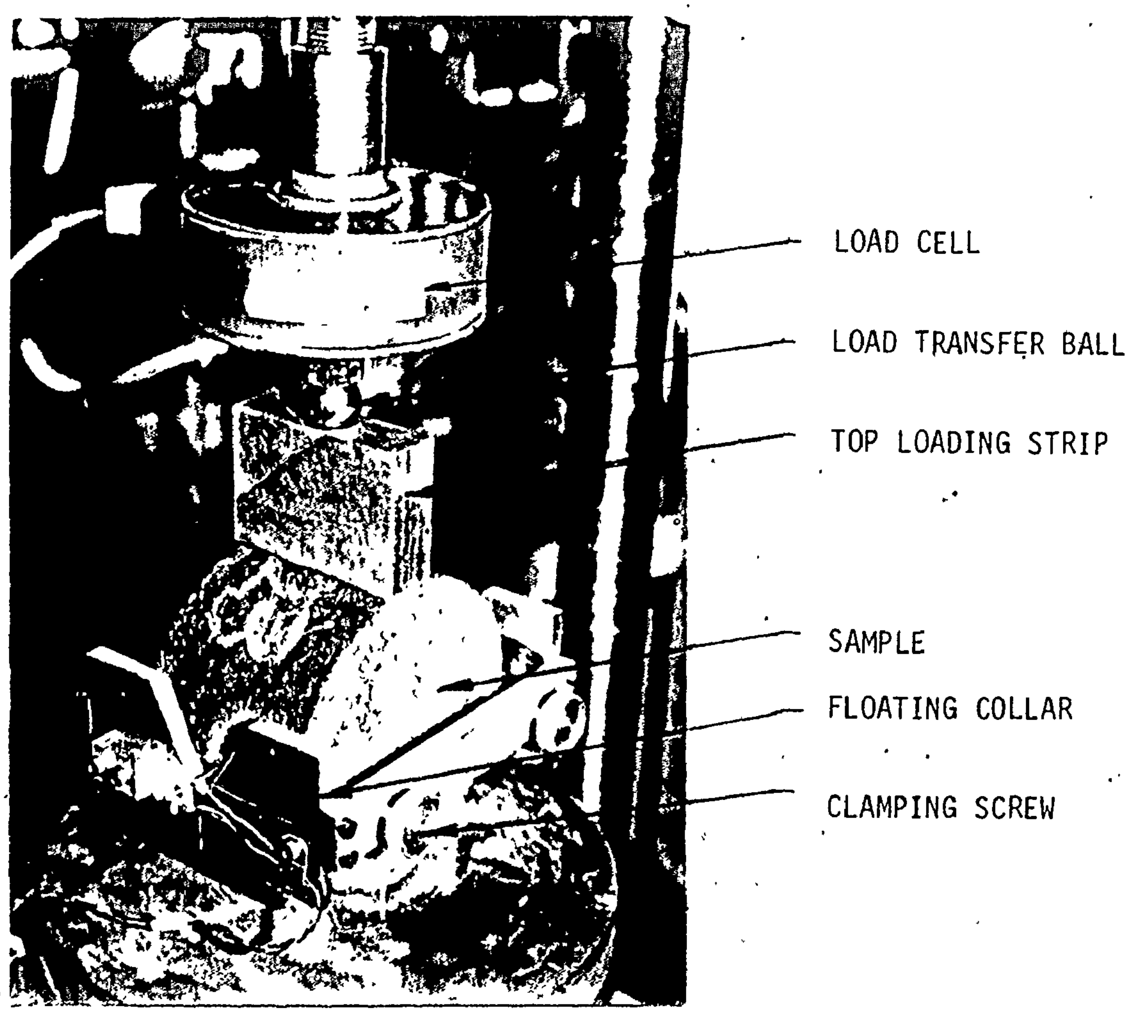


FIGURE 2.4: SPECIMEN MOUNTED IN RESILIENT MODULUS DEVICE

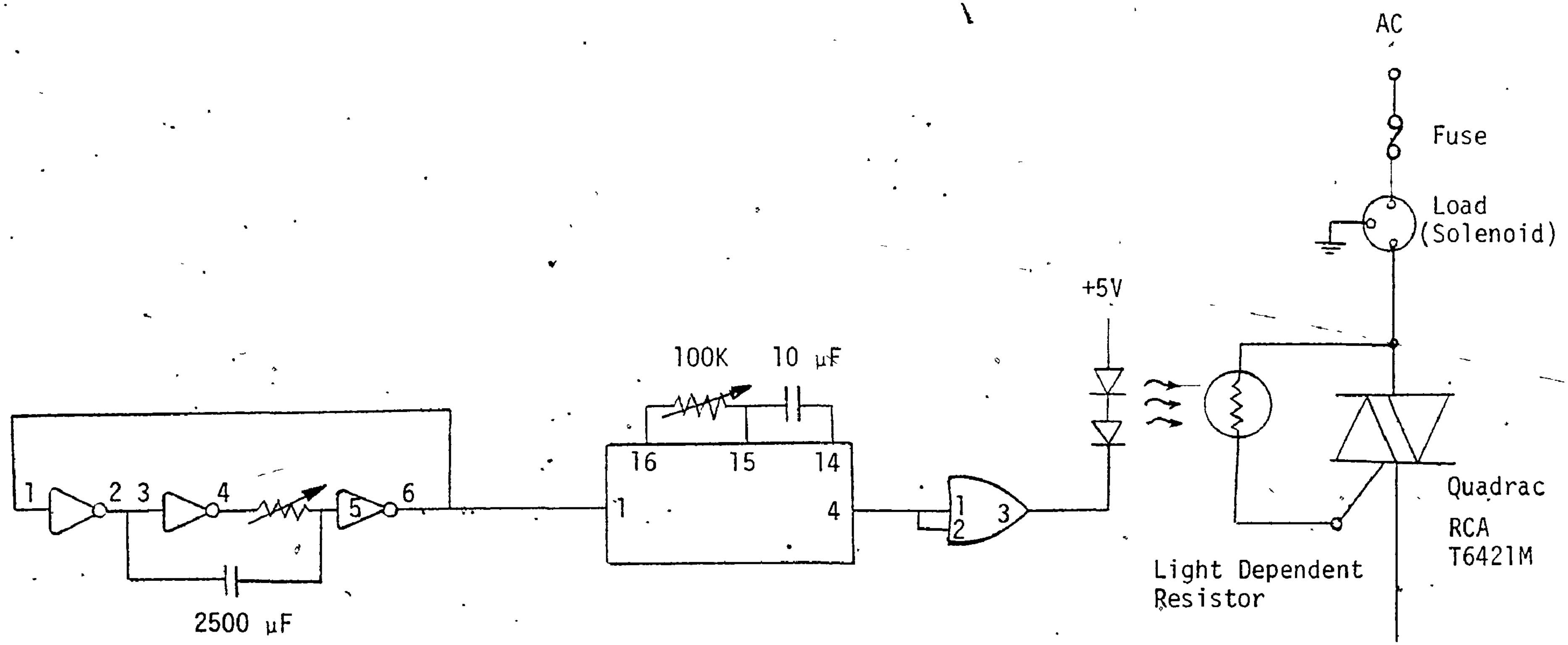
activated by a solid state timing circuit designed for this application. Load pulses were transmitted to the specimen through a curved loading strip as indicated in Figure 2.3. The narrow loading strip gives a more uniform loading distribution and is generally used during diametral testing of construction materials. A schematic diagram of the timing circuit is given in Figure 2.5. It consists of an oscillator set at a period of 2.9 seconds, which triggers a monostable multivibrator producing a pulse with an adjusted width of 0.1 seconds. The pulse is used to drive light emitting diodes which in turn trigger a semiconductor thyristor, performing the function of an AC power switch. Reasons for using this particular load frequency and duration are given later in this chapter.

2.1.4.2 Measuring System

The measuring system was designed to determine the magnitudes of the vertical load and the corresponding lateral deflections.

(a) Load

A commercially available load cell (Lebow 661-13A-11) with a capacity of 1500 kg was used to measure the vertical load. It is possible to subsitute an inexpensive "strain-bolt" type load cell in the piston ram to miniaturize this aspect of the equipment, and further decrease the costs.



Oscillator Period = 2.9 Sec.

Texas Instruments Inc.
SN7404 Hex Inverters

Retriggerable Monostable
Multivibrator

Pulse Width = 0.1 Sec
Texas Instruments Inc.
SN74123 Monostable

Driver
Texas Instruments Inc.
SN 75453 Positive-Or Driver

FIGURE 2.5: SOLID STATE TIMER CIRCUIT

2.1.4.3 Lateral Deflection

Figure 2.6 shows the device designed to determine the lateral deflection. Two strain gauges (Micro-Measurements EA-06-125BZ-350) are mounted on each side of the cantilever beam and wired in a full bridge as shown in Figure 2.6C. Lateral movement of the probe causes compressive strains on one face of the beam and tensile strains on the other. This results in a change in the resistance of each arm of the bridge circuit thus creating a potential difference. (The full bridge also provides temperature compensation). This signal is conditioned by the solid state amplifier described later in this section, and then fed to the recording system.

Two of these gauged cantilever beams are bolted to a floating collar designed to facilitate direct mounting of the lateral deflection devices on the specimens so ~~that~~ they ride with any vertical movement. A set-up holder, described in Appendix "A", ensures that the probes are positioned at either end of the horizontal diameter.

The lateral deflection devices described above meet all conditions of sensitivity and reliability required for this study. They are easy to fabricate, inexpensive, not temperature susceptible and may be calibrated while bolted to the floating collar. Because they are small, when waterproofed, they may be incorporated

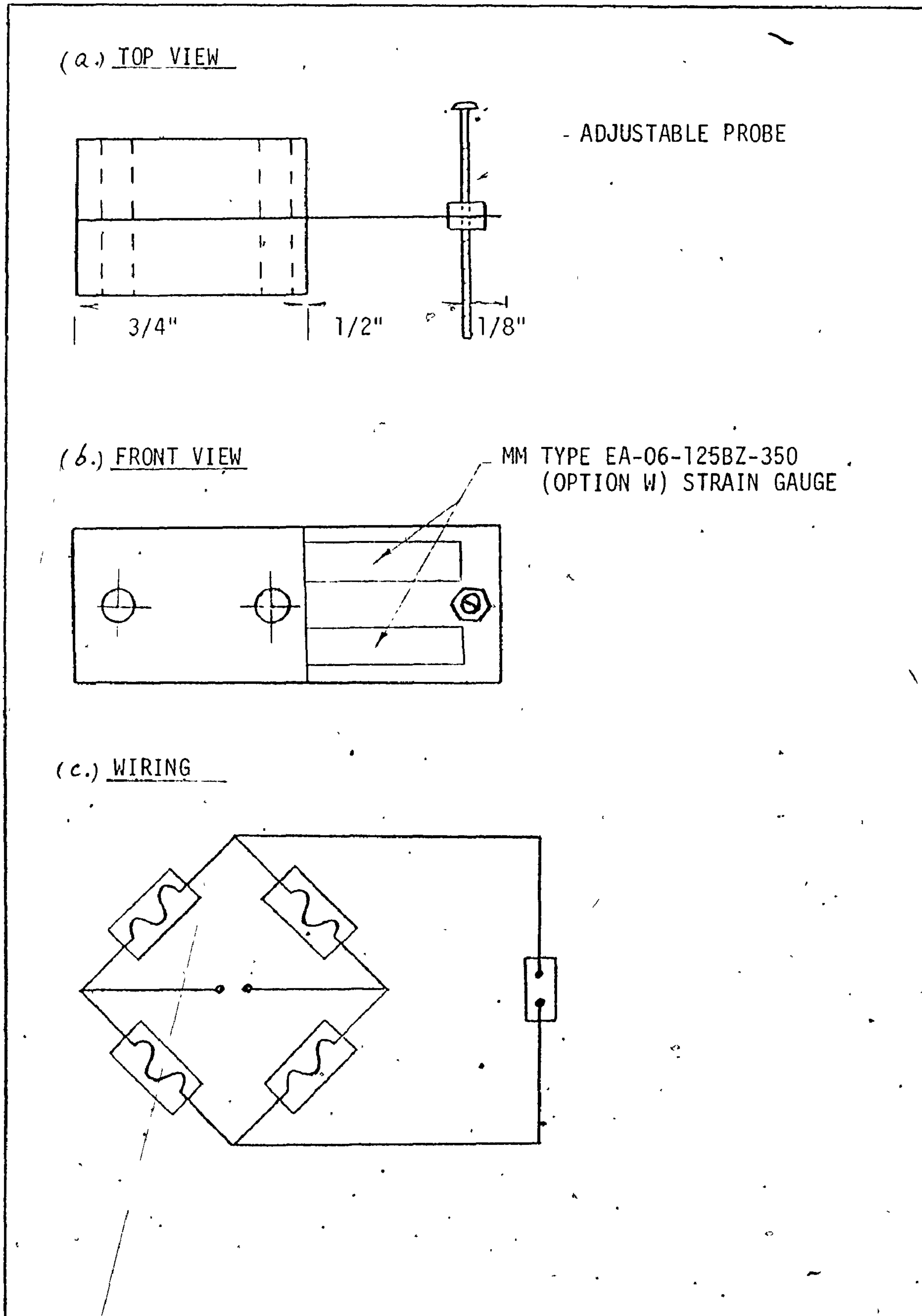


FIGURE 2.6 LATERAL DEFLECTION MONITORING DEVICE

into a system for use in available triaxial cells to study the effects of confining pressure on resilient modulus, a future phase of this investigation.

2.1.4.4 Recording System

A system for recording both load pulses and lateral deflections on a time base chart is necessary to complete the test equipment. Output from the load cell is fed directly to a light-beam oscillographic recorder (S and E 3006). Solid state amplifiers as shown in Figure 2.7 were developed to condition signals from the lateral deflection monitoring devices. The amplified signals were then also recorded on the oscillographic recorder.

2.1.5 Test Procedure

The experimental procedure involves mounting a specimen in the load frame and measuring the lateral deflection resulting from application of the pulsating load. A schematic representation of the experimental set-up is shown in Figure 2.8. Load pulses of 0.1 seconds repeated every 3 seconds were chosen because this corresponds to dynamic traffic loading patterns at "creep" speed which are most damaging, and has been used by other investigators.[11] Pauses of three seconds between applications of load permit virtually complete visco-elastic recovery of the specimen. Details of sample preparation and assembly are given in Appendix "B".

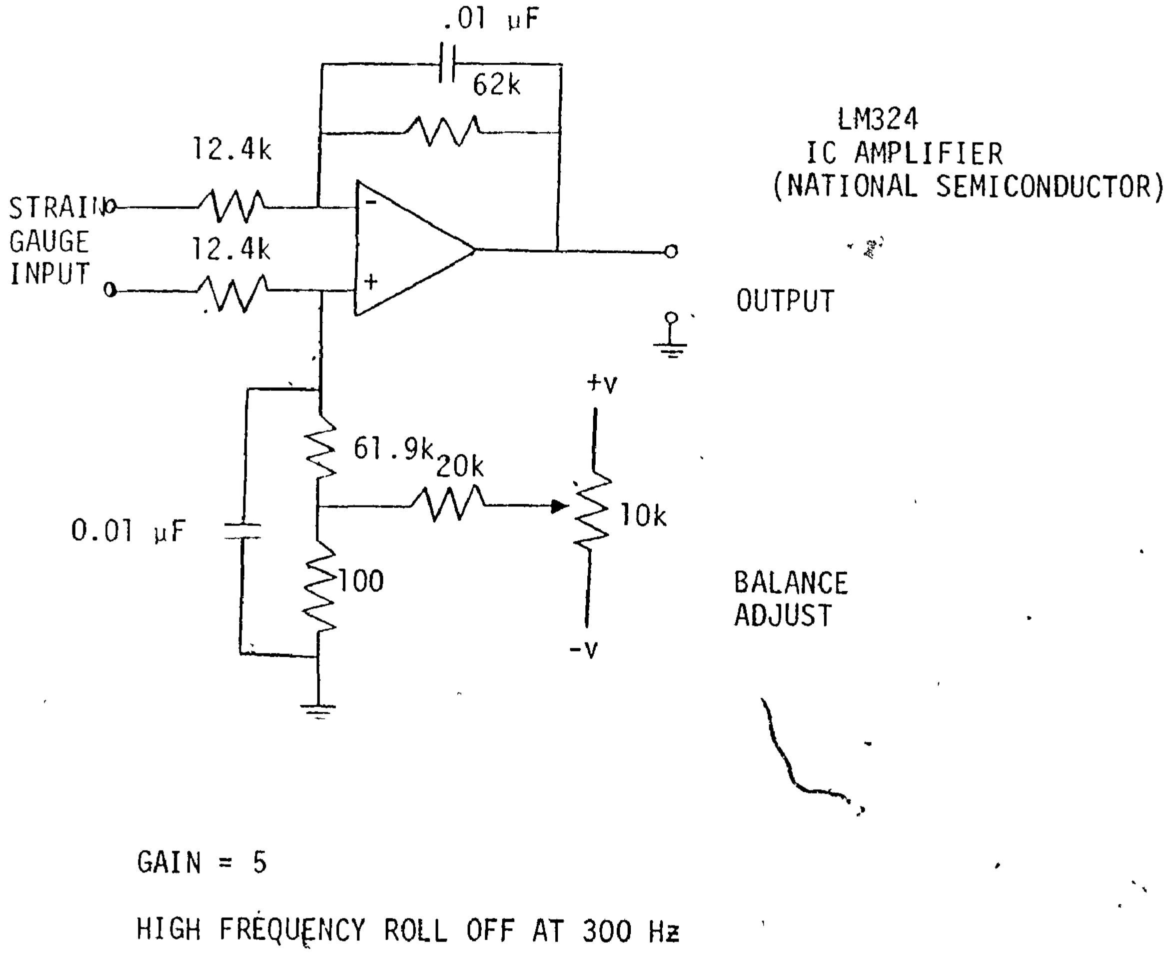


FIGURE 2.7 DIFFERENTIAL INPUT AMPLIFIER

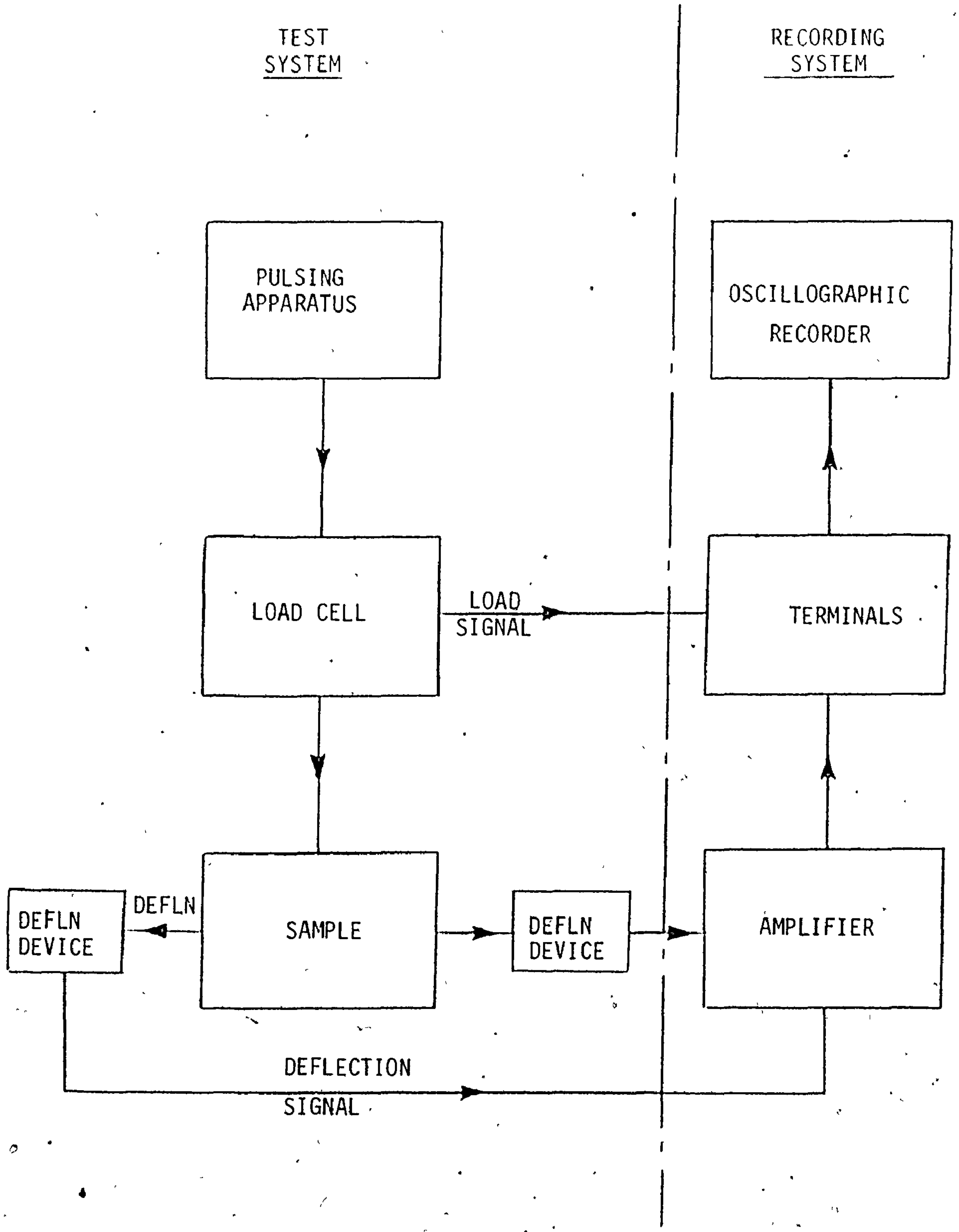


FIGURE 2.8 SCHEMATIC REPRESENTATION OF EXPERIMENTAL SET-UP

A typical trace obtained from a test on an asphaltic concrete specimen is shown in Figure 2.9. The resilient modulus is determined by measuring corresponding peak load and deformation from the recorded trace and substituting into equation 2.9.

$$M_R = \frac{\delta_L c_L}{t(\delta_1 c_1 + \delta_2 c_2)} (\nu + 0.2732) \qquad 2.9$$

where δ_L = trace value for loading
δ_1 = trace value for Gauge 1
δ_2 = trace value for Gauge 2
t = thickness of the specimen
c_L = load calibration factor
c_1 = calibration factor for strain Gauge 1
c_2 = calibration factor for strain Gauge 2
and
ν = Poisson's ratio

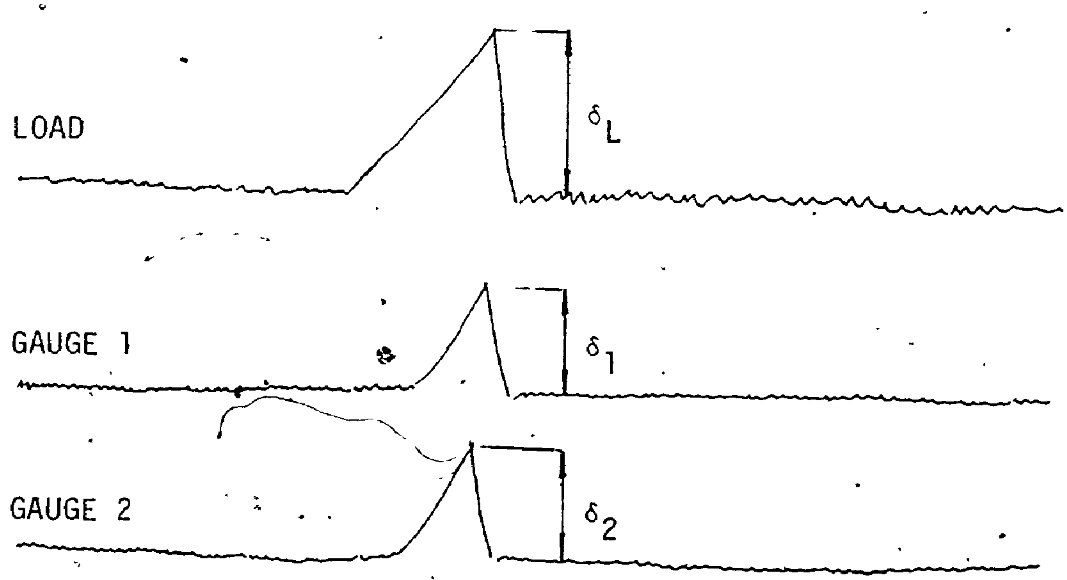


FIGURE 2.9: TYPICAL M_R TEST TRACE

2.2 POISSON'S RATIO TEST

Values for Poisson's ratio are need in analyses that use elastic layer theory. While assumed values are typically used and influences on stress are not large, Poisson's ratio does indicate potential lateral confining influences and does modify stress levels. Of greater significance to this particular study would be values of an "equivalent parameter"* under dynamic loading conditions for visco-elastic materials. This would relate more closely to the real situation of traffic loadings on asphaltic concrete pavements. References in the literature to the experimental determination of Poisson's ratio or an equivalent parameter are, at best, scant.

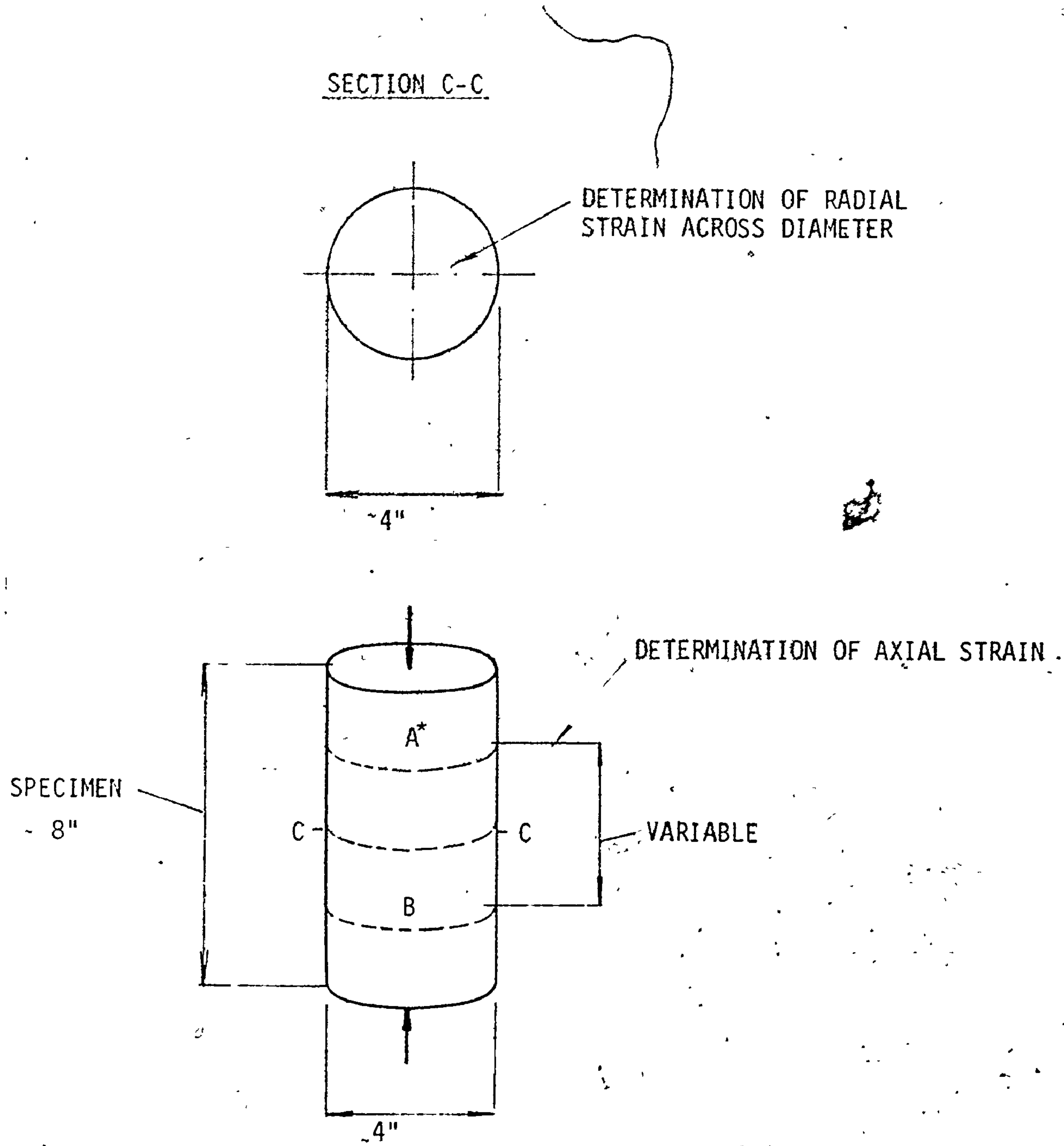
A system for the determination of Poisson's ratio (or equivalent) was developed as part of this study. This involved the design of equipment to monitor lateral and axial strains under repeated compressive loadings. The required measurements are illustrated in Figure 2.10 The values of the relevant parameter ν can then be computed on the basis of Equation 2.10.

$$\nu = \frac{\text{Lateral Strain}}{\text{Axial Strain}} = \frac{-\varepsilon_y}{\varepsilon_x} = \frac{-\varepsilon_z}{\varepsilon_x} \qquad 2.10$$

where: $\text{Lateral Strain} = \dfrac{\text{Radial Deformation}}{\text{Diameter}}$

and: $\text{Axial Strain} = \dfrac{\text{Deformation Over Test Length}}{\text{Test Length}}$

* termed the dynamic Poisson's ratio to reflect the test conditions, but recognizing that the Poisson's ratio is not typically considered loading dependent.



* A,B,C indicate typical locations of Collars A,B,C shown in Figure 2.11

FIGURE 2.10 : MEASUREMENTS FOR THE DETERMINATION OF DYNAMIC POISSON'S RATIO

2.2.1 EQUIPMENT

Figure 2.11 shows the device developed for Poisson's ratio determinations. The system is designed to fit into a 7 inch (178 mm) diameter standard triaxial cell for studying the effects of confining pressures. It uses 8 inch (203 mm) by 4 inch (102 mm) diameter cylindrical specimens to minimize end restraint influences.

The central ring (Collar C) in Figure 2.10 used to measure the lateral deformation. It is spring mounted directly on the specimen to avoid restraining radial deformation and to allow it to ride with with vertical movements. The axial deformation is measured by the outer rings (Collars A and B). The adjustable rods on Collar B allow the measurement of axial deformations over various sections of the cylindrical specimens.

The operation of the device involves the measurement of axial and corresponding lateral deformations resulting from the application of compressive loads along the axis of the cylindrical specimens. The axial deformation in monitored by the average relative deflection of the strain gauge beams mounted on Collar A and the probe rods on Collar B. The lateral deformation is measured directly by the strain gauge beams mounted on opposite sides of Ring C, as shown in Figure 2.10. The strain gauge cantilever beams used in this system are similar to those developed for the resilient modulus device.

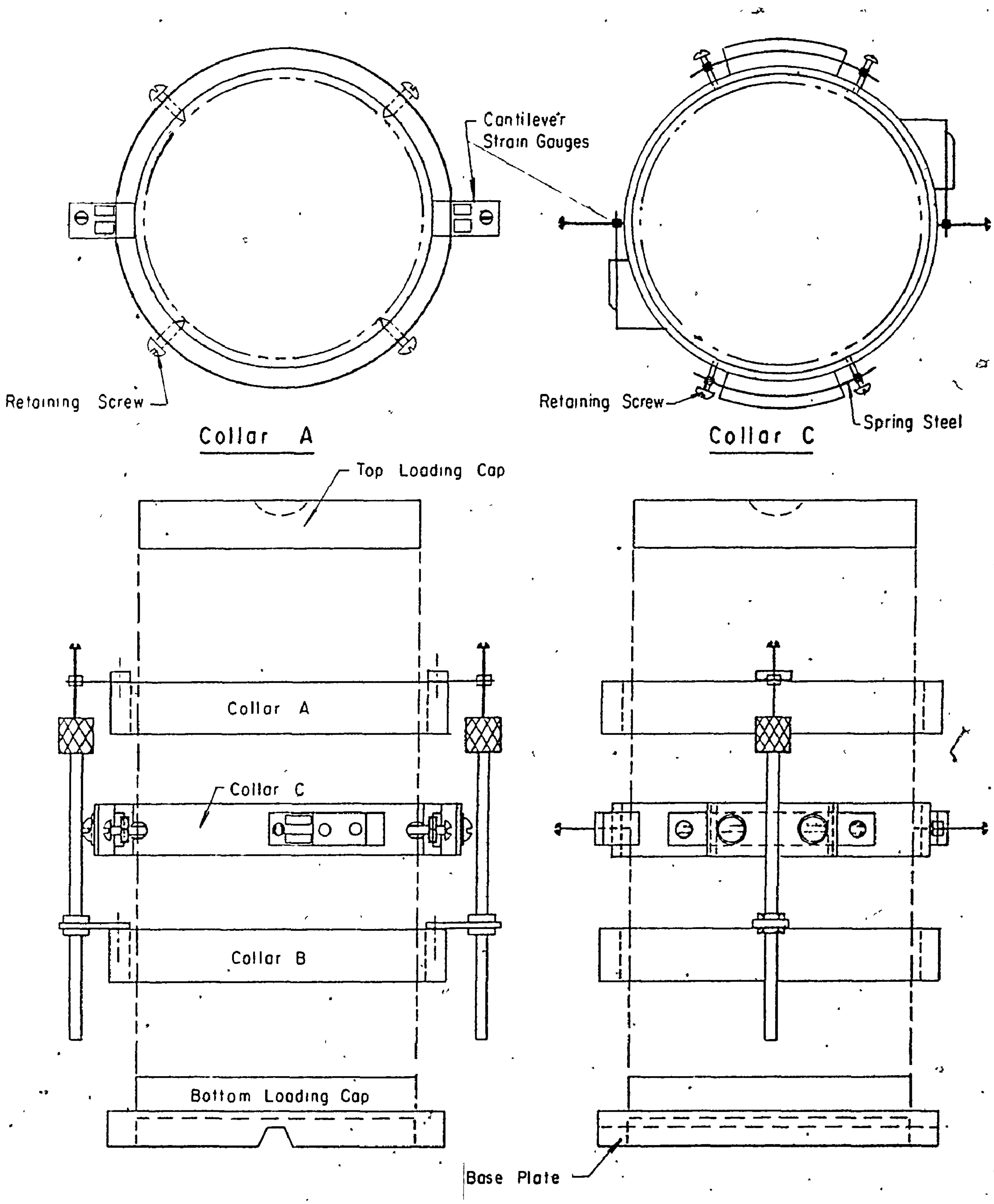


FIGURE 2.11 - POISSON'S RATIO MEASURING DEVICE

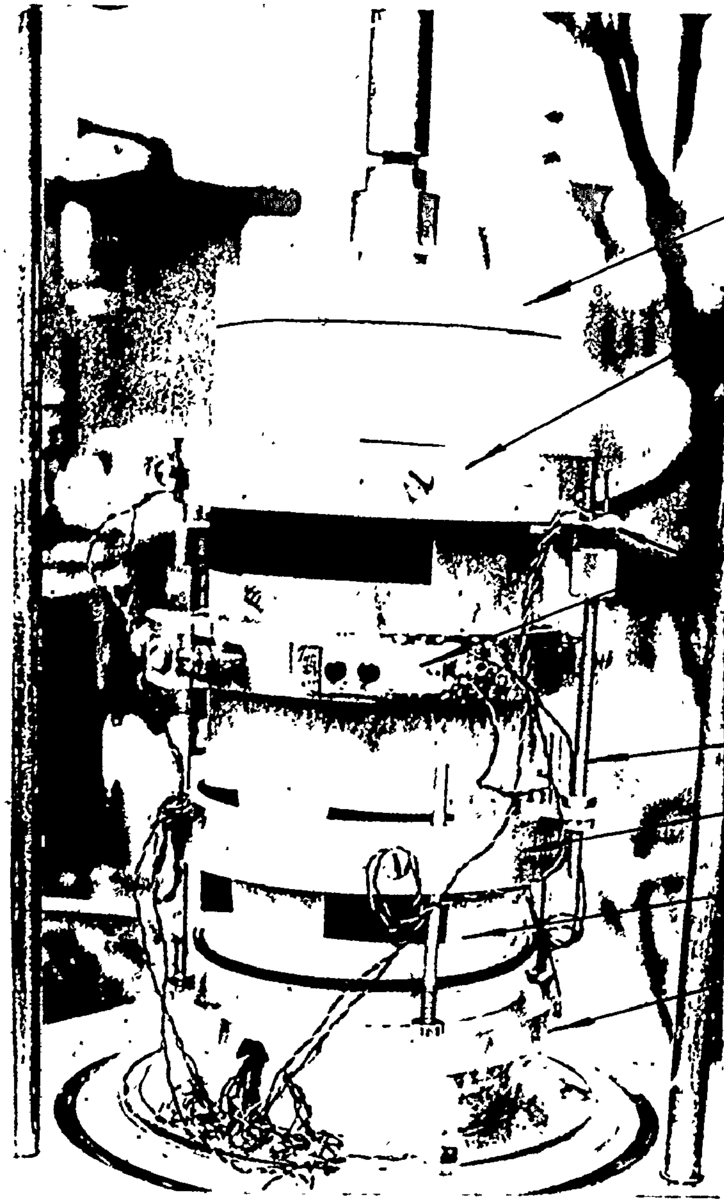


FIGURE 2.12: SPECIMEN MOUNTED IN POISSON'S RATIO DEVICE (Lee[26])

2.3 COMMENTS

While Schmidt[11] developed equipment for the determination of resilient modulus, it is relatively expensive and not suitable for use in a triaxial cell. The equipment used for this study, while similar, is based on readily available laboratory components and is small enough to fit into a standard 7 inch (178 mm) diameter triaxial cell. The potential problems involved in miniturizing and waterproofing the lateral deflection measuring system used by Schmidt were considered so great that the lateral deflection devices described earlier were designed and fabricated. Other advantages of the adopted system were given earlier. Difficulties with electrical noise pick-up were experienced when an electrically powered mechanical timer was used to produce the required load pulses. This problem was solved by designing the solid state timing circuit to perform this function, and solid state amplifiers to condition the signals from the deflection devices. The end result was a cheap, simple and reliable assembly for the determination of resilient modulus.

It was recognized that the lateral deflection device developed for use in the resilient modulus apparatus was eminently suitable for incorporation into a system for the dynamic measurement of Poisson's ratio. Such a system, capable of being fitted into a standard 7 inch (178 mm) diameter triaxial cell, was designed and built, but not used in the current study.

While the timer circuits and solid state amplifiers described here performed satisfactorily, it was recognized that simpler and more efficient designs could be developed. This problem is presently being studied, and improved designs will be incorporated in equipment used in future phases of this investigation.

CHAPTER 3

TEST RESULTS

3.1 GENERAL

The program of investigation outlined in Chapter 1 was undertaken using the apparatus described in Chapter 2. This chapter reports the results of the experimental work and evaluates the accuracy and relevance of the accumulated data. Assumptions made, and reasons for making them are stated in the appropriate points in the chapter. As a prelude to the presentation of the experimental findings, current mix design procedures and the relevance of M_R determinations in mix design are briefly discussed below.

3.2 MIX DESIGN STUDIES

Results from the Marshall and Hveem stabilometer asphalt mix design procedures (Figure 3.1) are widely used to obtain optimum asphaltic concrete mix designs based on the air voids concept. The specific design procedures are given in references such as the Asphalt Institute Manual Series 2, Mix Design Methods for Asphalt Concrete (18), and will not be detailed here. The aim is to produce economic mixes that yield the required design properties indicated in Table 3.1. Both procedures at best yield information on stability (shear strength) and flow (flexibility) at failure and allow the optimum asphalt content to be determined for various air void requirements.

TABLE 3.1

FACTORS IMPORTANT IN OBTAINING SATISFACTORY PERFORMANCE FROM DENSE-GRADED ASPHALTIC CONCRETE PAVEMENTS (19)

DESIRABLE PROPERTIES	MODE OF FAILURE	DESIRED CHARACTERISTIC IN PARTICULAR ELEMENT		
		ASPHALT	MINERAL AGGREGATE	MIX PROPORTIONS
Stability of mix	Distortion: rutting or shoving	High viscosity	Rough particle surfaces-angular or cubical shape	Low asphalt and void contents; High percentage of fines (passing #100 sieve
Resistance to fatigue failure	Fracture in flexure	High viscosity for pavements thicker than 6"; low viscosity for pavements 2" and thinner	Not subject to stripping	High asphalt content
Resistance to low temperature cracking	Fracture in tension	Low viscosity	--	High asphalt content, low void content
Resistance to aging	Fracture or disintegration	Low viscosity, resistant to aging	Not subject to stripping	High asphalt content, low void content
Resistance to raveling or stripping	Disintegration, asphalt-aggregate bond broken	Suitable surface charge	Not subject to stripping	High asphalt content
Imperviousness to water and air	Weakening to underlying layers - or disintegration or instability of pavement	--	Not subject to stripping	High asphalt content, high percentage of fines (passing #200 sieve)
Skid resistance	Surface becomes slick	--	Rough surfaces, resistant to polishing, not subject to stripping	Low asphalt content

Gradation, air voids, VMA* stability and flow are all closely specified by agencies such as The City of Hamilton and The Ontario Ministry of Transportation and Communications. The general specifications for The City of Hamilton, which are similar to those used throughout Ontario are outlined on Table 3.2 [20]. It should be noted that no direct mention of structural capacity or fatigue resistance is made in these specifications.

*voids in the mineral aggregate

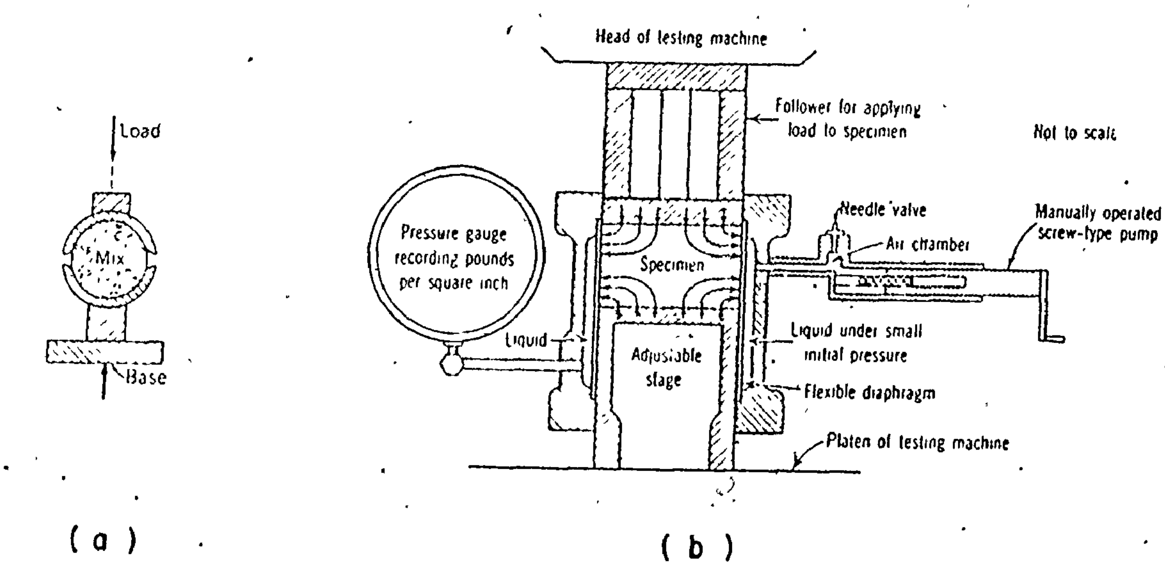


FIGURE 3.1 SCHEMATIC DIAGRAMS FOR STABILITY TESTING OF ASPHALTIC CONCRETE SPECIMENS

(a) MARSHALL (b) HVEEM

(After Reference 19)

TABLE 3.2

CITY OF HAMILTON - PHYSICAL REQUIREMENTS FOR MIXTURES [20]

Property of Laboratory Compacted Mixture	HM1	HM3 HM3-Fine	HM5	Type A	Type B	Type C	Type D	Type E	Steel Slag
Marshall Stability (lbs. at 140°F)	1200 Min.	1200 Min.	1200 Min.	500 Min.	500 Min.	500 Min.	500 Min.	500 Min.	3500 Min.
Flow Index (Units or 0.01 inch)	7-16	7-16	7-16	7-12	7-12	7-12	12 Min.	7-12	8-16
% Voids in Compacted Mineral Aggregate, allowing for absorbed asphalt	16 Min.	18 Min.	14 Min.	18-25	18-25	18-25	18-25	18-25	20 Min.
% Air Voids *	3-5	2-4	3-6	2-8	2-8	2-8	2-6	2-8	3-5
% Asphalt Binder Content **	5-10	5-10	4-9	7-0-8.5	8.5-15.5	6.0-10.0	7.5-10.0	6.0-10.0	5-7
% Asbestos	-	-	-	-	-	-	1.5-2.0	-	-
% Rubber Content ***	-	-	-	-	-	-	-	5.0-10.0	-

* The per cent air voids shall be as required by the City, within this range, for the conditions existing at the particular location.

** Asphalt Binder Content is the weight of cutback asphalt, asphalt emulsion or asphalt cement incorporated into the mix, expressed as a percentage by weight of the total mix.

*** Rubber Content is the weight of reclaimed rubber incorporated into the mix, expressed as a percentage of the total weight of asphalt cement and rubber solids in the mix.

The currently employed mix design methods, although required for stability and air voids control are really not directly related to the structural design aspects of the pavement system. If a rational design method is to be achieved, present procedures must be combined with tests of the resilient modulus type which yield parameters that more directly reflect structural and fatigue resistance criteria.

In the following sections the results of resilient modulus tests on Lucite using the developed equipment are compared to those reported by Schmidt. Experimental M_R values for a wide range of asphaltic concrete mixes under various temperature conditions are also reported.

3.3. COMPARISON OF MEASURED M_R VALUES FOR LUCITE AND RESULTS REPORT BY SCHMIDT

The resilient modulus M_R for Lucite was determined using the apparatus and method previously described. Specimens were subjected to a range of repeated dynamic loadings and values computed using the measured diametral deformations and a Poisson's ratio of 0.36 (Schmidt). Experimental values, together with those reported by Schmidt for a similar material are shown in Figure 3.2. The measured values compare favorably to the modulus supplied by the manufacturer (650 ksi @ 23^{o}C). It is noted that measured values for resilient modulus appear to be generally lower for tests conducted at higher diametral stress levels. This possible trend will be investigated in a future phase of this research program.

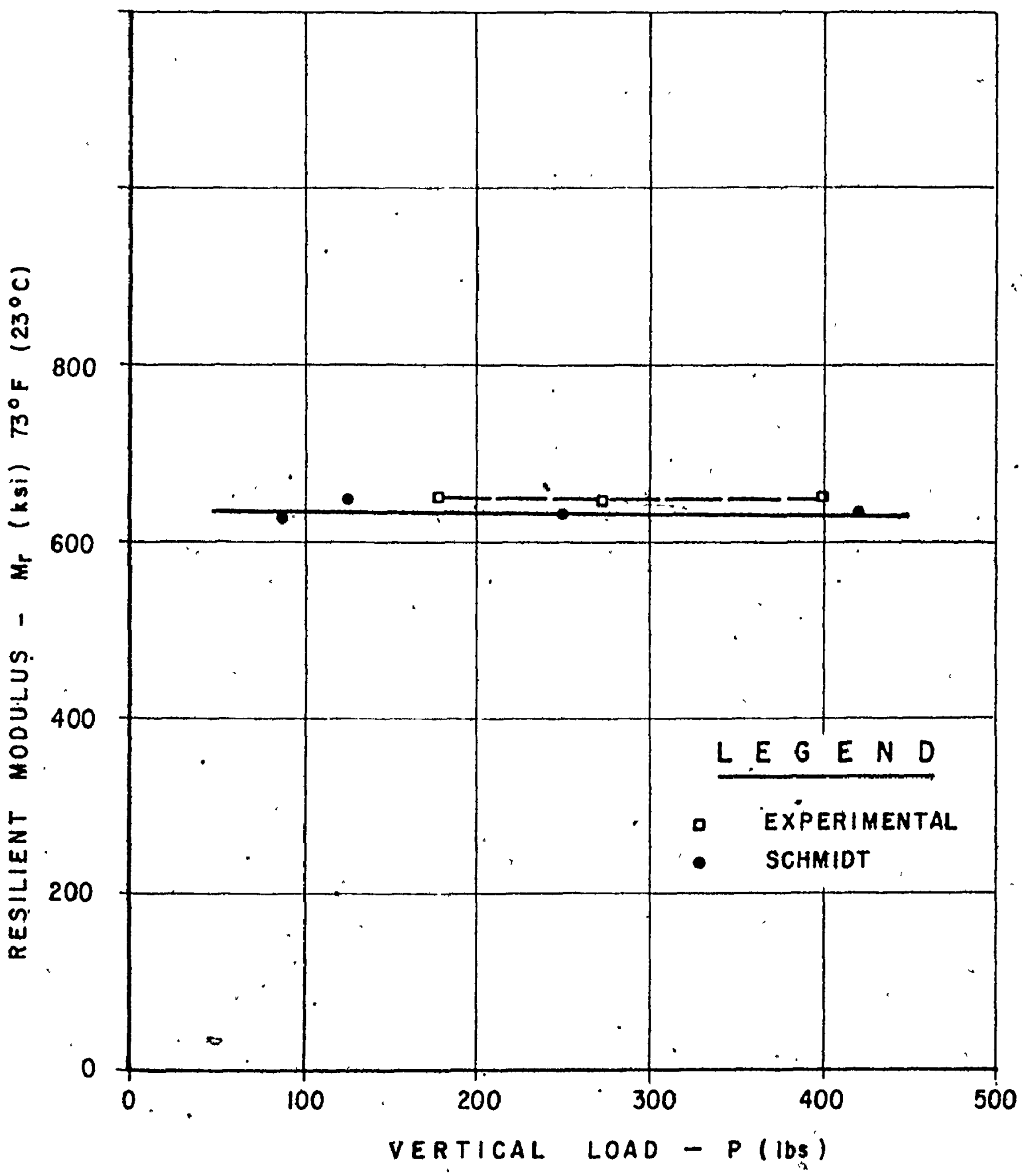


FIG. 3.2
COMPARISON OF EXPERIMENTAL RESILIENT MODULUS VALUES FOR LUCITE WITH THOSE REPORTED BY SCHMIDT

3.4 INFLUENCE OF ASPHALT CONTENT AND AGGREGATE TYPE ON M_R

The resilient modulus of specimens conforming to the City of Hamilton HM1, HM3, HM5 and steel slag specifications with a range of asphalt contents from 3 to 9 per cent were determined using the resilient modulus device. Details of aggregate gradations and asphalt cement properties are given in Appendix "C". Results of these tests are presented in the summary Table 3.3 and Figure 3.4. The values reported for each mix type and asphalt cement content are mean values of two tests performed at right angles on each of three specimens per type. Peak loads of 25, 50 and 100 pounds were applied to test speciments at 23^{0}C with no significant differences in the computed M_R values. Lower peak loads (25 and 50 pounds) were used at 38^{0}C to minimize the possibility of permanent deformation. Asphaltic concrete stiffness greatly increases at lower temperatures. Consequently, higher peak loads (100 and 200 pounds) were used for tests conducted at 0^{0}C. Poisson's ratio was assumed to be 0.35. Differences between actual and assumed values for this parameter under the given test conditions could influence the results ~~by up~~ to 10 per cent over the temperature range considered. The evaluation of Poisson's ratio over representative temperature ranges is an area to be considered in future research. Individual test results were computed on the basis of average values taken from 5 repeated axial load pulses. Variations of approximately ±5 per cent were typical in the individual values, a significant portion of which could be attributed to electrical noise pick-up in the signal traces.

TABLE 3.3

SUMMARY OF TEST RESULTS

MIX TYPE	PER CENT ASPHALT CONTENT	MARSHALL STABILITY	MARSHALL FLOW	PER CENT AIR VOIDS	M_R (ksi) 0°C	M_R (ksi) 23°C	M_R (ksi) 38°C
HM3	3	1275	8.6	13.5	2191	305	65
	5	2215	10.2	7.8	2258	340	60
	6	2710	10.5	3.4	2101	250	48
	7	1804	12.6	2.4	1906	170	--
	9	581	17.2	0.8	1583	60	--
HM1	5	2303	11.1	5.7	2270	330	62
	6	2423	12.7	3.1	2105	190	41
	7	1204	16.5	2.1	1946	150	--
HM5	4	2240	10.1	5.8	1880	150	--
	5	2580	11.5	4.2	1890	145	--
	6	1430	13.6	1.8	1580	120	--
Steel Slag(OH)*	4	5590	16.5	4.0	2803	450	107
	5	5350	19.3	3.2	2799	450	80
	6	3430	23.1	1.6	2428	340	--
Steel Slag(BOF)+	5	5370	19.1	4.5	----	480	--
	6	3675	21.1	3.7	----	380	--

* OH - Open Hearth

\+ BOF - Basic Oxygen Furnace

NOTE: Poisson's ratio assumed to be 0.35 in each case.

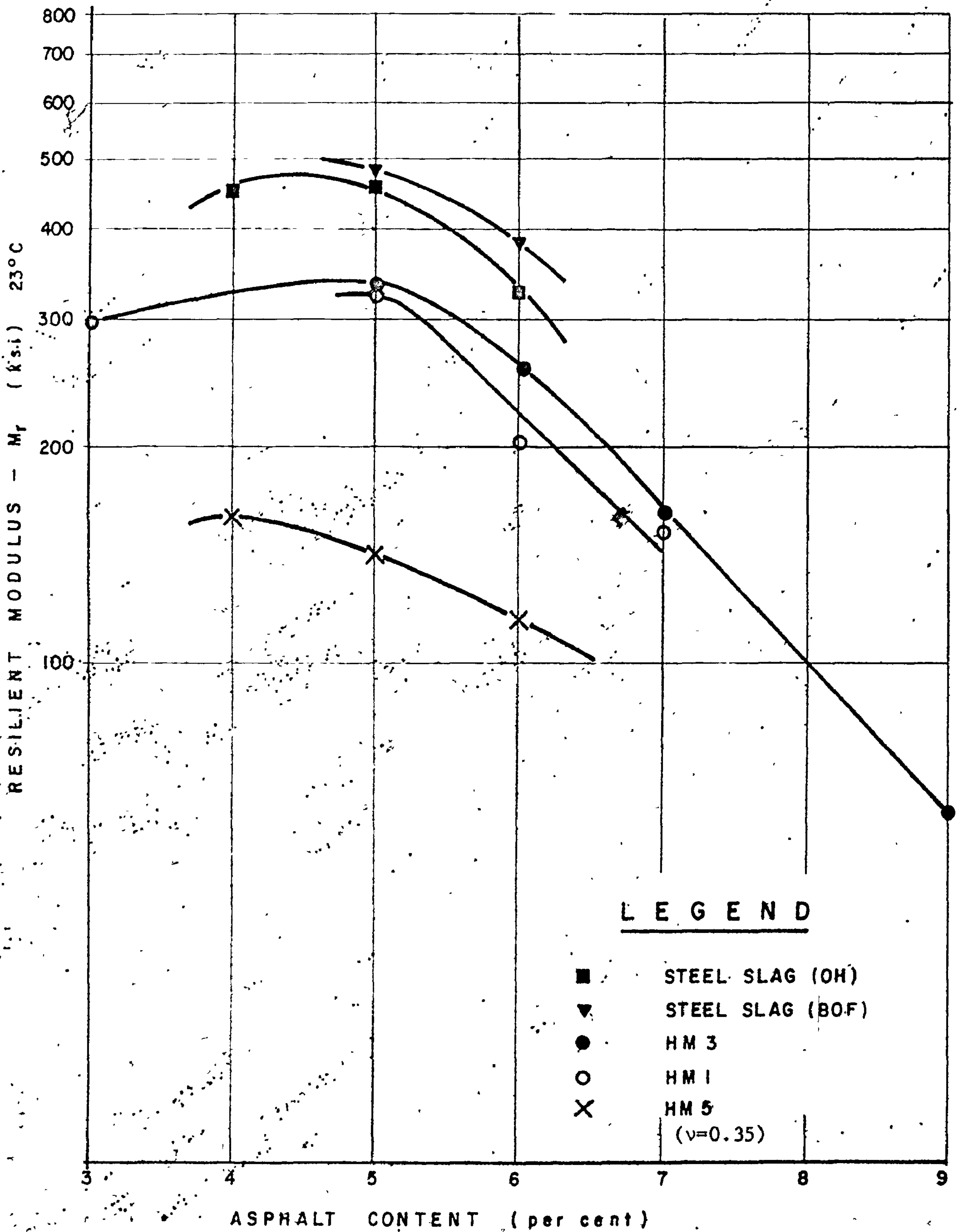


FIG 3.3

INFLUENCE OF ASPHALT CONTENT ON RESILIENT MODULUS OF ASPHALTIC CONCRETE MIXES

Figure 3.3 indicates optimum M_R values in the 4 to 6 per cent range of asphalt cement content. In general, the optimum asphalt cement content values for standard HM type mixes were higher than for the heavier steel slag aggregate specimens. This appears reasonable since material properties are more likely to be controlled by volumetric asphalt cement to aggregate ratios than weight ratios. It is recognized that different levels of absorption by different aggregates will influence this relationship. The recorded M_R values for steel slag specimens are significantly higher than those obtained for the HM type mixes. Test results for HM1 and HM3 indicate similar resilient modulii. The influence of aggregate type on M_R will be further examined in a future phase of this investigation.

Trends reflected in Figure 3.3 are in general agreement with previous research on the dependence of M_R values on asphalt content (11). The highest M_R for each mix type tends to be at a somewhat lower asphalt cement content than that for the corresponding optimum Marshall sability.

3.5 INFLUENCE OF TEMPERATURE ON M_R

Material properties used as input in rational pavement design systems must be generated under conditions that simulate anticipated field conditions. This section discusses the effects of a reasonable range of temperature on the M_R of HM type as well as steel slag mixes. Tests were performed at three discrete temperatures, 0^oC (32^oF), 23^oC (73^oF) and 38^oC (100^oF). The samples were prepared for testing by enclosing them in two individualy sealed plastic bags and placing them in the appropriate temperature controlled environment. A refrigerator and two thermostat controlled water baths were used to provide the required temperature conditions. Samples were conditioned for a minimum of eight hours and testing was started within two minutes after removal from the temperature controlled environment. If set-up times in excess of two minutes were experienced that test was aborted and the sample reconditioned. The results are listed in Table 3.3 and the variations of experimental M_R values for HM3 and steel slag mixes are shown in Figures 3.4 and 3.5. An assumed value for Poisson's ratio of 0.35 was used in the computations, which can influence the results by up to 10 per cent as explained previously.

Results of these tests establishes temperature as the parameter with the greatest influence of resilient modulus. A review of the experimental findings indicates that the stiffness of steel slag and HM3 mixes are affected in a similar manner by changes in temperature. At higher temperatures the relationship between M_R and temperature approaches linearity on a semilog plot. Similar results have been reported by Schmidt [21]. This suggests the possibility of predicting M_R values for different temperatures

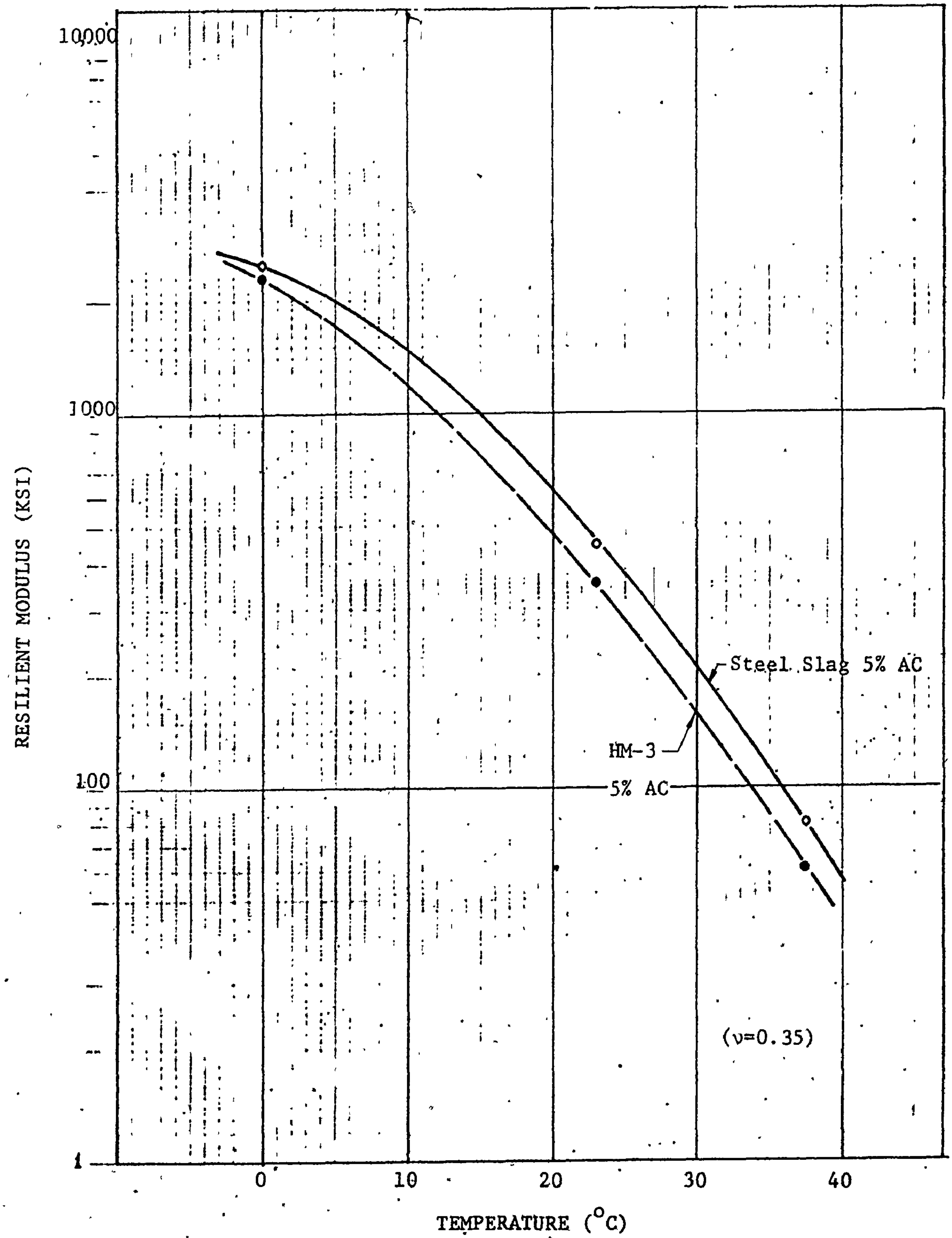


FIGURE 3.4 - M_R vs. Temperature

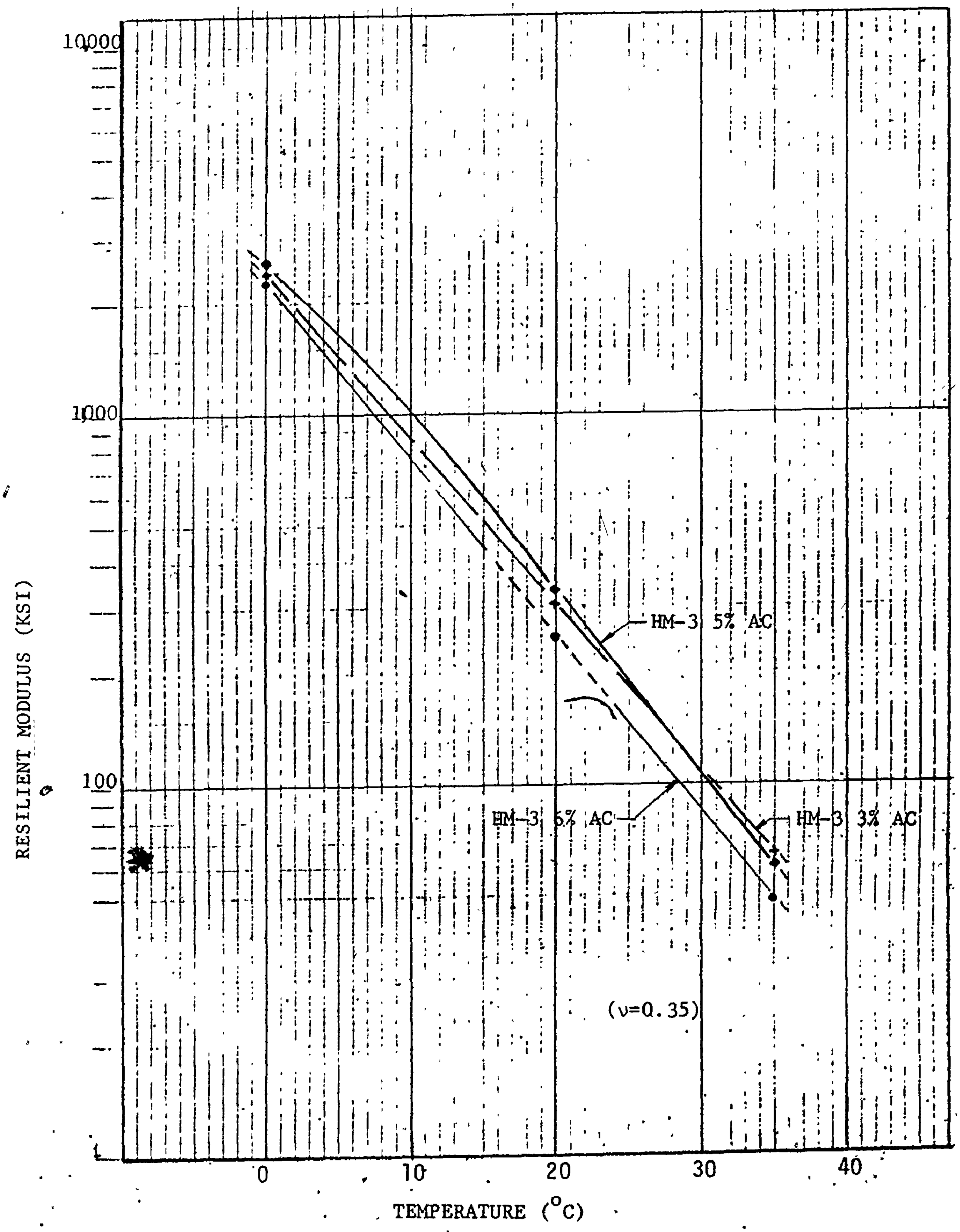


FIGURE 3.5 - M_R vs. Temperature for HM-3 specimens with varying AC.

on the basis of measured values at selected discrete temperatures. However, it is considered that a much wider testing program must be undertaken to establish such a relationship. Figure 3.5 suggests that the stiffness of asphaltic concrete mixes with higher asphalt contents is more susceptible to temperature variation. A comprehensive testing program is planned for a future phase of this investigation to study these apparent trends. Further, the relative susceptibility to temperature changes of asphalt emulsion mixes will be considered.

3.6 CONCLUDING REMARKS

The reliability of the test system was established by comparing generated stiffness values for Lucite samples to those reported earlier[11]. The results of the testing program identify temperature, asphalt content and aggregate type as the key parameters that affect the measured M_R values. Further testing is needed to completely establish these trends.

CHAPTER 4

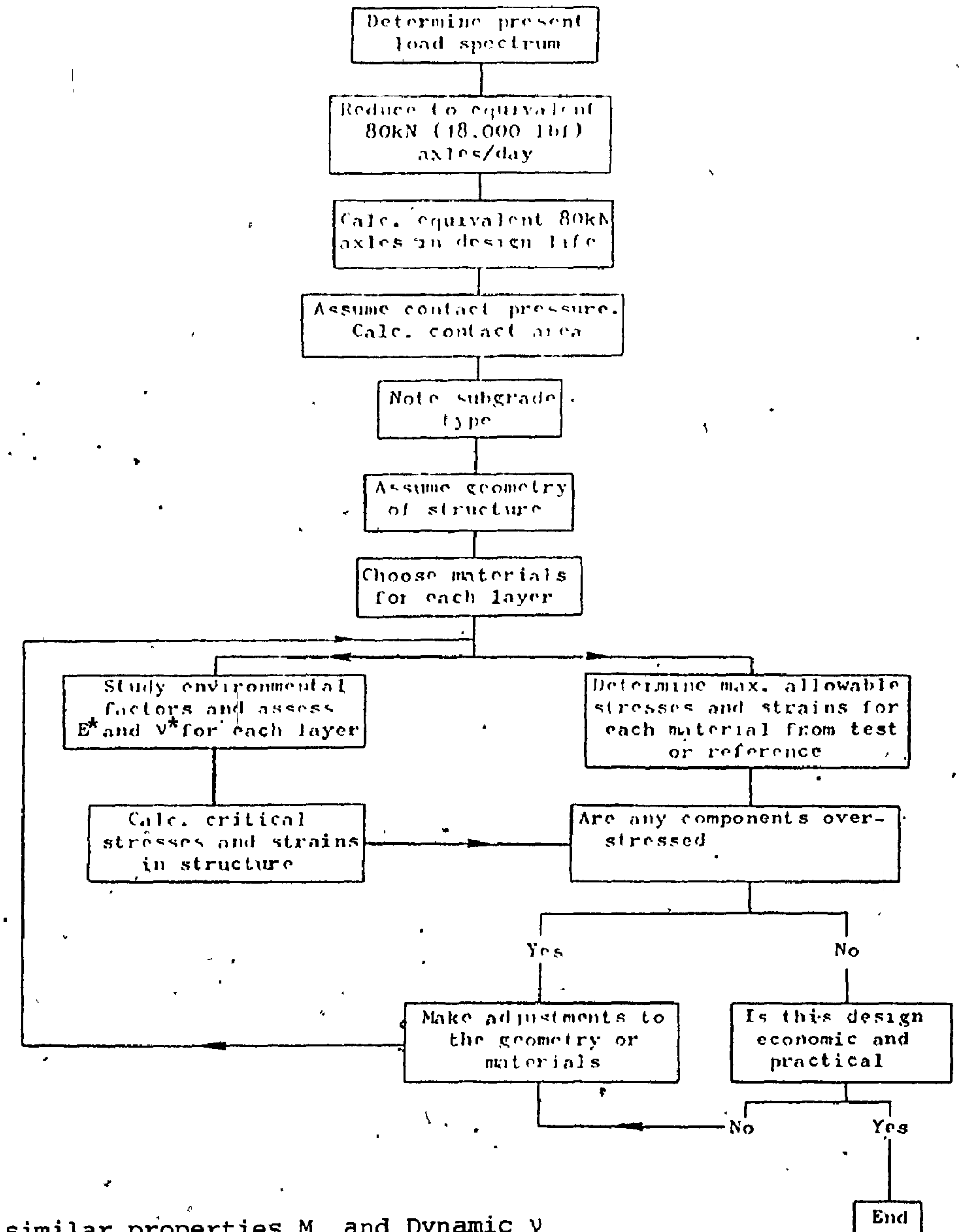
INFLUENCE OF MATERIAL CHARACTERISTICS ON PAVEMENT DESIGNS BY THE RATIONAL METHOD

4. GENERAL

This chapter establishes the importance of the general theme of this study within the rational pavement design framework. A typical design process is outlined, and a comparative study using multi-layer elastic theory is undertaken to determine thickness requirements for asphaltic concrete pavements of varying layer coefficients (elastic properties) under identical loading and subgrade conditions. Input data for the design examples presented are obtained from the experimental findings of this study and results reported by other researchers.

4.1 DESIGN PROCESS

The rational approach to flexible pavement design is based on the use of analytical techniques to determine the response of constituent layers of the pavement system under representative traffic and environmental conditions. Calculated stresses and strains at key points in the system are compared to maximum allowable values to determine the adequacy of the design. It is essentially an iterative procedure where initial estimates of layer thicknesses and materials used are modified until a structurally sound and economic design is produced. Figure 4.1 is a flow diagram which outlines the design process.[22]



* or similar properties M_R and Dynamic ν

FIGURE 4.1: FLOW DIAGRAM FOR RATIONAL STRUCTURAL DESIGN OF FLEXIBLE PAVEMENTS(22)

4.1.1 TRAFFIC AND ENVIRONMENTAL CONSIDERATIONS

The number and magnitude of wheel loads expected in the design life of a pavement are of extreme importance in design. The equivalence factors derived from the AASHO road tests have been extensively used to reduce mixed traffic loadings to an equivalent number of standard 18 kip (80 KN) axle loads. However, use of this technique requires a knowledge of the expected axle load spectum, especially at the heavy end, since these loads have the greatest influence on pavement performance. Typical specta for common road types are available in most developed countries. Hopefully, the utilization of portable axle weight analysers will result in readily available traffic information for most design situations.

Environmental conditions significantly influence the performance of pavement structures. However, it is difficult to incorporate environmental effects into the rational flexible pavement design process. The current strategy is to establish the pertinent layer coefficients for conditions existing when the pavement structure is at its weakest. These conditions are typically identified during field test programs such as the Brampton Road Test[23] undertaken by the Ministry of Transportation and Communications.

4.1.2 ANALYTICAL TECHNIQUES

The available methods for the structural analysis of flexible pavements include elastic, viso-elastic and finite element approaches. It is recognized that asphaltic concretes and unbound soils exhibit non-linear and somewhat time dependent stress-strain characteristics. The more complex visco-elastic theories, and finite element methods of analysis are capable of dealing with situations that cannot be directly considered by linear elastic theory. However, it has been demonstrated that the linear elastic analysis provides adequate solutions for most rational flexible pavement design purposes[22]. Further, the current state of the art does not justify the use of the more sophisticated theories.

The iterative type of approach to problem solving outlined in the rational design process (Figure 4.1) lends itself to solution by computer. A number of programs have been developed for this purpose [6,7]. The BISTRO computer program, a powerful and flexible system, and one which had been adapted for the use of the McMaster CDC 6400 was used in this study. The required input parameters are given in Table 4.1.

TABLE 4.1

REQUIRED INPUT FOR STRUCTURAL ANALYSIS OF FLEXIBLE PAVEMENTS USING THE BISTRO COMPUTER PROGRAM

No.	Detail
1	Number of layers
2	Modulus of Elasticity and Poisson's Ratio (or equivalent) and thickness of each layer
3	Number of circular uniformly distributed loads
4	Contact pressure, radius and co-ordinates of the centre of each load
5	Stresses, strains and deflections required.
6	Number of positions where results are required.
7	Layer number and co-ordinates of each position.

4.1.3. MATERIALS CHARACTERIZATION

Realistic values of the relevant material properties must be generated if the rational approach to flexible pavement design is to be used. Further, test equipment must be inexpensive, and readily available to small materials testing laboratories before general use by all levels of the road building industry can be expected. This research program focussed on the materials characterization aspects of rational design, with particular emphasis on asphaltic concrete mixes. The current state of knowledge, together with research needs and trends have been discussed in Chapter 1.

4.1.4 DESIGN CRITERIA

Critical levels of stress and strain in flexible pavement structures under working conditions have been investigated by various agencies and researchers. The question of interaction between layers is important in this context since a given level of stress or strain, while not being critical to the material in that particular layer, may result in failure at some other point in the structure. With the current state of knowledge, the following criteria were judged suitable for this study:

(1) Tensile strain at the bottom of the lowest asphalt cement bound layer; and

(2) Vertical strain at the top of the subgrade.

Brown and Pell[24] have demonstrated that pavement failure through cracking results if the tensile strain at the bottom of the lowest asphalt cement bound layer is greater than some limiting value. This value is a function of temperature, number of load applications and resilient modulus. The limiting tensile strain criterion used in this study is that developed by Shell Oil Researchers[25].

The importance of the second criterion is indicated by the very purpose of pavement design, i.e., the prevention of excessive deformation of the subgrade under traffic loadings. It is likely that permissible compressive strain in the subgrade is a function of soil stiffness. However, research and associated findings in the fundamentals of soil behaviour have not advanced far enough to allow permissible limits of strain to be established on the basis of soil stiffness alone. Consequently, the Shell Oil design criterion (25) based on correlations between proven CBR designs, results from AASHO road tests, and work by Dormon and Metcalf have been adopted for this study.

4.2 DESIGN EXAMPLE

4.2.1 STATEMENT OF PROBLEM

A theoretical analysis using elastic layer theory was undertaken to compare thickness requirements for pavement structures composed of asphaltic concrete mixes with different material properties. The example outlined is made for a number of simplifications since the purpose is simply to project possible results that can be expected from a more sophisticated analysis. General discussions on the key aspects of the design procedure have been presented in the preceeding sections.

Conditions assumed for design are as follows:

(1) Load Details:

Time pressure: 80 psi (550 KPa)

Radius of loaded area: 4.2 ins. (107 mm)

Centre to centre distance
of adjacent wheels: 12 in (305 mm)

(2) Traffic Details:

Number of Standard 18,000 lb (80 kN)
axle load applications over design life: 10^6

(3) Failure Criteria:

Allowable tensile strain at bottom of lowest asphalt cement-bound layer: 1.45×10^{-4}

Allowable compressive strain at the top of the subgrade: 6.50×10^{-4}

(4) Pavement Layer Thickness and Material Properties:

Pavement No.	Layer	Thickness ins(mm)	M_R ksi(KPa)	ν(assumed)
1	HM3	2.5 (63.5)	250 (1725)	0.35
	HM5	To be determined	150 (1035)	0.35
	Granular	15 (381)	50 (345)	0.30
	Subgrade	N/A	20 (138)	0.43
2	Steel Slag	To be determined	325 (2250)	0.35
	Granular	15 (381)	50 (345)	0.30
	Subgrade	N/A	20 (138)	0.43

As indicated in an earlier section, the allowable strains for design purposes are based on values reported by Shell Oil[25]. Resilient modulus values for the asphaltic concrete layers are estimates from test results conducted at 23°C, and reported in the previous chapter. It is recognized that the weakest condition of the pavement structure occurs at somewhat higher termperatures (~30°C). However, the values used are considered adequate for the purposes of this study. The resilient modulus of the subgrade is based on results from the Brampton Road Test[23] while that for the unbound granular material was computed from the following relationship suggested by Brown and Pell[2]:

$$M_{R_{Granular}} = 2.5\ M_{R_{Subgrade}}$$

4.2.2 RESULTS OF COMPUTERIZED ANALYSIS

The pavement structures, with loading conditions as specified in the preceeding section, were analysed using the BISTRO computer program. Initial estimates of layer thicknesses for steel slag and HM-5 asphaltic concrete were modified until acceptable designs were produced. The results of the analyses are as follows:

TABLE 4.2 RESULTS OF COMPUTERIZED STRESS-STRAIN ANALYSES

Pavement No.	Iteration No.	Layer	Thickness ins (mm)	Maximum Strains			
				Allowable		Computed	
				ε_h *	ε_v +	ε_h *	ε_v +
1	1	HM-3 HM-5 Unbound Granular Subgrade	2.5 (63.5) 2.5 (63.5) 15.0 (381) ∞	1.47×10^{-4}	2.43×10^{-4}	1.45×10^{-4}	6.5×10^{-4}
	2	HM-3 HM-5 Unbound Granular Subgrade	2.5 (63.5) 3.5 (88.9) 15.0 (381) ∞	1.24×10^{-4}	2.20×10^{-4}	1.45×10^{-4}	6.5×10^{-4}
	3	HM-3 HM-5 Unbound Granular Subgrade	2.5 (63.5) 3.0 (76.2) 15.0 (381) ∞	1.35×10^{-4}	2.31×10^{-4}	1.45×10^{-4}	6.5×10^{-4}
2	1	Steel Slag Unbound Granular Subgrade	3.5 (88.9) 15.0 (381) ∞	1.54×10^{-4}	2.74×10^{-4}	1.45×10^{-4}	6.5×10^{-4}
	2	Steel Slag Unbound Granular Subgrade	4.5 (114.3) 15.0 (381) ∞	1.29×10^{-4}	2.58×10^{-4}	1.45×10^{-4}	6.5×10^{-4}
	3	Steel Slag Unbound Granular Subgrade	4.0 (101.6) 15.0 (381) ∞	1.41×10^{-4}	2.43×10^{-4}	1.45×10^{-4}	6.5×10^{-4}

ε_h * - horizontal strain at bottom of lowest asphalt cement bound layer
ε_v + - vertical strain at the top of the subgrade

A review of these results indicates total asphaltic concrete thickness requirements of 5.5 inches (139.7 mm) and 4.0 inches (101.6 mm) for HM type and Steel Slag mixes respectively, to produce satisfactory designs. Although a detailed economic evaluation was not undertaken, the reduction of 1½ inches (38.1 mm) in thickness requirements is likely to result in significant savings. Thus, if pavements are designed on the basis of the rational structural approach, cost economies may be realized if asphaltic concretes with greater strength properties are used. Conventional empirical methods, in contrast, do not allow the better strength characteristics of particular types of asphaltic concretes to be reflected in reduced pavement thicknesses.

CHAPTER 5

CONCLUSIONS AND COMMENTS OF FUTURE WORK

A prototype resilient modulus device based on the diametral method, has been designed, fabricated and subjected to laboratory evaluation. The proven deflection measuring elements used in the resilient modulus system were subsequently incorporated in the development of laboratory equipment for the determination of "dynamic Poisson's ratio". The values of these material properties under operating conditions are of importance in the elastic analysis of flexible pavement systems.

The experimental work identified temperature, asphalt cement content, and aggregate type as variables that significantly influence the resilient modulus of asphaltic concrete mixes. Diametral stress levels may also affect the measured values.

Further research emanating from this initial phase includes:

(1) The study of confining pressure effects on the material properties of concern. This will establish the adequacy of the present unconfined system in routine mix design and construction control programs.

(2) The investigation of "aging" effects by carrying out tests on cores taken from existing pavements. In addition to aiding

the prediction of future behaviour of new pavements, this will permit the evaluation of existing systems and provide design data for possible overlays.

(3) The testing of materials other than asphalt cement - treated specimens (e.g.,lime-stabilized materials and portland cement concrete). In the case of portland cement concrete, one possible application is in the field of computer-based pile driving analyses by the wave equation method, where the determination of E values for concrete piles under driving conditions are of interest.

(4) Refinements to the system which will include improvements to the electronics and provisions to study the effects of various loading patterns.

Much of this work is currently in progress at the Construction Materials Laboratory at McMaster University, under the direction of M. Lee[26] and J. J. Emery.

REFERENCES

1. Highway Research Board, "Review of Existing Theories and Methods of Pavement Design", Hwy. Res. Circular No. 112, October, 1970.

2. Brown, S. F., and K. R. Peattie, "The Structural Design of Bituminous pavements for heavy traffic", Proc. Instn. Civ. Engrs, 1974. 57 (March).

3. Finn, F. N., et al, "Applications of Theory in the Design of Asphalt Pavements", Proc. 3rd. Int. Conf. Struct. Des. Asphalt Pavements, London, 1972.

4. Jung F. W., and W. A. Phang "Elastic Layer Analysis Related to Performance in Flexible Pavement Design" R.R. 191, March, 1974.

5. Finn, F. N., and R. G. Hicks, "Analysis of Results from the Dynamic Measurements Program on the San Diego Test Road", Proc. Ass. Asphalt Paving Technologists 1970, 39.

6. Peutz M.G.F. et al. "Layered Systems under Normal Surface Loads", Highw. Res. Reç. 1968, No. 228.

7. Warren, H. and W. L. Dieckman, "Numerical Computation of Stresses and Strains in a Multiple-Layered Asphalt Pavement System". California Res. Corp., Richmond, California, September, 1963.

8. Jones, A. "Tables of Stresses in Three-Layer Elastic Systems", Highway Research Board Bulletin, 342, 1962.

9. Peattie, K. R. "Stress and Strain Factors for Three-Layer Elastic Systems", Highway Research Board Bulletin, 342,1962.

10. Yoder, E. J., and M. W. Witczak, "Asphalt Mix Stiffness (Shell Nonograph)", Principles of Pavement Design (2nd Ed), John Wiley and Sons, Inc., New York, 1975.

11. Schmidt, R. J. "A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes" H.R.B. Record, No. 404, 1972.

12. Terrel, R. L. and Monismith, "Evaluation of Asphalt-Treated Base Course Material", Proc. ASS. Asphalt Paving Technologists, 1968.

13. Carniero, F.L.L.B and A. Barcellus, "Concrete Tensile Strength", Bulletin No. 13, International Ass. of Testing and Res. Laboratories for Materials and Structures, Paris, March 1953.

14. Akazawa, T. "Tension Test Method for Concrete" Bulletin No. 16, International Ass. of Testing and Res. Laboratories for Materials and Structures Paris, November, 1953.

15. Timoshenko, S. and J. N. Goodier, "Stresses in a Circular Disc" Theory of Elasticity (2nd Ed), McGraw Hill, New York,1951

16. Frocht, M. M. Photoelasticity, Vol. 2, John Wiley and Sons, New York, 1957.

17. Hondros G; "The Evaluation of Poisson's Ratio and The Modulus of Materials of Low Tensile Resistance by the Brazilian (indirect tensile) Test with Particular Reference to Concrete", Australian Journal of Applied Science, Vol. 10, No. 3, September, 1959.

18. The Asphalt Institute, "Mix Design Methods for Asphalt Concrete and other Hot Mix Types" Manual Series No. 2 (MS-2) 4th Ed. March, 1974.

19. Yoder, E. J. "Principles of Pavement Design", John Wiley and Son Inc. New York, 1959.

20. Department of Engineering "Manual on Standard Specifications and Drawings " The Corporation of the City of Hamilton, Hamilton, March, 1971.

21. Schmidt, R. J., "Effect of Temperature, Freeze-Thaw, and Various Moisture Conditions on the Resilient Modulus of Asphalt Treated Mixes," T.R.B. Record No. 515, 1974.

22. Brown S.F. and Pell, P.S. "Fundamental Structural Design Procedure for Flexible Pavements" Proc. 3rd Int. Conf. on the Struc. Des. of Asph. Pavts., London, England, 1972.

23. Hass, R.C.G., et al "Brampton Road Test Road: An Application of Layer Analysis to Pavement Design" M.T.C. Report No. RR182, November, 1972.

24. Pell, P.S. and Brown S.F. "The Characteristics of Materials for the Design of Flexible Pavement Structures", Proc. 3rd Int. Conf. on the Struc. Des. of Asphalt Pavements, London, England, 1972.

25. Izatt et al "The Shell Group Methods for Thickness Design of Asphalt Pavements" Annual Meeting NAPA Puerto Rico, January,1967.

26. Lee, M.A. "Resilient Modulus and Dynamic Poisson's Ratio of Asphaltic Concrete Mixes" M. Eng. Thesis, McMaster University, Hamilton, 1976.

APPENDIX "A"

SET-UP HOLDER

The set-up holder shown below ensures that the cantilever strain gauge beams are centrally located with respect to the specimen. The edges of the floating collar are groved to fit snugly over the holder at a fixed distance above the guide strip at the base of the holder. If samples smaller than the usual 4 inch diameter are used then the guide strip is shimmed until the strain gauge probes are on opposite sides of the horizontal diameter of the specimen. Lateral alignment is achieved by centering the specimen on the base guide strips and matching set-up lines on the floating collar and holder.

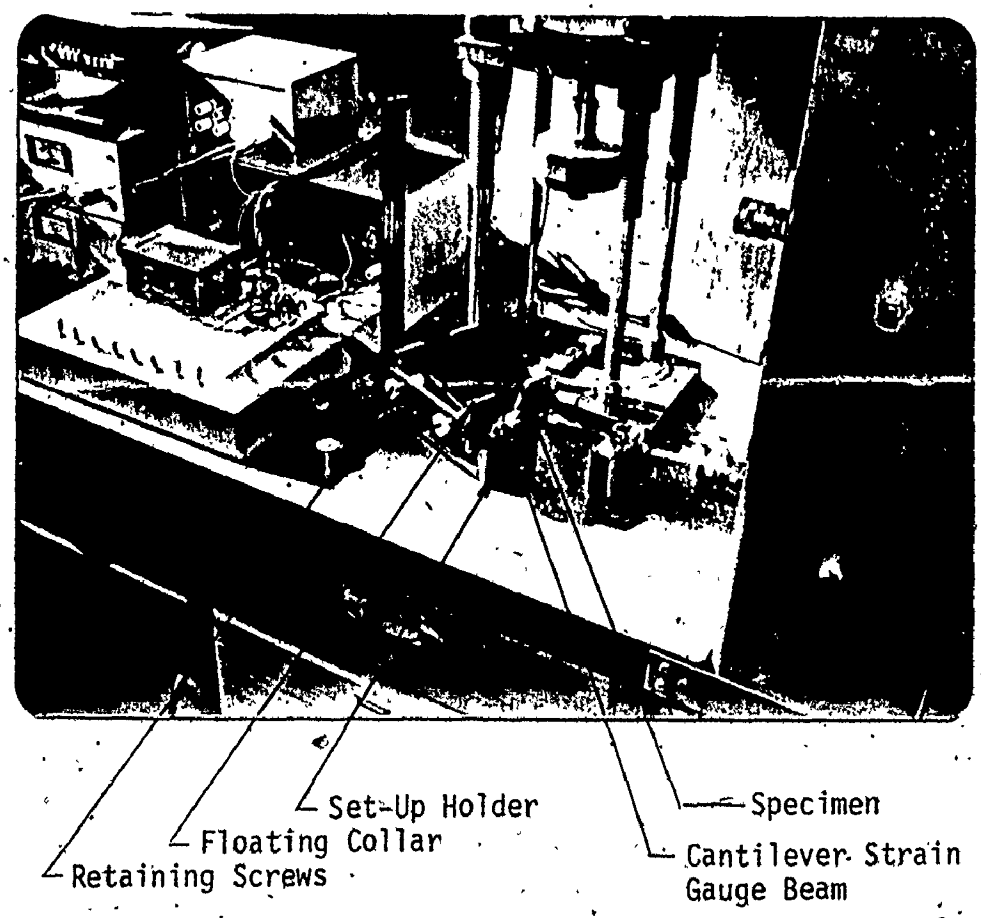


FIGURE A1: SET-UP HOLDER

APPENDIX "B"

SAMPLE PREPARATION AND ASSEMBLY

Laboratory samples for testing are made using the Marshall Method. The Ministry of Transportation and Communications procedures for compacting the Marshall Briquettes were followed during the current study.

Specimens for testing are marked along vertical and horizontal diameters, put into two individually sealed plastic bags and placed into the appropriate temperature controlled environment. A stabilization period of at least 8 hours is allowed before testing.

Prior to testing, the floating collar is placed on the set-up holder and the retaining screws and strain gauge beam probes retracted. The specimen is then quickly removed from plastic bags, placed in the holder, aligned, and fastened to the floating collar by tightening the retaining screws. The specimen and attached floating collar are then transferred to the loading frame, holding only the specimen. The top loading strip is assembled and the alignment verified with the bubble level. The strain gauge probes are rotated inwards until they just touch the specimen, then turned for a further one half rotation. A photograph of the assembed apparatus is shown in Figure B.1.

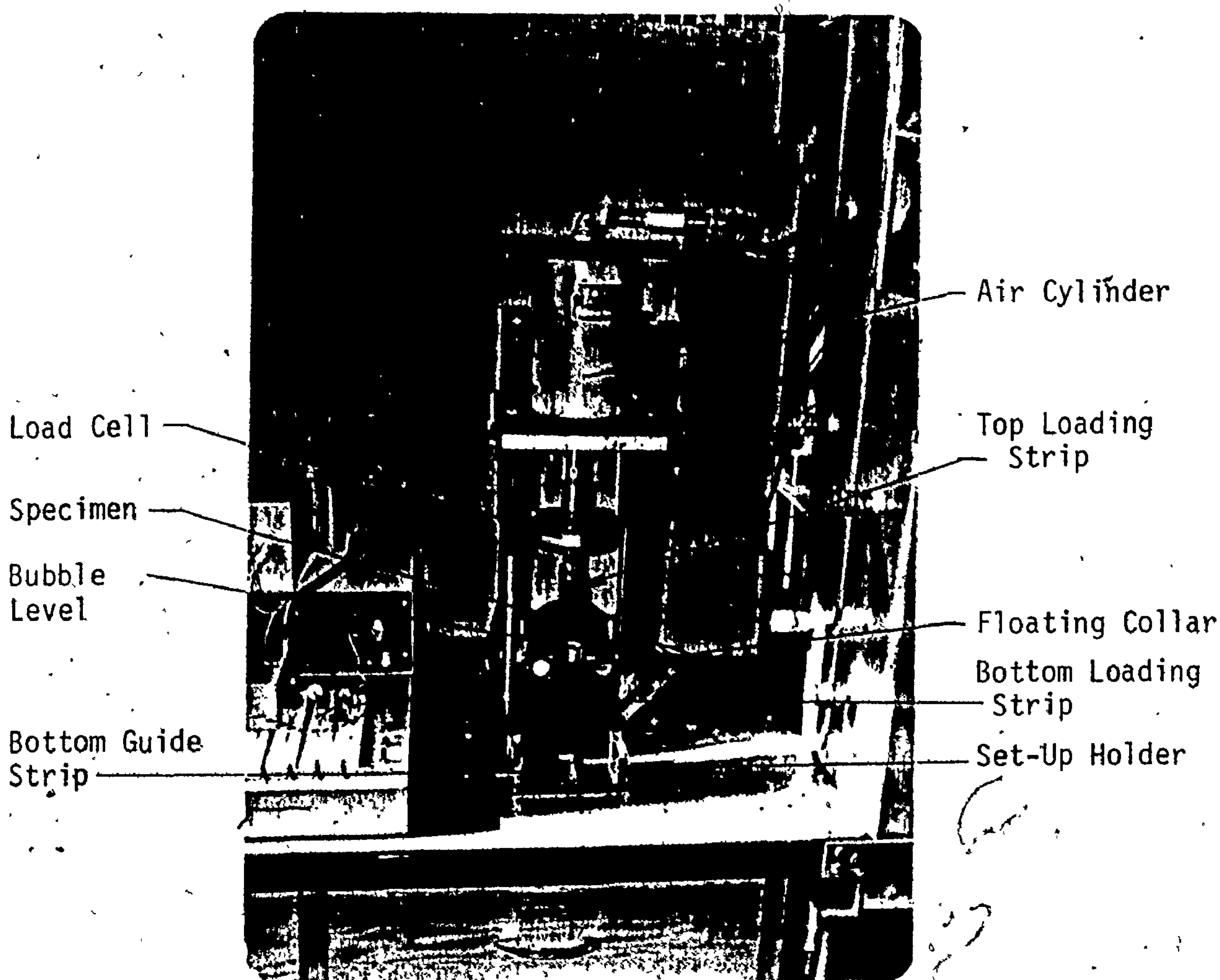


FIGURE B.1: ASSEMBLED SPECIMEN

APPENDIX "C"

PROPERTIES OF ASPHALT CEMENT AND MIXES

ASPHALT CEMENT

Type	:	85/100 Penetration
Ductility at $77^{o}F$ (cm)	:	Min. 100
Flash F (Cleveland Open Cup)	:	500
Penetration, 100g, 5 sec, $77^{o}F$	:	86 - 100
Ductility of Residue @ $77^{o}F$ (cms)	:	75
Retained Penetration @ $77^{o}F$	:	47
Kinematic Viscosity, cSt @ $275^{o}F$	:	300

Results of Marshall tests performed on typical samples of mixes used during the experimental work are shown on the following pages.

PROJECT NAME: M_R Determinations

LOCATION REFERENCE: McMaster University DATE: November, 1975.

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: HM-3 (3% AC)

	Test Values	Requirements
Voids (%)	13.5	2 - 4
Flow (.01")	8.6	7 - 16
Corrected Stability (lb.)	1275	1200 Min.
V.M.A. (%)	19.6	18 Min.
Bulk S.G.	144.3	-
Asphalt content(%)	3.1	-

EXTRACTION

GRADING: % PASSING

SIEVE SIZE	SAMPLE	SPECIFICATION
1-1/2"		
1"		
3/4"		
5/8"		
1/2"		
3/8"	100	100
No. 4 (3/16")	85.7	75 - 100
No. 8	66.3	50 - 80
No. 16	53.1	-
No. 30	34.4	-
No. 50	14.7	5 - 20
No. 100	5.2	-
No. 200	3.7	0 - 5
ASPHALT CONTENT	3.1	-

REMARKS: Poor coating. Mix dry

PROJECT NAME: M_R Determinations

LOCATION REFERENCE: McMaster University DATE: November 1975

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: HM-3 (5%)

	Test Values	Requirements
Voids (%)	7.8	2 - 4
Flow (.01")	10.2	7 - 16
Corrected Stability (lb.)	2215	1200 min.
V.M.A. (%)	19.5	18 min.
Bulk S.G.	150.1	-
Asphalt content(%)	4.9	-

EXTRACTION		
GRADING: % PASSING		
SIEVE SIZE	SAMPLE	SPECIFICATION
1-1/2"		
1"		
3/4"		
5/8"		
1/2"		
3/8"	100	100
No. 4 (3/16")	83.2	75 - 100
No. 8	64.7	50 - 80
No. 16	51.8	-
No. 30	30.7	-
No. 50	11.9	5 - 20
No. 100	5.3	-
No. 200	3.5	0 - 5
ASPHALT CONTENT	4.9	-

REMARKS: Good Coating - Mix Medium

PROJECT NAME: M_R

LOCATION REFERENCE: McMaster University DATE: November 1975

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: HM-3 (6% AC)

	Test Values	Requirements
Voids (%)	3.4	2 - 4
Flow (.01")	10.5	7 - 16
Corrected Stability (lb.)	2710	1200 min.
V.M.A. (%)	17.7	18 min.
Bulk S.G.	149.8	-
Asphalt content(%)	6.0	-

EXTRACTION		
GRADING: % PASSING		
SIEVE SIZE	SAMPLE	SPECIFICATION
1-1/2"		
1"		
3/4"		
5/8"		
1/2"		
3/8"	100	100
No. 4 (3/16")	83.8	75 - 100
No. 8	65.1	50 - 80
No. 16	51.6	-
No. 30	29.8	-
No. 50	12.4	5 - 20
No. 100	5.4	-
No. 200	3.6	0 - 5
ASPHALT CONTENT	6.0	-

REMARKS: Good Coating. Mix medium to rich.

PROJECT NAME: M_R Determinations

LOCATION REFERENCE: McMaster University DATE: November 1975

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: HM-3 (7% AC)

	Test Values	Requirements
Voids (%)	2.4	2 - 4
Flow (.01")	12.6	7 - 16
Corrected Stability (lb.)	1804	1200 min.
V.M.A. (%)	18.7	18 min.
Bulk S.G.	146.9	-
Asphalt content(%)	7.0	-

EXTRACTION		
GRADING: % PASSING		
SIEVE SIZE	SAMPLE	SPECIFICATION
1-1/2"		
1"		
3/4"		
5/8"		
1/2"		
3/8"		
No. 4 (3/16")		
No. 8		
No. 16		
No. 30		
No. 50		
No. 100		
No. 200		
ASPHALT CONTENT		

REMARKS: No Gradation Performed. Similar to HM-3 - 3, 5 & 6 per cent.

PROJECT NAME: M_R Determinations

LOCATION REFERENCE: McMaster University DATE: November, 1975

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: HM-3 (9% AC)

	Test Values	Requirements
Voids (%)	0.8	2 - 4
Flow (.01")	17.2	7 - 16
Corrected Stability (lb.)	581	1200 min.
V.M.A. (%)	21.4	18 min.
Bulk S.G.	144.1	-
Asphalt content(%)	8.9	-

EXTRACTION		
GRADING: % PASSING		
SIEVE SIZE	SAMPLE	SPECIFICATION
1-1/2"		
1"		
3/4"		
5/8"		
1/2"		
3/8"		
No. 4 (3/16")		
No. 8		
No. 16		
No. 30		
No. 50		
No. 100		
No. 200		
ASPHALT CONTENT		

REMARKS: No Gradation Performed on Extracted Material. Similar to other

PROJECT NAME: M_R Determinations

LOCATION REFERENCE: McMaster University DATE: November, 1975

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: HM-1 (6% AC)

	Test Values	Requirements
Voids (%)	3.1	3 - 5
Flow (.01")	12.7	7 - 16
Corrected Stability (lb.)	2423	1200 min.
V.M.A. (%)	17.6	16 min.
Bulk S.G.	149.9	-
Asphalt content(%)	6.1	-

EXTRACTION		
GRADING: % PASSING		
SIEVE SIZE	SAMPLE	SPECIFICATION
1-1/2"		
1"		
3/4"		
5/8"		
1/2"	100	100
3/8"	99	90 - 100
No. 4 (3/16")	78.4	60 - 80
No. 8	62.3	35 - 65
No. 16	52.7	-
No. 30	35.2	-
No. 50	16.8	6 - 25
No. 100	10.2	-
No. 200	7.0	2 - 10
ASPHALT CONTENT	6.1	-

REMARKS: Mix Rich. Similar aggregate compositions were used for all HM-1 [illegible]pe Mixes.

PROJECT NAME: M_R Determinations

LOCATION REFERENCE: McMaster University DATE: November, 1975

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: HM-5 (5% AC)

	Test Values	Requirements
Voids (%)	4.3	3 - 6
Flow (.01")	11.5	7 - 16
Corrected Stability (lb.)	2580	1200 min.
V.M.A. (%)	16.5	14 min.
Bulk S.G.	153.7	-
Asphalt content(%)	5.0	-

EXTRACTION		
GRADING: % PASSING		
SIEVE SIZE	SAMPLE	SPECIFICATION
1-1/2"		
1"	100	100
3/4"	92.1	90 - 100
5/8"	80.9	-
1/2"	65.7	-
3/8"	59.1	60 - 80
No. 4 (3/16")	51.6	35 - 65
No. 8	44.7	20 - 50
No. 16	36.8	-
No. 30	25.9	-
No. 50	13.0	3 - 20
No. 100	2.9	-
No. 200	4.9	2 - 8
ASPHALT CONTENT	5.0	-

REMARKS: Similar aggregate composition used for 4 and 6 per cent AC Mixes.

PROJECT NAME: M_R

LOCATION REFERENCE: McMaster University DATE: November, 1975

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: Steel Slag (OH) 5% AC

	Test Values	Requirements
Voids (%)	3.2	3 - 5
Flow (.01")	19.3	8 - 16
Corrected Stability (lb.)	5350	3500 min.
V.M.A. (%)	18.1	20 min.
Bulk S.G.	188.3	-
Asphalt content(%)	5.0	-

EXTRACTION		
GRADING: % PASSING		
SIEVE SIZE	SAMPLE	SPECIFICATION *
1-1/2"		
1"		
3/4"		
5/8"		
1/2"	98.2	100
3/8"	90.7	98 - 100
No. 4 (3/16")	65.8	75 - 95
No. 8	45.7	55 - 80
No. 16	31.4	35 - 60
No. 30	21.5	20 - 45
No. 50	16.3	10 - 30
No. 100	11.5	5 - 15
No. 200	6.2	0 - 10
ASPHALT CONTENT	5.0	-

REMARKS: * Current City of Hamilton Specifications. Similar Aggregate Compositions were used for 4 and 6 per cent AC Mixes.

PROJECT NAME: M_R Determinations

LOCATION REFERENCE: McMaster University DATE: NOvember, 1975

SUMMARY OF MARSHALL TEST VALUES

TYPE OF MIX: Steel Slag (BOF) 5% AC

	Test Values	Requirements *
Voids (%)	4.5	3 - 5
Flow (.01")	19.1	8 - 16
Corrected Stability (lb.)	5370	3500 min.
V.M.A. (%)	19.2	20 min.
Bulk S.G.	184.7	-
Asphalt content(%)	5.0	-

EXTRACTION

GRADING: % PASSING

SIEVE SIZE	SAMPLE	SPECIFICATION*
1-1/2"		
1"		
3/4"		
5/8"		
1/2"	97.4	100
3/8"	89.9	98 - 100
No. 4 (3/16")	65.8	75 - 95
No. 8	44.8	55 - 80
No. 16	31.4	35 - 60
No. 30	22.8	20 - 45
No. 50	16.6	10 - 30
No. 100	12.0	5 - 15
No. 200	7.9	0 - 10
ASPHALT CONTENT	5.0	-

REMARKS: * Current City of Hamilton Specifications. Similar aggregate