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THE UNIVERSITY OF ALBERTA

EVALUATION OF LOW TEMPERATURE AND PERMANENT DEFORMATION CHARACTERISTICS OF SOME POLYMER MODIFIED ASPHALTS

by

Sajjad Rizwan Hussain ©

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN
THE PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled **Evaluation of Low Temperature and Permanent Deformation Characteristics of Some Polymer Modified Asphalts** by **HUSSAIN, SAJJAD RIZWAN** in the partial fulfillment of the requirements for the degree of Master of Science.

Supervisor

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Date April 24, 1990

Dedicated To

My Parents

Abstract

There is a great deal of interest in the asphalt industry concerning modified asphalts, or now commonly known as engineered asphalts. Research programs conducted at the University of Alberta have involved the evaluation of various types of polymers added to conventional paving grade asphalt cements in order to provide comparative values under high and low temperatures common to Western Canada.

The primary objective of this research was to evaluate the characteristics of conventional and polymer modified asphalts provided by two different suppliers.

Two types of polymer modified asphalt samples and conventional asphalt cements were obtained from different suppliers and tested. Conventional physical tests were carried out to define their rheological properties, and various temperature susceptibility parameters were utilized in evaluating the anticipated performance of these asphalts.

Laboratory evaluation tests have included indirect tensile tests of asphalt concrete mixes at low temperatures ranging from 0 C to -30 C together with repeated load triaxial tests at 25 C, 35 C, and 45 C. Some ofthe polymer modified asphalts tested have been used to construct field trial sections on urban and rural pavements in Alberta.

Observations based on these laboratory tests have shown that polymer modified mixes generally exhibit higher failure stresses, higher failure strains, and lower failure stiffness at low temperatures down to -30 C, when compared with conventional asphalt cements. At higher temperatures of up to 45 C the polymer modified asphalt mixes exhibit considerably less permanent strain. It is expected that these characteristics should enable an asphalt concrete pavement with a polymer modified binder to be more resistant to thermally induced stresses at low temperatures and permanent deformation due to traffic loading at high temperatures.

Acknowledgments

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CHAPTER 1.0

INTRODUCTION

1.1 Background

Low temperature transverse cracking and permanent deformation are very serious and costly pavement distress modes found in many locations with relatively cold climates, especially in Canada and the United States.

At low temperatures, transverse cracking of the pavement occurs when the induced tensile stresses due to thermal contraction exceed the breaking strength of the asphalt concrete mix. At the initial stage, the cracking does not have any significant effect on the pavements, but with time, these cracks open and necessitate premature rehabilitation of the pavements. For over twenty years, ongoing research has been conducted at the University of Alberta, to evaluate the characteristics of laboratory compacted and core specimens at low temperatures.

Permanent deformation is the most common mode of pavement distress; repeated load applications, causing consolidation and lateral movement to occur, result in longitudinal depressions in the wheel paths. The occurrence of permanent deformation is the primary factor influencing the serviceability of the pavements, including riding quality and safety. Low serviceability results in premature rehabilitation of the asphalt concrete pavements. It is therefore very important for engineers to understand the influence of different mix properties on permanent deformation and low temperature transverse cracking, to minimize premature rehabilitation needs.

In order to alleviate the problem of permanent deformation and low temperature transverse cracking, the asphalt industry has shown a great deal of interest concerning engineered or polymer modified asphalts. Recently, various types of polymers have been used as additives to alter the asphalt binder and mix properties, thus improving their performance against both permanent deformation and low temperature transverse cracking.

Because of this interest in polymer modification, a research program was initiated to evaluate various types of polymers added to conventional paving grade asphalt cements in order to provide comparative data under both high and low service temperatures common to Western Canada. In order to predict the performance of the polymer modified asphalts, emphasis was placed on the methods used for evaluation of low and high temperature characteristics of asphalt concrete. Evaluations were conducted on both polymer modified asphalts and comparable conventional asphalt cements.

1.2 Objectives of The Thesis

The primary objectives of this thesis are:

1. To determine the rheological properties and temperature susceptibility of conventional and polymer modified asphalt cements.

2. To evaluate the low temperature performance in the laboratory of conventional and polymer modified asphalt cements.

3. To evaluate and compare the low temperature tensile characteristics of conventional and polymer modified asphalt concrete mixtures, utilizing indirect tensile test method.

4. To evaluate and compare the permanent deformation characteristics of conventional and polymer modified asphalt concrete mixtures, utilizing repeated load triaxial test method.

5. To present practical recommendations for application of asphalt concrete mixtures with conventional and polymer modified asphalts, to minimize low temperature cracking and permanent deformation.

1.3 Research Approach

The research program was divided into two parts, the first being a review of literature discussing asphalt additives used to improve performance of pavements in Canada and, more specifically, Alberta. The second part consisted of laboratory testing of selected conventional and polymer modified asphalts in order to determine their low temperature tensile and permanent deformation characteristics.

1.4 Experimental Program

Samples of conventional and polymer modified asphalts were obtained from Husky Oil Ltd. and Imperial Oil Ltd respectively. Conventional physical tests were conducted on asphalt cement samples to define rheological properties and temperature susceptibility parameters of the binders. These properties were then utilized in evaluating the low temperature characteristics of these asphalt cements.

In addition, the following tests were conducted to evaluate the characteristics of conventional and polymer modified asphalt mixes at both low and high temperatures:

1.4.1 Indirect Tensile Test

Indirect tensile tests were utilized to evaluate the low temperature tensile characteristics of the mixes. Twenty-four specimens, having a nominal height of 64 mm and diameter of

102 mm were fabricated using each asphalt cement, according to the procedure given in Asphalt Institute Manual Series MS-2. A California Kneading Compactor was used. This enabled a replication of six specimens for each test temperature of 0 C, -10 C, -20 C, and -30 C. These tensile properties obtained in these tests were utilized in evaluating the low temperature behavior of these asphalt concrete mixtures.

1.4.2 Repeated Load Triaxial Test

Repeated load triaxial tests method were performed at temperatures of 25 C, 35 C, and 45 C in order to evaluate permanent deformation characteristics of asphalt concrete mixtures at high temperatures. Eighteen cylindrical specimens having 204 mm height and 102 mm diameter, were fabricated from each asphalt cement sample, using the California Kneading Compactor. The resulting data was used in evaluating the high temperature behavior of these asphalt concrete mixtures.

1.5 Organization of The Thesis

The thesis is divided into eight chapters and five appendices.

Chapter 1 presents the background to this research, the objectives of the thesis, and the research approach used.

Chapter 2 presents a literature review of readily available selected asphalt additives, in Canada and the United States.

Chapter 3 describes the use of polymer modified asphalts in several test sections of the rural highway system and three major cities in Alberta.

Chapter 4 describes the problems associated with low temperature cracking of asphalt concrete pavements, and temperature susceptibility parameters of the asphalt cements.

Chapter 5 discusses the experimental program used in this research, including methods of evaluating the component materials in the laboratory. In addition, the results of the physical tests on asphalt cement samples used in this particular research are presented. This chapter also presents expected low temperature characteristics of these asphalt samples by means of Bitumen Test Data Chart (BTDC).

Chapter 6 contains a brief description of the indirect tensile test method. The chapter also presents and discusses the results of these tests, which are used to determine the low temperature tensile characteristics of asphalt concrete specimens prepared with conventional and polymer modified asphalt cements.

Chapter 7 presents the background on permanent deformation and

CHAPTER 2.0

LITERATURE REVIEW ON SELECTED ASPHALT ADDITIVES

2.1 Background

Asphalt has been successfully used without additives in the construction of flexible pavements. Nevertheless, the idea of using additives in asphalt to improve its performance has been around for a long time. With the increase of road transportation, and consequent demands for higher quality roads, the enhancement of road performance is becoming more important. According to Zanzotto et al. (1), the first patent for a polymer modified bituminous material was granted in 1823. Practical application of modified asphalt began in 1901, when the "Societe du Pavage en Asphalt Caoutchoute" was established in France. The first road with rubber modified asphalt was built in Cannes in 1902. The "Rubber Roadway Ltd." Company was established in Great Britain in 1915. Before the Second World War, asphalts were modified with natural rubber; they were reported to have performed well.

After the Second World War, the development of synthetic macromolecular materials, such as plastics and artificial rubbers, provided a great potential for asphalt modification, and testing of many of these new materials began, mainly in Europe, North America and Japan (1). The testing and use of additives remained fairly low until the early 1970's, when the price of asphalt escalated dramatically due to the oil embargo, causing problems in asphalt pavement construction (2). The high cost of asphalt in Europe made it more realistic to consider modification of asphalt. Since this time, great strides have been made in the development of modified asphalts, most notably in France and Austria.

Recently, the paving industry in North America has gradually shifted from high volume new construction to maintenance and resurfacing of the established roadway network (2). Encouraged by the European success with modified asphalts for these applications, several North American institutions and agencies have initiated large scale research programs to investigate asphalt additives. In Canada, in 1979, the Metro Toronto Department of Road and Traffic sponsored an investigation into pavement modification with scrap rubber, which was followed up by a similar project at the University of Toronto, sponsored by the Ontario Ministry of Transportation (3). In the USA, the National Strategic Highway Research Program (SHRP) allotted 10 million dollars in 1986 for research in this area over the next ten years (4). SHRP contract A-400 for 3.0-3.5 million dollars was called for fiscal year 1989. It was proposed to focus research on identifying modifiers which are economical and broadly marketable (5).

Reasons For Using Additives

The characteristics of asphalt cement and asphalt concrete pavement mixes change with temperature. Usually at low service temperatures asphalts become brittle, facilitating cracking of the pavements due to thermal contraction and frost heave. This is a major cause of pavement distress in regions having cold climates. At high service temperatures, the asphalt cement viscosity decreases, and loses most of its elasticity, resulting in excessive rutting (6). With the passage of time the asphalt continues to age, becoming less flexible. Combined with heavy traffic, this can cause ravelling, a gradual degradation of the asphalt surface, resulting in the loss of aggregate with fines. Table II-1 gives the major problems associated with asphalt pavements in Canada as identified by a major user agency group (7).

Epps (4) has stated that, in recent years, these problems have been compounded by: 1) a rise in the price of asphalt, 2) a general belief that asphalts have become more variable and their quality has declined, 3) an apparent higher incidence of reported placement difficulties and excessive permanent displacement under traffic loads, and 4) higher demands placed on pavements now than in the past.

According to Alberta Transportation figures, the price of asphalt cement reached a peak in 1985, of just over $300

TABLE II-1 MAJOR PROBLEMS REPORTED IN CANADA AND THEIR EXTENT (AFTER REF 6) per tonne, over 8 times the price in 1971 (8). The increased price of asphalt makes the high cost of the modifiers, in return for longer pavement life more attractive, but all of these factors have contributed to a general increase in interest in the use of additives with asphalt.

According to Terrel et al. (2), the technical motivation for modifying asphalt was based on two principle concerns of the user agencies, namely: 1) durable maintenance, and 2) pavement strengthening. Haas et al. (7) gives justification for using an additive as being 1) solve pavement problems such as rutting and cracking, and 2) achievement of economic, environmental, energy, and performance benefits.

2.3 Types Of Additives Available

An asphalt cement additive is a material which would normally be added to the asphalt either before, or during, mix production, to improve the properties of the resulting binder or mix. An ideal additive for asphalt cement would have the following characteristics: 1) higher stiffness at high temperatures, to reduce rutting and shoving, 2) lower stiffness at low temperatures, to reduce cracking, 3) lower stiffness at processing temperatures, to expedite spraying, pumping, mixing, and compaction, and 4) improved adhesion of asphalt to aggregate in the presence of water and water vapor to reduce stripping (9). According to Little (10), an additive that will increase mixture stability or reduce rutting will most likely decrease mixture flexibility or increase the probability of cracking. An additive capable of lowering the temperature susceptibility of the binder, or more importantly the mixture, may be expected to control both rutting and cracking. In addition, the ideal additive should also control age hardening and moisture susceptibility of paving mixtures.

Asphalt additives can be divided into the general categories of plastomers, elastomers, metal complexes, extenders, fillers, fibres, and antistrip agents.

Plastomers are polymers (long chain molecules) that exhibit plastic behavior at asphalt pavement service temperatures (1). Plastomers work by introducing a secondary structure to the asphalt, which increases its strength by taking up the load once the asphalt has deformed excessively. Typical examples of plastomers are polyethylene and polypropylene.

Elastomers, also polymers, include 1) pure natural rubber, 2) synthetic rubbers (e.g Styrene-butadiene and neoprene) usually in the form of latex emulsions, and 3) reclaimed rubbers, a blend of natural and synthetic rubbers in a vulcanized form obtained from scrap tires (11). They work in much the same manner as plastomers, with the added benefit that their strength increases with strain, and they have the ability to ability to recover from strain to varying degrees (12). Natural rubbers are thermoplastic; they have linear molecules, which tend not to have sufficient strength for most applications. For this reason natural rubber molecules are often cross-linked, or vulcanized, which makes them stronger but causes them to lose their ability to liquefy at high temperatures (1). Synthetic rubbers are solids (as are vulcanized rubbers) at low temperatures; however, this is caused by vitrification and thus is due to physical, not chemical forces. Therefore, they liquefy and flow at high temperatures.

According to an article in Better Roads (11), metal complexes are chemical compounds consisting of a metal ion linked to an organic compound. They are used mainly as anti-strip and oxidant/antioxidant agents. The commercial product "chemcrete", is a complex of manganese and organic acids which catalyses the oxidation of asphalts causing rapid hardening in the pavement. Extenders are inexpensive substances that are added to the mixtures to replace some of the asphalt, thus reducing the cost of the binder, without sacrificing performance. Sulphur was used as an extender prior to 1970, until the cost of sulphur relative to asphalt increased dramatically.

Fillers add stability to a pavement by helping to fill the voids between the pieces of aggregate. Carbon black fillers consist of 97 percent pure carbon, with flux oil added. Fibres are added to improve the integrity of the asphalt and are used extensively to reduce reflective cracking. Before its health risks became apparent, asbestos fibre was commonly used for asphalt modification. Antistrip agents improve the adhesion between the binder and the aggregate. Lime and portland cement are common antistrip agents, with lime generally considered to be the most effective.

Any additive can have several positive effects on asphalt properties, and any improvement sought can be obtained from one of several additives. When using an additive to lower the temperature susceptibility, a softer than usual asphalt should be used (13). The soft asphalt provides flexibility to the mix, reducing the cracking potential at low temperatures; the additive increases the viscosity at high temperatures to reduce the potential for permanent deformation.

2.4 Additives Used In Canada

In Canada, the study of asphalt cement additives and extenders was initiated in 1981, under a Roads and Transportation Association of Canada research program (14). The major types of additives available and used in Canada (on trial basis, in research studies, or in regular projects) include: antioxidants, antistripping agents, polymers, recycling agents,

2.4.1 Sulphur Modified Asphalt

The addition of elemental sulphur to bituminous mix formulations had received the widest interest of the transportation agencies, due to the existence of a major market for sulphur asphalt and a sharp upward trend in the cost of bitumen binder in the 70's (15). Also, with regards to the physics of elemental sulphur, its incorporation in a continuous phase in bituminous paving mixtures minimizes problems such as thermal shock and creep.

Different approaches have been proposed and used for the incorporation of sulphur in paving mixes. The most promising method is sulphur asphalt, or sulphur-extended asphalt mixtures. The first trial project was constructed in North America, at Port Colborne Ontario in 1974 (16). Two more comprehensive sections were constructed at Blue Ridge and Wind Fall, in Alberta, later that year (17). By the early 1980's, 23 more projects had been constructed in North America, Europe, and the Middle East using the Gulf Canada Limited asphalt process technology (16). Sulphur to asphalt ratio ranges from 30/70 to 40/60.

The results of several studies (Gulf Oil Canada, Shell Canada and Pronk of Calgary) suggest considerable savings attained through the use of sulphur-extended asphalt, as well as increased strength of the finished product. The use of sulphur asphalt binder resulted in major improvements to the properties of mixes made with low quality aggregates (16).

Results from low temperature experiments indicate that the stiffness is significantly affected by the penetration grade of the asphalt used. Therefore, it is the nature of the asphalt cement in sulphur asphalt binder which controls the low temperature cracking potential of the binder. In fact, the ability to use a softer asphalt when using sulphur can substantially improve the low temperature properties of the mix. A number of performance benefits can be achieved by the use of sulphur asphalt: thickness reduction due to increased stiffness, resistance to water, improved resistance to damage from fuel spillage, and use of low quality aggregate.

During the paving seasons of 1979 and 1980, several test sections on different roads in northern British Columbia were paved, using sulphur-extended asphalt. It was found that the presence of sulphur in the binder resulted in increased resistance to compaction and quicker setting up of the exposed surface of the mat (18). A pavement evaluation on a lumber haul road showed rutting in the wheel paths to be less for the sulphur-extended asphalt although sulphur-extended surfaces did not seal as well as surfaces utilizing regular mixes.

Sulphur is beneficial provided it remains in the liquid state during the compaction, but the liquid also produces vapours. In 1964, Shell Canada developed "Thermopave", which enabled the utilization of low quality aggregates (16). The crew exposed to the sulphur-extended asphalt experienced varying degrees of eye, throat, and chest irritation due to the presence of elemental sulphur vapor. Sulphur-extended asphalts are no longer being used as the cost of sulphur, compared to asphalt is no longer economically feasible.

2.4.2 Short Asbestos Fibre

The use of asbestos in connection with materials used in pavement construction is not new (19). Asbestos uniqueness is in the fineness of its ultimate fibre size, which accounts for its high flexibility and allows for microscopic dispersion in the mixture. Another pertinent property of asbestos is its heat stability.

Simulated long-term traffic compaction tests performed at the Asphalt Institute show the ability of asbestos to maintain long-term stability (9). Flexural tests indicated that by controlling the asbestos content, the rigidity of an asphalt pavement is greatly increased under initial loading and at the same time the ability of the pavement to deflect before cracking is improved (19). The addition of short asbestos fibres effectively maintains the structural integrity of the asphalt film exposed at the surface of the pavement for an indefinite period of time. Asbestos has also been used as a mineral filler in asphalt paving mixtures. It reduces the maximum density of the mix, increases the voids in mineral aggregate, increases the asphalt requirement to achieve maximum stability, and reduces the degree of ravelling and wear (20). Despite these advantages, asbestos is no longer used because it has been shown to be carcinogenic.

2.4.3 Rubberized or Latex Modified Asphalt

Styrene-butadiene rubber (SBR) is the type of material which has been most widely used in North America to date, although chlorobutadiene-1 and neoprene have also been used to a lesser degree (21).

Addition of a small quantity of rubber usually produces the following changes in the asphalt: increases high temperature stability, improves low temperature flexibility, improves adhesion of the asphalt to the aggregate, and retards oxidation of the asphalt (21). When rubberized asphalt is used in a surface treatment, it minimizes the pavement tendency to bleed (22), i.e the formation of excessive asphalt on the surface. Better sealing of an existing surface results in correspondingly greater resistance to weathering. There is less loss of aggregate with rubberized asphalts than with conventional asphalts. Due to high surface tension and viscosity, rubberized cut-back asphalts do not set up as fast as conventional cut-backs.

The styrene-butadiene rubber latex finds application in both dense-graded and open-graded mixes. The latex is added to the denser graded mix primarily to reduce rutting and shoving, improve ageing, increase flexibility, and give better adhesion of the asphalt to the aggregate (21). Styrene-butadiene latex modified asphalt has a higher viscosity at high temperatures, which minimizes rutting and bleeding, and higher penetration at low temperatures which contributes to a reduction of cracking (23).

Rubber is used in emulsion crack fillers to give asphalt increased ductility and adhesion, allowing the asphalt to deform with changes in temperature without cracking. It also gives the product the adhesion properties necessary to stick to the walls of the crack (22). Rubber is added to tack coat emulsions to improve the adhesion of the product. These modified emulsions outperform the conventional emulsion tack coats on difficult-to-tack surfaces, such as Portland cement. The special rubbery quality, including greater surface tension and higher viscosity, requires the use of somewhat higher application temperatures than those ordinarily specified for conventional asphalts.

2.5 Polymer Modified Asphalt

The term polymer can be applied to many structures, each of which has its own chemical properties (24). Polymers may be adhesive or non-adhesive, rigid or flexible, depending upon the chemical structure of the molecule. Obviously, many of these are inappropriate for asphalt modification.

According to Zanzotto et al. (1), polymers can be identified according to three principal formulation reactions: 1) polymerization, in which the main molecular chain contains carbon atoms, 2) polycondensation, in which the main molecular chain also contains atoms other than carbon, for example: oxygen, nitrogen, and sulphur, and 3) polyaddition. Different types of polymers have been discussed previously under types of additives. In order to classify the various polymer modified materials used for the hot mixes, Figures II-1 to II-3 are presented. An attempt is made to relate the generic names to the several commercial products available and their anticipated performance.

2.6 Expected Improvements of Asphalt Properties

Improvements in the physical properties of binders and paving mixes produced by the addition of polymers, include the following: 1) increased adhesion and cohesion, 2) improved resistance to fatigue, 3) improved temperature sus-

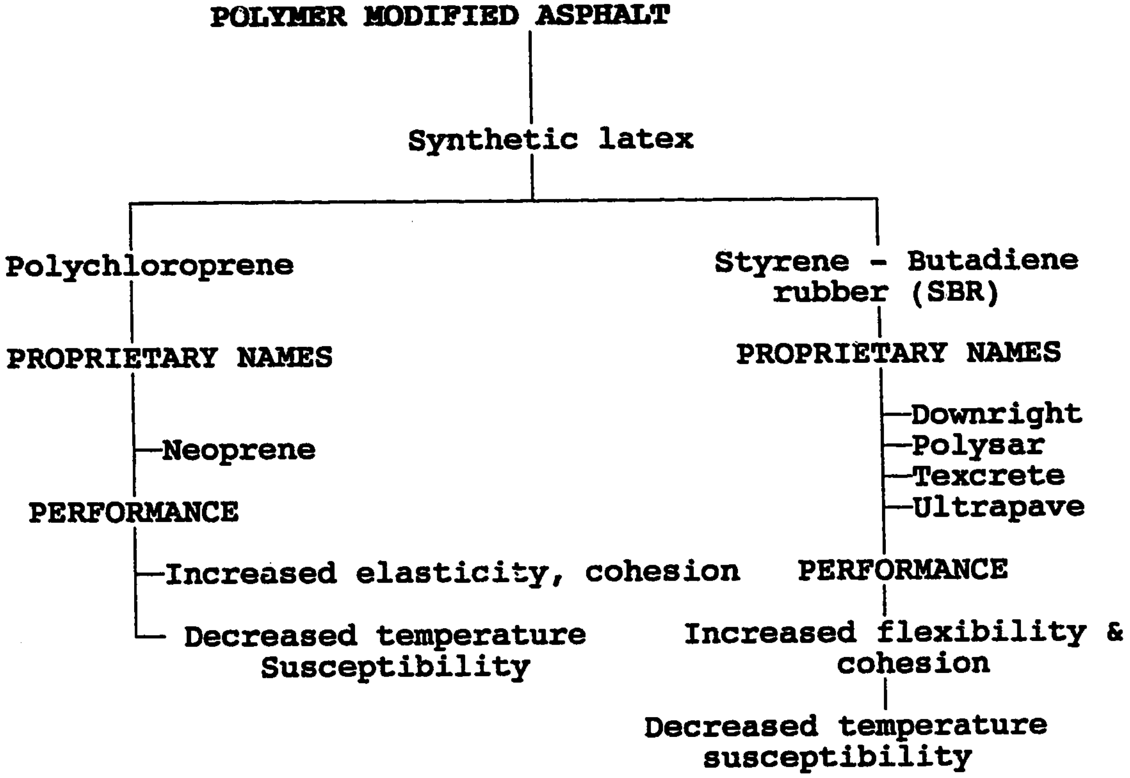

FIGURE II-1 SUMMARY OF THE CHARACTERISTICS OF ASPHALT MODIFIED WITH SYNTHETIC LATEX

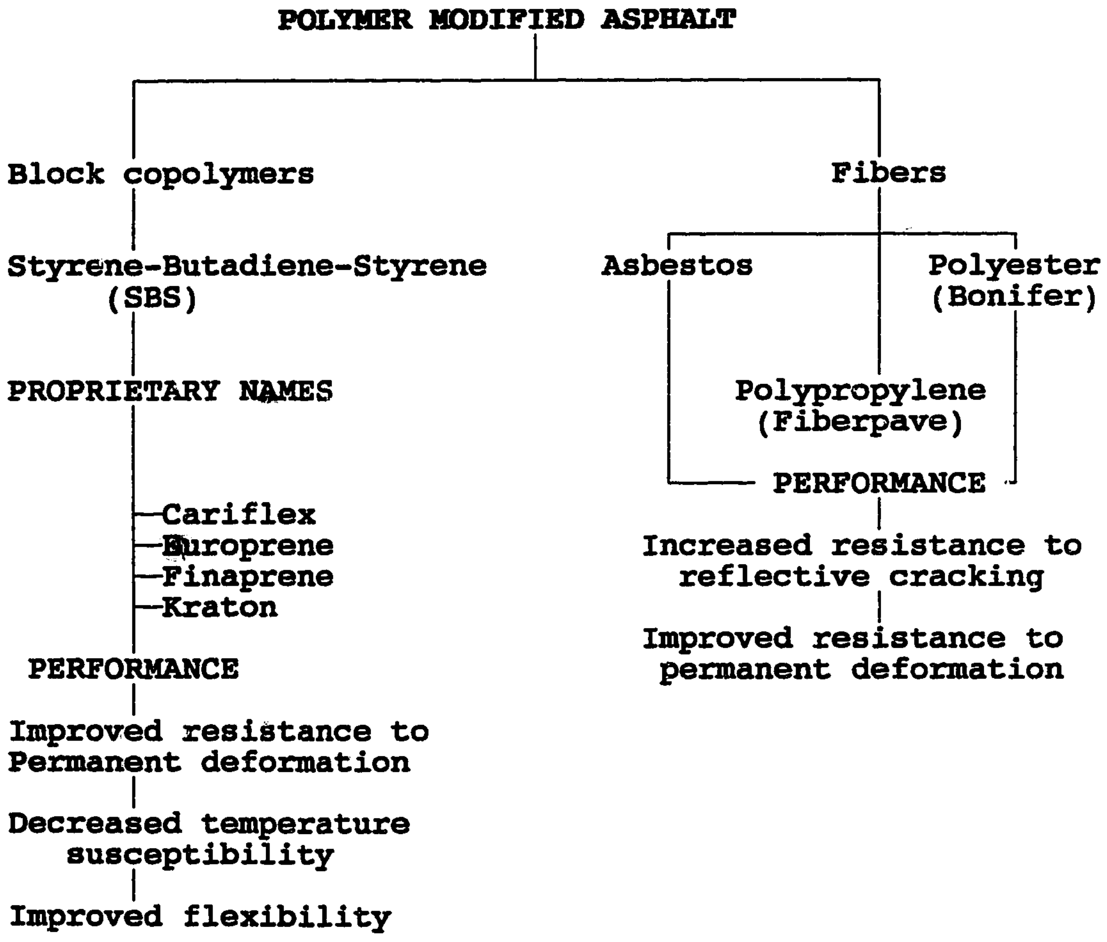

FIGURE II-2 SUMMARY OF CHARACTERISTICS OF ASPHALT MODIFIED WITH BLOCK COPOLYMERS & FIBERS

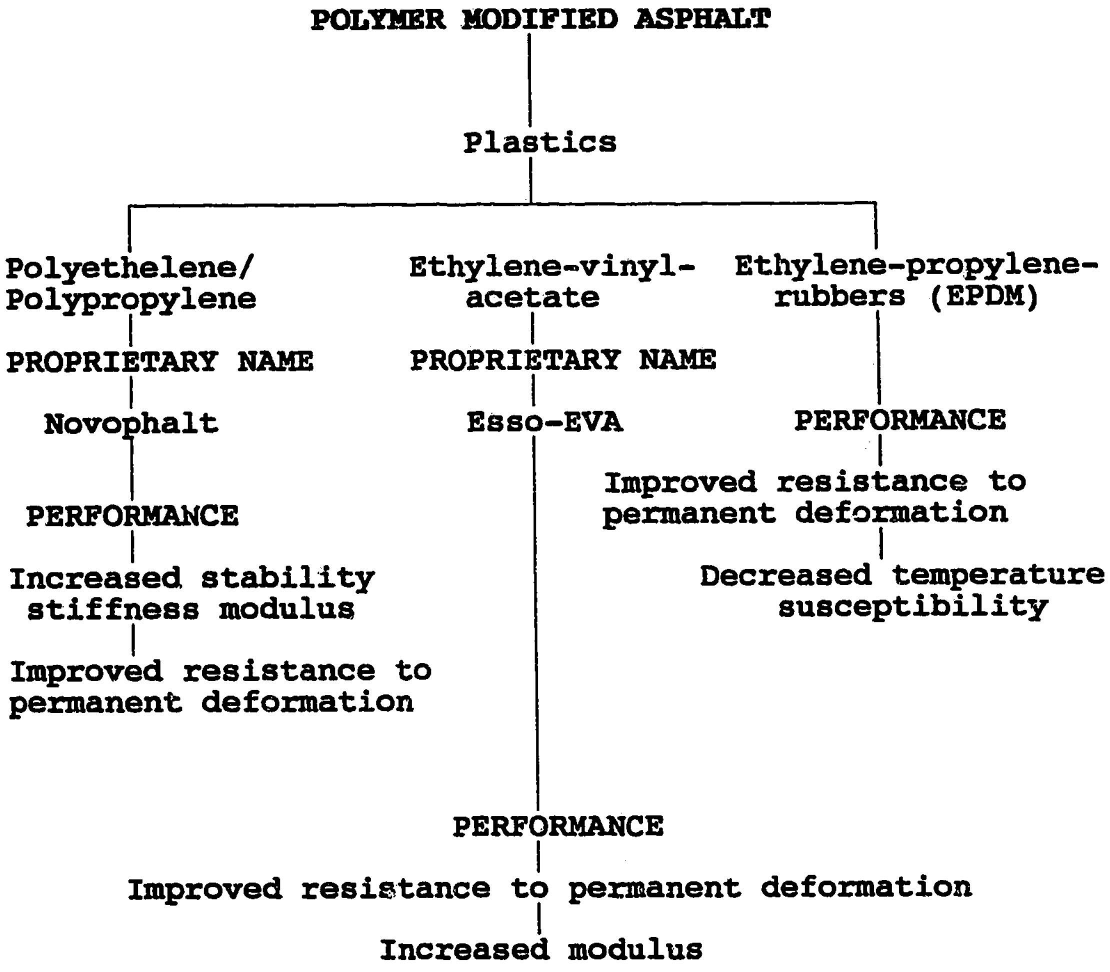

FIGURE II.3 SUMMARY OF CHARACTERISTICS OF ASPHALT MODIFIED WITH PLASTICS

ceptibility which is the rate at which the consistency of an asphalt cement changes with the temperature, 4) increased modulus, 5) increased resistance to rutting, and 6) increased durability (24). Other improvements include: improved elastic creep response, and increased wet mix strength (3), as well as increased stability, and the capability for placement in a very thin lift (1).

The addition of carbon black lowers the temperature susceptibility of asphalt pavements, by increasing the ability of the mix to resist deformation at high temperatures, while leaving the low temperature response unaffected (25). It has been shown to increase the fatigue life of the pavements in both hot and cold climates. The increased resistance to abrasion, increased protection from ultra violet radiation, and inhibition of oxidation are other claimed benefits (10) of carbon black addition. Extensive field trials in the USA indicate that although performance is satisfactory, high costs make the use of carbon black justifiable only in situations where very high stabilities are required (4).

In maintenance and repair situations, modified binders are more versatile than conventional binders. Zanzotto has reported that, in fine surface mix, the actual asphaltic cement content can be reduced by 1 percent (1) thus reducing the increased cost of binder. When high quality construction methods and aggregates are used with modified asphalts, longer service life can be achieved, further reducing the costs (2).

The experiences gained by constructing test sections has indicated that with most additives, standard mixing and compacting methods and temperatures are acceptable (1,5). The increase in the viscosity of polyethylene-modified asphalts indicates that longer mixing times and/or increased temperatures are required (3).

Laboratory test results on asphalts containing fibres (10) indicate that they provide increased resistance to reflective cracking. This has been confirmed by field tests in Vermont USA where the use of Fibrepave polyethylene fibres resulted in only 9 percent reflective cracking compared to 31 percent in control sections.

2.7 How Polymers Work

According to Zanzotto et al. (1), to achieve the goal of improving asphalt properties the polymer must create a secondary network in the asphalt in order to serve as an asphalt reinforcement. To achieve this purpose the polymer must create a fine dispersion in asphalt. The polymer concentration in the asphalt is 7 to 10 percent. These quantities are considered high for the modification of road asphalts, where the quantities of the polymer range between 3 to 6 percent.

Plastomers are polymers that express plastic behavior marked by irreversible deformation under load. They generally increase the cohesion properties, but contribute less to the modification of asphalt temperature susceptibility, at both low and high temperatures. They are added in higher quantities and they contribute significantly to increase in asphalt viscosity, consequently requiring higher temperatures for mixing and compaction. Their compatibility with asphalt is often poor.

Elastomers generally contribute more to the modification of asphalt temperature susceptibility, at both low and high temperatures; in addition, elastomers increase elasticity, and improve resistance to fatigue.

A recently developed speciality elastromer is the styrene-butadiene-styrene block copolymers. These exist in two separate phases at typical service temperatures. The three-dimensional network consists of hard spherical polystyrene domains in a rubbery matrix (6). The polystyrene domains act as physical crosslinks, which give strength to the system, with the rubbery network imparting elastic properties to the binder at lower service temperatures.

2.8 How Polymers Are Incorporated

There are three options available to incorporate polymers into asphalts:

In the first option, the modified asphalts may be prepared by auxiliary equipment at the site of the asphalt plant. Additional equipment and qualified personnel are required to service equipment for on-site incorporation.

A second option is through injection of latexes, directly into the mixing drum. This requires asphalt plant modification; extreme care must be taken in spraying the latex evenly into the asphalt mix. Intimate dispersion of polymers with asphalt binder can be extremely difficult.

The third option used is premanufactured polymer modified asphalt; no asphalt plant modifications are necessary. Many major asphalt suppliers are actively involved in research and production of premanufactured polymer modified asphalts. This method allows optimum conditions for modified asphalt production, with a high level of control. The manufacturer guarantees the constant quality of the product.

One very critical parameter, which is vital to any of the above methods used to incorporate polymers, is that of compatibility. Moran (26) defined compatibility to include mixtures which are thermodynamically immiscible but, because the phases resist complete separation the blended components form a stable continuous phase relative to each other.

The best performance of polymer modified asphalts during the service life of the pavements can be achieved when there is a fine dispersion of the polymer in asphalt. Moran (26) concluded that it is essential to achieve good dispersion stability in order to guarantee adequate high temperature storage stability. Adequate polymer dispersion and a polymer network structure in the asphalt are essential to obtain high-performance asphalts. The key to maintaining optimum long term performance is compatibility between the polymers and the asphalt. Incompatibility can lead to early failure during service due to premature ageing and loss in consistency properties.

2.9 Physical Properties of Polymer Modified Asphalt

Generally, the addition of polymers results in lower penetration, higher absolute viscosity, increased ring-and-ball softening point, increased low temperature ductility which reflects greater elasticity, improved age hardening characteristics, and higher penetration viscosity number (1). The physical properties of the two polymer modified asphalts used for this research shall be discussed in detail in Chapter 6.

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CHAPTER 3.0

USE OF POLYMER MODIFIED ASPHALT IN ALBERTA

3.1 Introduction

Several test sections have been constructed, by Alberta Transportation and Utilities, on rural highways in Alberta using different polymer modified asphalts. Also, many trial sections have been constructed on urban highways, in several cities of Alberta, using polymer modified asphalts. This chapter briefly discusses the test sections constructed on rural and urban roadways of Alberta, using different polymer modified asphalts.

3.2 Test Sections Constructed on Rural Highways in Alberta Using Polymer Modified Asphalt

In 1986, Imperial Oil Ltd. and Husky Oil Ltd. requested Alberta Transportation and Utilities to construct short test sections using their polymer modified asphalts (1). The Husky polymer modified asphalt was said to be significantly less temperature susceptible than the current "A" asphalt grades used in the Province of Alberta (2) which should result in less pavement rutting at high temperatures and transverse cracking at low temperatures. Figure III-1 shows the current specifications of Alberta Transportation and Utilities. Because of stability problems the polymer

FIGURE III-1 ALBERTA TRANSPORTATION SPECIFICATIONS

(AFTER REF 2)

modified asphalt supplied by Husky Oil Ltd. required it to be delivered in a specially equipped tanker with hydraulically driven impellers to provide constant agitation. Recommended mixing and compaction temperatures for these asphalts were 165 C and 145 C respectively.

The Imperial product, referred to as Esso Engineered Bitumen or EB, was reportedly able to offer increased resistance to high temperature pavement rutting. No claims were made for superior low temperature performance. However, Imperial Oil Ltd. indicated its performance to be at least as good as that of "A" grade asphalts (1). No special handling was required, as the modified polymer was considered to be compatible with their base asphalt and thus would not settle out. Imperial polymer modified asphalt has the ability to be successfully placed under colder weather conditions than those necessary when placing conventional asphalts.

Both companies indicated that, by using their specific polymers and formulations with their base asphalts, different polymer modified asphalt products could be produced that would meet specific performance and economic requirements. It has been reported that Imperial Oil Ltd. designed their product to resist high service pavement rutting, while Husky Oil Ltd. put additional emphasis on the control of low temperature induced transverse and reflective cracking (1).

In 1986, Alberta Transportation and Utilities constructed two test sections using Imperial Oil Ltd. samples and one using a Husky Oil Ltd. sample (1). The test sections selected were as follows:

Highway 41:20

Highway 41:20 north of Vermillion from Junction Secondary road 631 to the Junction Highway 45 W, was selected as the best available project due to its proximity to the Husky Lloydminister refinery and moderately high truck traffic. The pavement structure consisted of a 50 mm asphalt stabilized base course on top of 180 mm soil cement, both layers constructed in 1983. In 1986, an overlay of 50 mm asphalt cement pavements (ACP) was placed on top of 150 mm recycled asphalt pavements (RACP). The Husky polymer modified asphalt mix was placed on the top lift of this 50 mm ACP overlay.

Highway 16:02

Highway 16:02, from the Junction of Highway 40 N to West of Switzer Drive in Hinton, was one of the two selected for the Imperial Oil polymer modified asphalt. It consisted of 130 mm new ACP construction on top of 300 mm of granular base. The polymer modified asphalt mix was placed on the top of this 130mm ACP.

Highway 2:36

Highway 2:36 was selected as the second project for the use of the Imperial Oil polymer modified asphalt. The test section was located from the north of Junction 37 to the north of Junction Secondary Road 642, near Mournville. This project was constructed with 130 mm ACP on top of a 300 mm granular base.

Both polymer modified asphalt products exhibited higher viscosities than conventional asphalts of the same penetration range. All polymer modified asphalt sections exhibited a certain degree of tenderness, which was not apparent with conventional asphalt concrete pavements. Husky polymer modified asphalt was less temperature susceptible than current "A" asphalt grades, offering increased resistance to high temperature pavement rutting and low temperature transverse cracking. Esso Engineered Bitumen offered increased resistance to high temperature pavement rutting.

In 1987, two additional test sections were constructed by Alberta Transportation and Utilities (3). The test sections were as follows:

Highway 2:16

The project limits for Highway 2:16 are the northbound lanes from Calgary's north entry limits at km 12.681 to north of Airdrie at km 10.00 (2:18). This is a 6 lane divided highway with an average annual daily traffic of 20 500 vehicles. This highway was chosen for its high traffic volume. The pavement structure for highway 2:16 is 250 mm cement stabilized base placed in 1971, 50 mm asphalt cement stabilized base placed in 1971, and 100 mm ACP placed in 1972. Husky polymer modified asphalt mix was placed on top of the existing surface.

Highway 2:18

This test section location includes outer lane and shoulder, from approximately km 3.5 to km 5.9 of Highway 2:18. This section was chosen because it had a tangential alignment on a level grade. Also, it was located away from major intersections and interchanges as not to be greatly affected by the acceleration and deceleration of truck traffic. The pavement structure for highway 2:18 is 250 mm cement stabilized base placed in 1970, 50 mm asphalt stabilized base course placed in 1970, and 100 mm ACP placed in 1971. Husky polymer modified asphalt was used at this test section.

In August 1989, Alberta Transportation and Utilities constructed a test section on the southbound lane of Secondary Highway 794 from the Junction of Highway 16X to north of Alcomdale, using Imperial polymer modified asphalt. This newly constructed test section formed the basis for the experimental program for the evaluation of Imperial polymer modified asphalt in the laboratory.

3.3 Test Sections Constructed on Urban Highways in Alberta Using Polymer Modified Asphalt

Several trial sections have been constructed on the urban roadways by three cities in Alberta, using different polymer modified asphalts. The different test sections constructed are as follows:

3.3.1 City of Edmonton

Figure III-2 shows various project sites involving modified asphalts within the City of Edmonton. In 1981, sulphur-extended asphalt was used on Victoria Trail. No significant problems were encountered during construction (1). However, the sulphur-extended asphalt pavement was found to crack more readily than conventional mix pavements. No clear structural difference between conventional pavements and sulphur-extended asphalt pavements was observed, but conventional pavements showed a greater degree of deformation as compared to the sulphur-extended asphalt pavements.

Beginning in 1986, several polymer modified asphalt concrete pavements have been placed in various locations throughout the city. Products from Esso Resources were placed in three separate locations. Two other locations utilized using Husky Oil Ltd. polymer modified asphalt and "Novophalt" products respectively (4). Three of these test sections were placed during summer of 1987 and hence, long term performance data

FIGTURE III-2 VARIOUS PMA TEST SECTIONS IN EDMONTON

(AFTER REF 1)

are not yet available. The test sections are presently being monitored by the City, and hopefully the results will be documented in the near future.

3.3.2 City of Calgary

Until the mid-1980's, surface overlay materials in Calgary incorporated asbestos fibres. For about a decade, these asphalt mixes proved to be cost-effective materials for surface course construction. However, due to concern for the environment and for occupational health, use of asbestos was stopped and an alternative material had to be found (5). While such an ideal material was being sought variety of surface overlays have been tested. These included asphalts modified with latex, teralite, diatomaceous earth, and several polymers. Field test sections using these materials began in 1984 and are being constructed to present. In 1986, Esso EB-304 polymer modified asphalt was placed on 16th Avenue S.E., from 28 Street to 44 Street S.E. The Esso polymer modified mixture was placed at a lower temperature than the conventional asphalt mixes. Thin overlay mixes, using three grades of Husky/Nova PMA 272, PMA 285 and PMA 285A, were placed at different locations in the City. A 32 mm mix of Husky's polymer modified asphalt cement (PMA 2), and 19 mm surface overlay was placed in an existing intersection using the local aggregate available.

3.3.3 City of Lethbridge

In the late 1980's, the City of Lethbridge was experiencing problems with premature rutting on their roads. The rutting was mainly occurring on high traffic volume roads, especially at the intersections (6).

In 1987, EBA Engineering Consultants Ltd. began an extensive field and laboratory test program. They concluded that the rutting had occurred primarily in the asphalt concrete layer and that there was no measurable structural or wear rutting. This led to the conclusion that the problem were caused by use of an unstable mix. They recommended that test sections be built in problem locations to verify the superior laboratory performance of the different mixes in the field. The test sections were constructed during the summer of 1988. Four of these test sections were constructed using Husky polymer modified asphalt PMA 2 and another four with PMA 4. Figure III-2 shows the location of different test sections. According to the EBA report, the mixes used at different test sections were as follows:

FIGURE III-3 VARIOUS POLYMER MODIFIED ASPHALT
TEST SECTIONS IN LETHBRIDGE
(AFTER REF 7)

Mix "CODE	BINDER TYPE	AGGREGATE
A	150/200	Conventional 125 mm
B	150/200	Modified 16 mm
C	PMA 2	Modified 16 mm
D	PMA 4	Modified 16 mm+30% RAP
E	200/300	Modified 16 mm+30% RAP

In an effort to monitor the performance of different mixes, a precise level survey was performed to determine the exact cross-section of each test section prior to their opening to traffic. The elevation was determined at 75 mm intervals along a marked section. This levelling was repeated at regular intervals to determine whether any rutting had developed. Table III.1 shows the summary of the rut depth data during the late summer of 1988 precise level survey (7). Comparing the field performance of Mix B and Mix C, it is observed that rutting was higher in the case of Mix C (PMA 2), at only two locations: 13 St. and 3 Ave.S. In all other sections there was excessive rutting on the sections which were constructed using Mix B, demonstrating that PMA 2 is performing better than 150/200.

TABLE III-1 RESULTS OF PRECISE LEVEL SURVEY (AFTER REF 7)

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CHAPTER 4.0

LOW TEMPERATURE CRACKING AND TEMPERATURE SUSCEPTIBILITY OF ASPHALT CONCRETE PAVEMENTS

4.1 Introduction

Low temperature cracking of asphalt concrete pavements in cold climate regions is a very serious problem. In Canada and the United States, where low temperatures are frequently experienced, asphalt pavement cracking is very common. It is also known as non-load associated cracking, shrinkage cracking, or thermal cracking. Deme and Palsat (1) report that a 1965 survey of 502 km of highways in Manitoba revealed that for two-thirds of their length, the spacing between transverse cracks ranged from three to nine meters. Results of a 1968 survey of 3160 km of Alberta primary highways showed an average transverse crack spacing of 21 m. In a survey of 1985 by Palsat (2), 600 km of asphalt concrete pavements on about 60 projects constructed in Alberta between 1974 and 1979, transverse cracking frequencies were reduced to between 0 to 5 transverse cracks/km. This improved performance could be associated with the changes in asphalt specifications introduced in 1967.

Low temperature cracking of asphalt concrete pavements is primarily caused by low winter temperatures. Although the initial occurrence of fine transverse cracks has little effect on pavement performance, these cracks widen with time. Surface water intrudes into the pavement and underlying materials, generally resulting in heaving or depression of the pavement surface adjacent to the cracks. There may be spalling of the asphalt concrete at the cracks which may lead to the development of potholes. This reduces the riding quality and pavement life, resulting in an increased user cost. Additionally, considerable maintenance is required due to the rapid deterioration of riding quality; this results in a need for resurfacing before the normal design life of the pavements.

Several factors such as climate, subgrade type, grade of asphalt cement, mix properties, pavement age, and traffic effects, are known to influence the rate of formation and extent of low temperature cracking.

This chapter discusses the mechanism of low temperature cracking, factors affecting pavement cracking, and temperature susceptibility of asphalt cements.

4.2 Low Temperature Cracking Mechanisms

Low temperatures induce tensile stresses in the pavement materials due to contraction in a longitudinally restrained pavement. When tensile stresses exceed the tensile strength of the material, transverse cracks occur. Due to cyclic effects, there is a gradual increase in the size of crack openings.

Several mechanisms for low temperature cracking have been suggested (3,4,5,6,7,8,9) including:

1. Stresses which are induced by the pavement's thermal shrinkage results in surface cracking, which propagates through the asphalt concrete layer. The cracking may be initiated by sudden thermal shock or low temperature cycling.

2. Stresses in the non-asphalt-treated base layer can cause transverse cracks which ultimately reflect through to the surface.

3. Transverse shrinkage cracks in the subgrade propagate through the pavement structure by differential movement, to be reflected through to the pavement surface.

4. Non-uniformities can cause differential frost-heaving of the subgrade, resulting in pavement surface cracking.

Among these cracking mechanisms only the first is directly associated with the pavement binder and mix components, hence it is the primary concern of this study.

4.3 Factors Affecting Low Temperature Cracking

Many factors affect the low temperature performance of asphalt pavements. The major factors identified in the literature are:

4.3.1. Climate

Low temperature cracking is a major concern in most regions of Canada and the northern United States, where the winter temperatures drop below -30 C (10). The lower the in-service winter temperatures, the greater is the magnitude of the induced thermal stresses. For this reason there is a greater incidence of cracking expected in regions with lower in-service winter temperatures.

4.3.2. Asphalt Characteristics

The rheological properties of asphalts at low temperatures are generally considered to be the most important factors influencing transverse cracking (11). The relationship between asphalt cement consistency, including both penetration and viscosity, and asphalt temperatures, as well as the influence of these factors on transverse cracking has long been apparent (4,5,12,13,). In a recent report (14) the effects of several properties of asphalt cements have been discussed in detail. For a given consistency, an increase in the temperature susceptibility of the mix increases the chances that transverse cracking will occur. This will be discussed in detail under temperature susceptibility of asphalt cements.

4.3.3. Asphalt Stiffness

Asphalt stiffness, S(t,T), as characterizing asphalt consistency, over a range of temperatures and loading times, was introduced by Van der Poel (15). This is analogous to Young's modulus for elastic materials given by the ratio of stress to strain. The total strain is a time and temperature dependent value induced by an uniform tensile stress. The asphalt stiffness, which is a function of loading time and temperature, is defined as:

$$S(t,T)=(\text{tensile stress})/\ (\text{strain})_{(t,T)}$$

where:

$S(t,T)$ = Time and temperature dependent stiffness,

$\text{Strain}_{(t,T)}$ = Time and temperature dependent strain.

Higher asphalt stiffness at low temperatures results in a greater incidence of transverse cracking.

4.3.4. Pavement Structure

The occurrence and frequency of transverse cracking has been shown to be affected by the thickness of the asphalt concrete layer (2,5,13). Generally, the thicker the layer, the lower the frequency of cracking. This may result from the insulating properties of asphalt concrete.

4.3.5. Age

As the oxidation of asphalt takes place with the passage of time, the asphalt hardens and becomes stiffer. This increases the chance that cracking will be initiated and also increases the frequency of cracking with age.

4.3.6. Traffic

At the Ste. Anne Test Road (16) it was observed that traffic affects the severity of cracking, with significantly more transverse cracking occurring in the primary traffic lane, as compared to the passing lane. Fromm et al. (17), reported a case during the winter months, where heavily loaded trucks were carried by the roadway in one direction only. They found that there was a greater incidence of transverse cracking on the heavily travelled side.

4.3.7. Subgrade

Type of subgrade also affects pavement cracking (4,6,13). Pavements which are constructed over sandy subgrades exhibit a higher cracking frequency than pavements over clay subgrades. It has been observed that the frequency of cracking is often significantly reduced for sections of road constructed through low lying muskegs or sloughs, compared to sections constructed through well-drained terrain, indicating influences of moisture temperature as well as soil type (13).

4.3.8. Mix Properties

Mix properties, like density, air voids, and asphalt content have an influence on mix stiffness and the rate of asphalt ageing. These mix properties could therefore influence the cracking frequency of asphalt concrete pavements.

4.4 Temperature Susceptibility of Asphalt Cements

One major concern of a pavement designer is the temperature susceptibility of an asphalt concrete paving mix. Temperature susceptibility is the rate at which the consistency of an asphalt cement changes with a change in temperature, and is a very important property of asphalt cements. For example, a pavement that is stiff at high service temperatures in order to resist rutting, yet flexible enough to resist low temperature cracking, would be less temperature susceptible than a pavement of similar stiffness at high temperatures which becomes brittle and cracks easily at low temperatures.

Asphalt temperature susceptibility is dependent on the temperature range considered. Asphalt cement, being a viscoelastic material, behaves like an elastic solid at low temperatures or short loading time, but as a viscous fluid at high temperature or during long loading times. Over the years, several methods of measuring and comparing temperature susceptibility of asphalt cements have evolved. These are briefly discussed in the following section.

4.5 Temperature Susceptibility Parameters

Some of the most commonly accepted temperature susceptibility parameters are Penetration Index (PI), Penetration Ratio (PR), and Penetration Viscosity Number (PVN).

4.5.1 Penetration Index (PI)

Pfeiffer and Doormaal (18) developed the temperature susceptibility factor Penetration Index, which is a function of the slope (A) of a plot of logarithm of penetration versus temperature. The penetration index is based on the observation that the logarithm of penetration for asphalt cements was nearly a linear function of temperature. The Penetration Index given by:

$$PI = \frac{20 - 500\,A}{50\,A + 1} \text{ -----------(1)}$$

where:

$$A = \frac{\log Pen \;@\; T1 - \log Pen \;@\; T2}{T_1 - T_2}$$

T = Temperature (C)

Pen = Penetration, 100 gm, 5 sec, (dmm)

It was also noted that, at the softening point of asphalt cements, the penetration of the asphalts was about 800 dmm.

Hence, Pfeiffer and Doormaal suggested another equation for the Penetration Index, based on penetration at 25 C and the Ring & Ball softening point as input parameters.

$$PI\ (R\&B) = \frac{20 - 500\ B}{50\ B + 1} \quad \text{------}2$$

Where:

$$B = \frac{\text{Log } 800 \text{ dmm} - \text{Log Pen @ } 25\text{ C}}{S.P - 25}$$

S.P = Ring & Ball softening point, C

The penetration index shows the temperature susceptibility of asphalt cements and can be used to estimate the stiffness modulus of asphalt cements at low temperatures; the nomograph developed by Van der Poel (15), shown in Figure IV.1, may be used. A greater negative value of PI indicates a greater temperature susceptibility The usual range of Penetration Index is between +2 and -2.

4.5.2 Penetration Ratio (PR)

The commonly accepted penetration ratio (PR) is (19):

Pen @ 4 C

FIGURE IV-1 NOMOGRAPH FOR DETERMINING THE STIFFNESS MODULUS OF ASPHALT CEMENTS (AFTER REF 15)

$$PR = \frac{Pen\ @\ 4\ C}{Pen\ @\ 25\ C} \times 100 \text{---------}(3)$$

A lower PR is an indication of greater temperature susceptibility.

4.5.3 Penetration Viscosity Number (PVN)

Mcleod (20) proposed a method for determining temperature susceptibility, based on commonly available laboratory data known as the Penetration Viscosity Number (PVN). The Penetration Viscosity Number is based on the penetration at 25 C and either kinematic viscosity in Centistokes at 135 C or absolute viscosity in poise at 60 C. The PVN can be calculated from the following equations:

1. For the temperature range: 25 C to 135 C

$$PVN = -1.5 * \frac{4.258 - 0.7967 \text{ Log } P - \text{Log } X}{0.7951 - 0.1858 \text{ Log } P} \text{---}(4)$$

Where:

P = Penetration at 25 C, 5 sec, dmm

X = Kinematic Viscosity at 135 C, Centistokes

2. For the temperature range: 25 C to 60 C

$$PVN = -1.5 * \frac{6.489 - 1.590 \text{ Log } P - \text{Log } X}{1.050 - 0.2234 \text{ Log } P} \text{----}(5)$$

Where:

P = Penetration at 25 C, 5 sec, dmm

X = Absolute viscosity at 60 C, poise

A larger negative value of PVN indicates a greater temperature susceptibility. Generally, the range of PVN is between +2 and -2. Puzinauskas (21) showed that no definite correlation exists between Penetration Index and Penetration Viscosity Number.

4.6 Asphalt Stiffness

As already discussed, the asphalt stiffness S(t,T), is used as a means of characterizing asphalt consistency over a wide temperature range and is given by:

$$S(t,T) = (\text{tensile Stress})/(\text{Strain})_{(t,T)}$$

where:

$S(t,T)$ = Time and temperature dependent stiffness

$\text{Strain}_{(t,T)}$ = Time and temperature dependent strain

The total strain is a time and temperature dependent value which is induced by a tensile stress. The resulting asphalt stiffness is a function of asphalt temperature and time of loading, but is independent of loading stress. The method of selecting an appropriate asphalt cement to ensure that the asphalt stiffness does not exceed a certain "critical" or "limiting" value at the lowest pavement temperature, to control low temperature transverse cracking has been proposed by many researchers (16, 20, 22, 23). Gaw (22) proposed a critical value of 1 X 10^9 N/m^2 at 0.5 hour loading time based on St. Anne Test Road section (16). A corresponding value from Van der Poel's nomograph is 0.8 X 10^9 N/m^2 (14). Readshaw (23) based the British Columbia asphalt specifications on a critical asphalt stiffness of 2 X 10^8 N/m^2 at 2 hours loading time.

4.6.1 Methods To Determine Asphalt Stiffness

There are basically two approaches utilized to determine the low temperature stiffness of asphalt cement, namely direct testing and indirect estimation.

4.6.1.1 Direct testing

Direct testing may involve the following instruments:

1. Shell sliding plate Rheometer (to measure stiffness at low temperatures) (24),
2. Schweyer Rheometer (to measure stiffness at low temperatures) (25),
3. Ensley Forced Sphere (to measure stiffness at low temperatures) (26),
4. Duomorph (to measure stiffness at low temperatures).

4.6.1.2 Indirect Estimation

The indirect methods provide an estimate of asphalt cement stiffness without direct laboratory measurements. These methods includes the transformation of routine index test data into stiffness values, using Van der Poel's nomograph (Figure IV -1). Three commonly used methods are: 1) Original Van der Poel's method (15), 2) Heukelom's modified method (27), and 3) McLeod's method (20).

According to Van der Poel's method the penetration at 25 C and the softening point temperature (R&B) of the binder are measured. Using equation (2) the penetration index can be calculated; then by using nomograph in Figure IV -1 the stiffness can be estimated for any particular temperature and loading time.

In the case of Heukelom's modified method, the penetrations at 25 C and 4 C are plotted on a Bitumen Test Data Chart (BTDC) (Figure IV.2), and the temperature corresponding to 800 pen is read by extending the line on the BTDC to 800 pen. The penetration index is calculated by using equation (1). The stiffness can be estimated using the nomograph in Figure IV.1, with loading time, the temperature difference between the desired temperature (T) and T(800 pen), and with PI(dpen/dT), as input parameters.

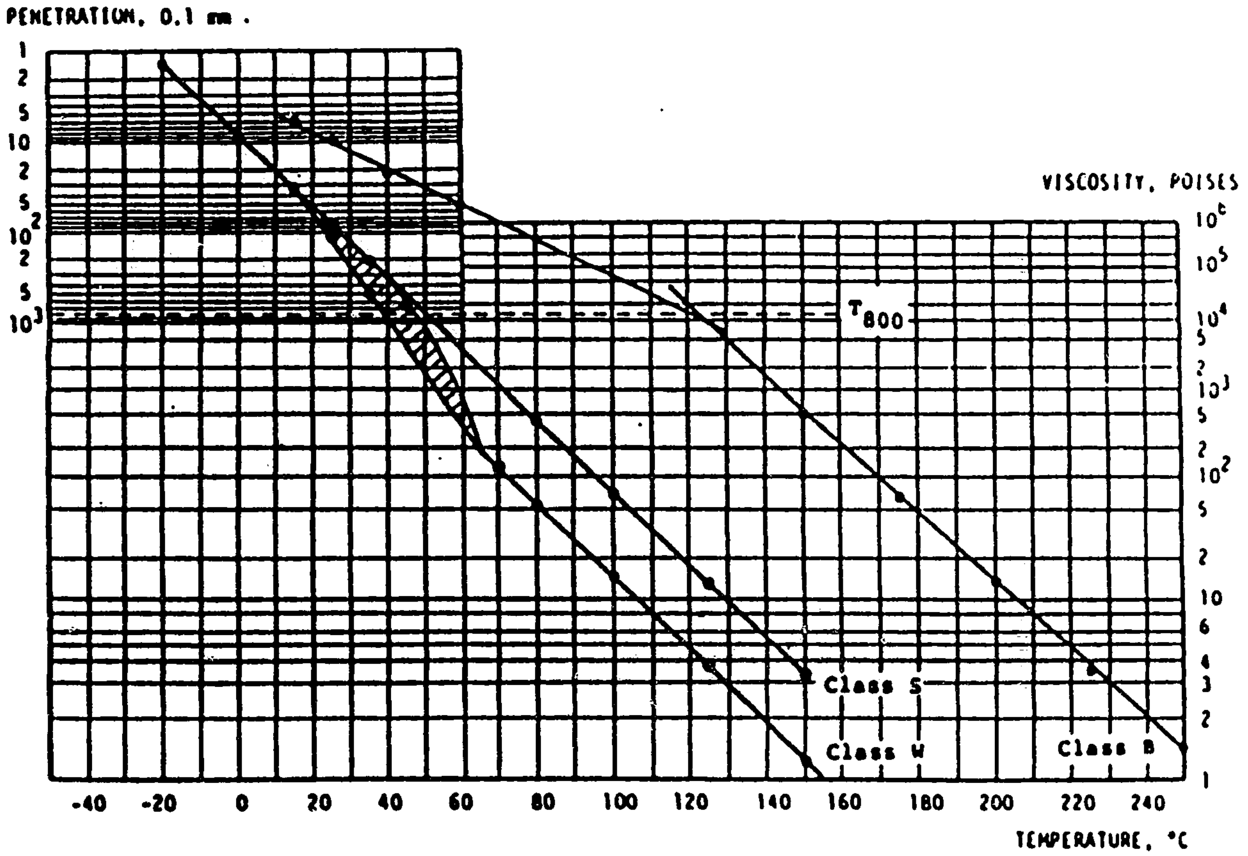

FIGURE IV-2 BITUMEN TEST DATA CHART

Mcleod uses PVN as an indication of temperature susceptibility and as one of the input parameters to determine the asphalt cement stiffness. By using equation (4), PVN can be calculated and the base temperature, which is analogous to R&B softening point temperature, is determined using Figure IV.3. The stiffness of asphalt cement is then estimated using the nomograph (Figure IV.4) with the loading time, the temperature difference between the desired and the base temperature, and the PVN as input parameters.

4.7 Cracking Temperature

A more direct indication of pavement performance at low temperatures is the temperature at which the pavement starts to crack, known as the cracking temperature. It can be calculated based on the asphalt stiffness by the concept of limiting (or critical stiffness) (22), the concept of limiting stress (28), and the nomographic method (29). These methods neglect the influence of factors such as asphalt content, air void content, and aggregate properties, assuming that asphalt properties alone have the major influence on pavement transverse cracking. The details of these methods have been discussed in References 22, 28, and 29.

4.8 Stiffness of Mix

Asphalt mix stiffness is an indication of the resistance to compaction under stress. Asphalt mix stiffness may be

FIGURE IV-3 RELATIONSHIP BETWEEN PENETRATION PVN AND BASE TEMPERATURE (AFTER REF 20)

FIGURE IV-4 NOMOGRAPH FOR DETERMINING THE STIFFNESS MODULUS OF ASPHALT CEMENTS (AFTER REF 20) determined using the nomograph (30) in Figure IV.5 using the following steps:

1. Determine the stiffness of the asphalt binder by the methods described under Section 4.6.1.2,

2. Calculate the volume percent of asphalt and aggregate in the mix,
3. Enter the Figure IV.5 and read off the stiffness of the asphalt mix.

FIGURE IV-5 NOMOGRAPH FOR PREDICTING THE STIFFNESS
MODULUS OF MIXES (AFTER REF 23)

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CHAPTER 5.0

EXPERIMENTAL PROGRAM AND MATERIALS

5.1 Introduction

The primary objective of the testing program involved in this investigation was to evaluate and compare the characteristics of conventional and polymer modified asphalts under both low and high temperatures. In 1987, a comprehensive program to determine the cause of premature pavement rutting and to identify measures that could be implemented to mitigate this mode of distress, was uandertaken by the City of Lethbridge, in conjunction with Alberta Transportation and Utilities (1). In addition to conventional Marshall and Hveem type mix design creep and repeated load triaxial tests were performed with various aggregate combinations and binders.

Following this initial study and the resulting recommendations, a series of test sections were constructed in the City of Lethbridge in June of 1988, in order to verify the anticipated improved performance of the mixes with respect to instability rutting. One of these test sections utilized a polymer modified asphalt cement (PMA 2), supplied by Husky Oil Ltd. with virgin aggregate. Another test section utilized a softer material, designated as PMA 4, incorporated into a mix containing 30 percent RAP (2). This reclaimed asphalt pavement material (RAP) was obtained from previous cold milling projects in the City.

The construction of these test sections provided an opportunity to undertake our independent laboratory testing of these materials, that are considered representative of those used in the field.

Additionally, in August 1989, Alberta Transportation and Utilities constructed a several test section kilometer long on Secondary Highway 794, northwest of Edmonton. This highway carries heavily loaded aggregate hauling trucks from Villenuve. The aggregate used to fabricate test specimens along with another polymer modified asphalt is representative of the aggregate and asphalt cements used in the construction of the test section.

In this chapter, a brief description of the tests involved in this study is presented; however, the individual tests will be fully discussed in succeeding chapters. A detailed description of sample fabrication is presented in this chapter.

5.2 Testing Program

In order to determine the physical properties of the conventional and polymer modified asphalts, a series of tests were conducted on the asphalt binders. Tables V-1 and V-2

Types of tests	150/200	Husky PMA 2	150/200A	Imperial PMA
Pen @ 25 C, 100 gm,5 sec,dmm	X	X	X	X
Pen @ 4 C, 100 gm, 5 sec,dmm	X	X	X	X
Absolute Viscosity,60 C,poise	X	X	X	X
Kinematic Viscosity,135 C,Cst	X	X	X	X
R & B softening Point, C	X	X	X	X

TABLE V-1 TESTS CONDUCTED ON ASPHALT CEMENTS

Tests	Temperature C
Indirect Tensile Test	0, -10 , -20, -30
Repeated Load Triaxial Test	25, 35, 45

TABLE V-2 TESTS CONDUCTED ON ASPHALT CONCRETE SPECIMENS summarize the testing plan undertaken on these binders, identify the various mixes evaluated in this investigation, and cite test procedures or methods developed in previous studies (4) and used here.

5.3. Aggregate Properties

After the aggregate and asphalt samples were received they were evaluated for gradation and rheological properties. For this investigation two aggregate sources and gradations were tested: the aggregate processed for test sections constructed in Lethbridge and the aggregate used for construction of the test section on Secondary Highway 794.

5.3.1 Gradation of Lethbridge Aggregate

Four different plant separated fractions of aggregates were obtained during the construction operation in the City of Lethbridge. The processed aggregates consisted of the following:

1. 16 000 to 5 000 sieve size (A & B) crushed coarse aggregate.

2. Processed fine aggregate D (passing 5 000 sieve size) containing natural pit fines and manufactured fines.

3. Crushed fine aggregate (C) produced by reducing a oversized

aggregate previously screened out.

A washed-sieve analysis was carried out for each individual aggregate fraction A, B, C and D. A computer program, utilizing Lotus 1-2-3, was developed to calculate combined gradations from trial proportions based on the principles in the Asphalt Institute Manual Series (MS-2) (5). Several gradations for design and construction of the test sections are given in Table V-3. Different trial ratios were employed, using this program to obtain a gradation as close as practical to the design gradation selected for specimen preparation. The proportions were 16% A, 26% B, 13% C and 45% D.

5.3.2 Gradation of Secondary Highway 794 Aggregate

Two fractions of aggregates were sampled from crushing operations by Alberta Transportation and Utilities, the coarse aggregate portion and manufactured fines. The test sections were constructed using either 25 or 30 percent manufactured fines. Information on gradation of the test sections blends became available following the fabrication of the specimens.

Washed-sieve analyses were carried out for each aggregate fraction. Washed sieve analyses of the combined blends were also conducted. Table V-4 gives the design gradation, along with the test section gradations obtained by Alberta Transportation and Utilities. Following initial construction

Sieve (mm)	16.0	12.5	10.0	5.0	2.5	1.25	0.063	0.315	0.160	0.080
Percent Passing										
U of A Lab. Spec.	100	97.0	83.0	60.3	43.8	30.9	21.7	13.7	8.2	5.6
EBA Mix C Design	100	95.7	85.2	58.4	49.2	37.6	26.8	15.4	8.9	5.1
Test Sec C	100	94.7	81.7	57.7	45.0	32.0	22.7	13.3	7.9	4.7
EBA Mix B Design	100	94.0	80.0	59.0	47.0	34.0	26.0	16.0	10.0	6.6
Test Sec B Lethbridge	100	94.3	77.3	54.7	44.7	32.0	23.0	13.3	8.0	4.9

TABLE V-3 LETHBRIDGE AGGREGATE GRADATION

Sieve Size (mm)	16.0	12.5	10.			0.63	0.135	0.160	0.080
				Percent Passing					
AT & U Grad. 70% C 30% M.F.	100	90.0	80.0	55.0	30.0	25.0	19.0	11.5	5.9
Test Section 75% C 25% M.F.	100	94.0	83.0	58.0	34.0	29.0	22.0	14.2	7.2
U of A Grad. 75% C 25% M.F.	100	98.0	85.0	54.0	30.0	25.0	18.0	11.0	6.9

C = Coarse
M.F = Manufactured fines

TABLE V-4 SECONDARY HIGHWAY 794 AGGREGATE GRADATION using the design proportions of 30 percent manufactured fines, adjustments were made to use 25 percent manufactured fines. The laboratory gradation used for the specimen fabrication can be seen either to be slightly coarser or close to the actual gradation of the test section constructed in the field.

5.4 Asphalt Binder Properties

The suppliers of conventional asphalt cement and PMA were Husky Oil Ltd. and Imperial Oil Ltd. The asphalts cements were of 150/200A penetration grade. The specification of the individual polymer modified asphalt was left up to the supplier.

5.4.1 Conventional Physical Tests

Two types of physical tests were carried out to define the rheological properties and temperature susceptibility parameters which were used in evaluating the low temperature characteristics of the conventional and polymer modified asphalt cements. The conventional physical tests carried out in the laboratory were given previously in Table V-I. In the second phase of the laboratory testing, the indirect tensile test was used, and the tensile properties obtained from the tests were utilized in evaluating the asphalt cements for low temperature performance. The indirect tensile test is discussed in detail in Appendix A; only the conventional tests will be discussed in this chapter.

In the laboratory testing program, the common physical tests applicable to asphalt cements were carried out on the conventional and polymer modified asphalts. The primary emphasis was placed on the evaluation of the consistency properties of the materials, such as viscosity, penetration, and the temperature susceptibility parameters of the materials, which include penetration viscosity number (PVN), penetration Index (PI), and penetration ratio (PR).

Standard ASTM procedures were utilized for all physical tests. Penetration tests at 25 C and 4 C were done following ASTM D-5 procedures, by loading the needle with 100 gms for 5 seconds. Viscosity tests at 135 C and 60 C were conducted according to ASTM D2170 and ASTM D2171 standard test procedures .

5.5 Presentation And Discussion Of Test Results

Table V-5 summarizes the results obtained in the laboratory, with comparable values reported for the binders used in the test sections. With the exception of the absolute viscosity at 60 C for the PMA 2 and Imperial PMA the test values are within ASTM limits for multilaboratory precision for two results. Problems associated with the use of conventional tests on polymer modified binders, such as shear susceptibility, have been discussed by Zanzotto et al. (1) and may have contributed to this large difference of the mean viscosity. A direct comparison of penetration

Properties	150/200	Husky PMA 2	150/200A	Imperial PMA
Penetration @ 25 C (dmm)	146 (153)*	136 (133)*	158	96 (95)**
Penetration @4 C (dmm)	15	23	13	24 (20)
Absolute Vis @ 60 C, Pa.s	89.0 (96.0)	259 (340)	88	449 (713.9)
Kinematic Vis @ 135 C mm2/s	270 (271)	774 (848)	261	1079 (1133)
R & B Soft Point (C)	38.0	59.5	43.0	63.0

* from Table NO. 2, EBA, 1989 (After Ref 2)
** from Alberta Transportation Lab Report

TABLE V-5 PHYSICAL PROPERTIES OF ASPHALT CEMENT SAMPLES

values would indicate that the PMA 2 and Imperial PMA are harder than conventional at 25 C, but are softer at 4 C. The PMA 2 and Imperial PMA are considerably more viscous at 60 C and 135 C; one could infer from the data that the PMA 2 and the Imperial PMA should be more resistant to cracking at low temperature and more resistant to permanent deformation at high service temperatures. Also, penetration of Imperial PMA is less than PMA 2 at 25 C, with approximately the same penetration at 4 C. Imperial PMA is much more viscous than Husky PMA 2 at 60 C. A precaution had to be taken with Imperial PMA as it was not stable and had to be stirred before testing procedures could be conducted. The higher viscosity at 135 C of Husky PMA 2 required higher mixing temperatures but Imperial PMA had the same mixing temperature as 150/200A. Ring and Ball softening points of Imperial PMA and Husky PMA 2 are higher as compared to the conventional asphalt cements.

5.5.1 Temperature Susceptibility Parameters

Table V-6 presents the temperature susceptibility parameters, PVN (25-60), PVN (25-135), PI (R&B), and PI (dPen/dT). These parameters have been calculated by using the data from Table V-5 and equations described in Chapter 4. The 150/200A is the most temperature susceptible according to the PI(dPen/dT) method. The PI (R&B) for the 150/200 appears to be erroneous despite being a minimum of 4 replicate tests for Ring and Ball. According to the PVN method, the values of the

Parameters	150/200	Husky PMA 2	150/200A	Imperial PMA
PI(dPen/dT)	-1.05	0.57	-1.62	2.33
PI (R&B)	-2.19	4.18	0.15	3.57
PVN(25-60)	-0.26	0.86	-0.13	1.25
PVN(25-135)	-0.39	1.24	-0.35	0.78

TABLE V-6 TEMPERATURE SUSCEPTIBILITY PARAMETERS

temperature susceptibilities are lower as compared to the PI(R&B) and PI(dPen/dT) methods. The difference is obvious, since the PI(dPen/dT) employs two penetration readings in the lower temperature region, whereas the PVN employs one penetration and one viscosity reading, which account for a wider and higher temperature region.

5.5.2 Bitumen Test Data Chart

Figures V-1 and V-2 show the plots of viscosities and penetrations for the conventional and polymer modified asphalt cements on the improved Bitumen Test Data Chart (BTDC) developed by Heukelom (6). The chart provides a convenient method to present graphically basic asphalt properties. The straight lines joining the viscosity data and the penetration data indicate the degree of temperature susceptibility in two temperature ranges. Steeper slopes indicate greater temperature susceptibility. From the Bitumen Test Data Chart, it is noted that the slopes of the straight lines joining the 150/200 and 150/200A asphalts are steeper than the slopes for PMA 2 and Imperial PMA, indicating that the conventional asphalts are more temperature susceptible. The slopes for 150/200 and 150/200A are nearly the same, indicating that they have nearly the same temperature susceptibilities. For 150/200 and 150/200A asphalts, the straight line joining the two viscosity values meet closely to the ring and ball softening point, whereas the ring and ball softening point of the PMA 2

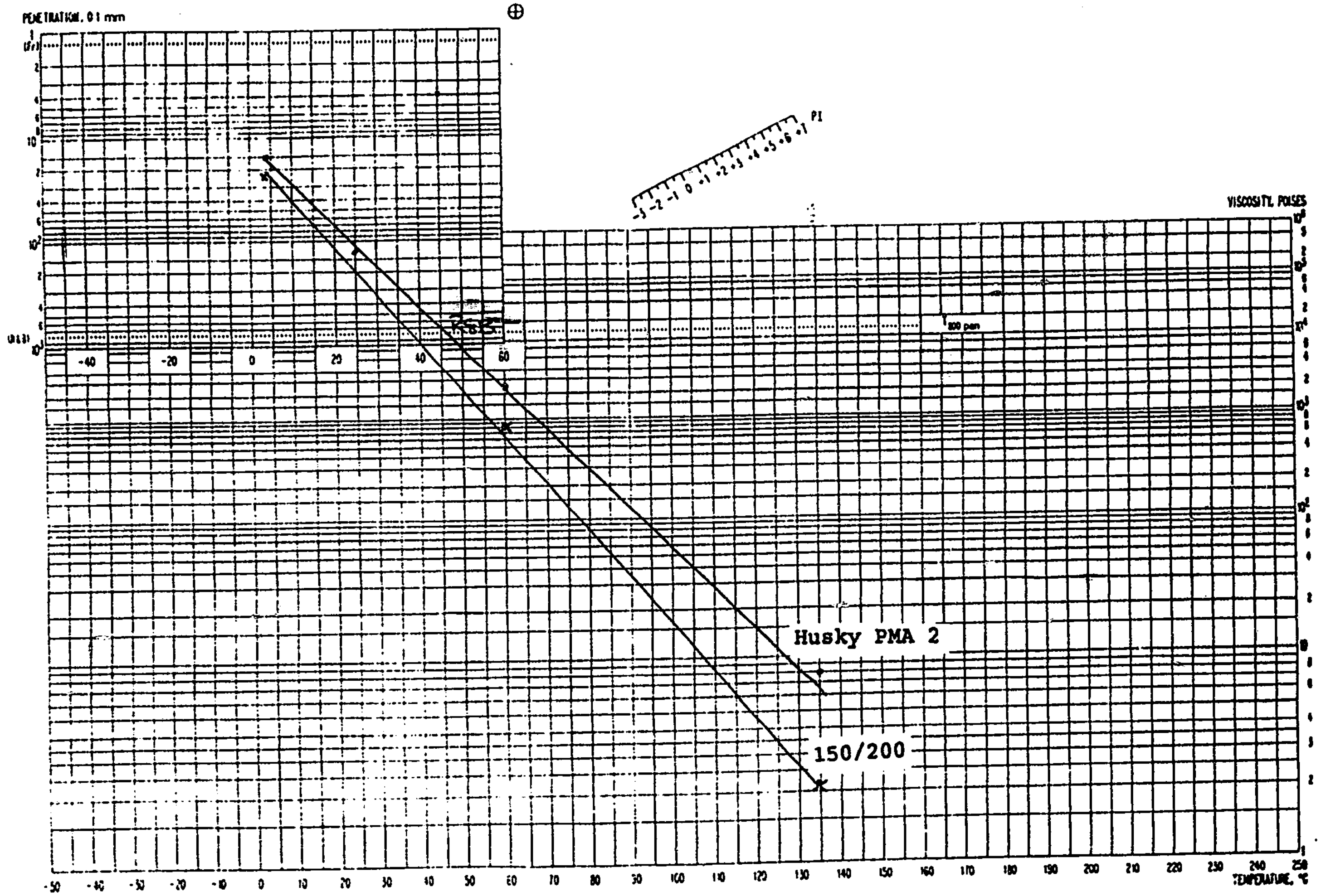

FIGURE V-1 BITUMEN TEST DATA CHART SHOWING TEST RESULTS OF 150/200 AND HUSKY PMA 2

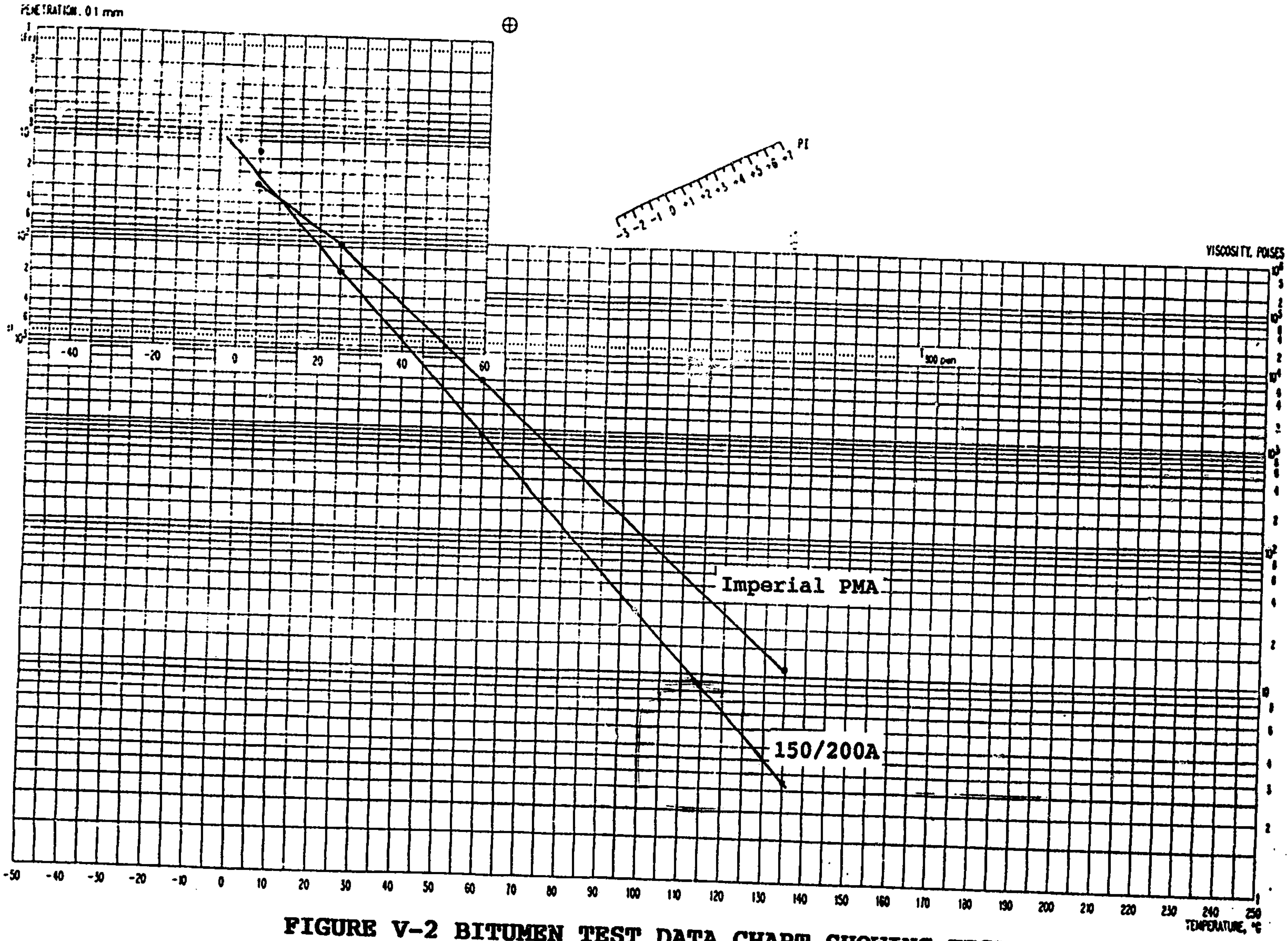

FIGURE V-2 BITUMEN TEST DATA CHART SHOWING TEST RESULTS OF 150/200A AND IMPERIAL PMA and Imperial PMA fall on the right side of the line. From the graphical method it is observed that the PI of polymer modified asphalts is less than the PI of conventional asphalt cement samples. Hence, polymer modified asphalts would be less temperature susceptible than the conventional asphalt cements.

A comparison of the temperature at which penetration is equal to one has been considered as an indicator of low temperature performance (7). The uppermost intercept (i.e. where penetration is equal to 1 in the penetration portion of the plot) is an indicator of low temperature performance; poorer low temperature performance will be expected when this intercepts occurs at higher temperatures. Extrapolating data in Figures V-1 and V-2, it is noted that 150/200 and 150/200A asphalts have nearly the same intercepts; these intercepts are at higher temperatures than the Husky PMA 2 and Imperial PMA intercepts indicating that polymer modified asphalts will show superior performance than conventional asphalt cements.

5.6 Mix Design

On the basis of the preliminary mix designs run in the laboratory, an asphalt content of 6% by the mass of dry aggregate (5.67% by the mass of mix) was used for the preparation of specimens using the Lethbridge aggregate and Husky PMA 2 or 150/200 asphalt cement as the binders. This slightly higher binder content than that used in the test sections (5.67% vs 4.70% for Mix B and 4.90% for Mix C) may have been influenced by the fact that marginally higher amounts of aggregate passed the 0.16 mm and 0.08 mm sieve sizes.

The design proposed by Alberta Transportation and Utilities for Secondary Highway 794 was used for the fabrication of specimens, with a proposed binder content of 5.8% by the weight of dry aggregate. Imperial PMA and 150/200A asphalt cements were used as the binders.

5.7 Preparation of Laboratory Asphalt Concrete Specimens

5.7.1 For Indirect Tensile Test

A total of ninety-six Specimens, with nominal height of 64 mm (2.5 inch), and 102 mm (4 inch) diameters, were compacted in a California Kneading Compactor, using the procedure given in the Asphalt Institute MS-2 Manual (5). This enabled replication of 6 specimens for each of four test temperatures of 0 C, -10 C, -20 C, and -30 C.

The 150/200 asphalt samples were compacted by kneading compaction at a temperature of 135 C, and achieved a mean density of 2358 kg/m^3 with a calculated air void content of 3.1%. The PMA 2 samples were compacted at 165 C to an average density of 2359 kg/m^3, and with the same air void content.

The 150/200A samples were compacted at a temperature of 135 C, and achieved a mean density of 2339 kg/m^3 with a calculated air void content of 3.3%. The Imperial PMA samples were also compacted at 135 C to an average density of 2340 kg/m^3, with the same air void content of 3.3%.

5.7.1.1 Procedure For Specimen Preparation

1. Heat the mold in the oven to the compaction temperature.

2. Place the compaction mold in position in the mold holder; insert a 102 mm (4 in) diameter paper disc to cover the base plate.

3. Weigh 1200 gms of mixture, which has been heated to the compaction temperature in the feeder tray.

4. Spread mixture uniformly in the feeder tray, and transfer approximately one-half of the mixture to the compaction mold.

5. Rod the portion of the mix in the mold with a bullet nose steel rod, 20 times in the centre of the mass, and 20 times around the edge. Transfer the remainder of the sample to the mold and repeat the roding procedure.

6. Place the mold assembly into position on the mechanical compactor, and give 20 tamping blows at 250 psi pressure, to accomplish a semi-compacted condition so that the mix will

not be unduly disturbed when the full load is applied.

7. After the semi-compaction, to complete the compaction in the mechanical compactor increase compactor foot pressure to 500 psi and apply 150 blows.

8. Apply 6 blows by the hand tamper.

9. Remove specimen from the mold and let it cool.

5.7.1.2 Testing Conditions

The testing was carried out in accordance with the procedure described in Appendix A at temperatures of 0 C, -10 C, -20 C, and -30 C.

5.7.2 For Repeated Load Triaxial Test

A total of seventy-two specimens with nominal heights of 204mm and 102 mm diameters, were also compacted with the California Kneading Compactor, using split molds with 204 mm heights, 102 mm diameters, and 50 mm at the top.

Several trial specimens were fabricated to determine the best procedure to fabricate specimens with uniform densities throughout their thickness, using a Kneading Compactor. In order to check the uniformity of the densities, the samples were cut into several lifts, and individual densities were determined and compared. This procedure required several trials, in order to determine a procedure for compaction which would give a fairly uniform density throughout the specimen thickness.

The 150/200 pen grade asphalt samples were compacted at 135 C using a California Kneading Compactor and achieved an average density of 2359 kg/m^3; PMA 2 specimens had a slightly lower density of 2355 kg/m^3. Both had a calculated air void content of 3.1%.

The 150/200A pen grade asphalts and Imperial PMA were compacted at 135 C and achieved densities of 2338 kg/m^3, with air void content of 3.4%.

5.7.2.1 Procedure For High Temperature Specimens

Separate the mix (approximately 4200 gms) into pans, in three portions. Put one half of the first portion into the mold and start compacting at 1.73 MPa. Add the remainder to the first pan, during the first 20 blows.

Increase the pressure of the tamping foot to 2.07 MPa; add the asphalt concrete in the second pan during the next 75 blows. Stop the compactor and install the collar on the top of the mold. Increase the pressure to 3.45 MPa, and over the next 75 blows add the third portion of the material. Special care should be taken to stop filling the mold just before the level of the compacted asphalt concrete reaches the top. If the mold is filled to the top, the compactor might get stuck.

Remove the mold and frame from the compactor; remove the collar from the mold and add some of the reserved finer material to about 3.2 mm above the top of the mold and compact by hand tamper using 6 blows.

Cool the sample in the mold for about half an hour; remove the mold by loosening the screws on the side of the mold sliding the sample 6.4 mm in the mold with the jack, then removing the screws completely and peeling the mold from the sample. Label the sample with grease pencil; clean the mold with Varsol oil.

While adding the asphalt mixture to the mold, it is important to get a good assortment of aggregate sizes in each scoop, in order to avoid segregation of the aggregate within the sample. The only exception is a portion of the finer material from the third pan, which is saved for the top of the sample. This is done to ensure a smooth, level top surface.

Summary of Compaction

1.73 MPa	(250 psi)	20 blows
2.07 MPa	(300 psi)	75 blows
3.45 MPa	(500 psi)	75 blows

5.7.2.2 Testing Conditions

The testing was carried out in accordance with the procedure described in Appendix D, at temperatures of 25 C, 35 C, and 45 C.

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CHAPTER 6.0

INDIRECT TENSILE TEST

6.1 Introduction

In Alberta, research on low temperature cracking of asphalt pavements, due the thermally induced stresses, is not new, and has been ongoing since the early 1960's. The most important factor influencing this problem is the tensile behavior of asphalt concrete pavements at low temperatures, such as the temperatures experienced in Western Canada.

The indirect tensile test has been used at the University of Alberta to evaluate the characteristics of laboratory and core specimens. Anderson and Hahn described the initial use and details of the test method in 1968 (1). Since that time, the test method has been used to evaluate asphalt concrete prepared from a variety of asphalt cement and aggregate combinations (2). Cores have been tested from the Ste. Anne Test Road in Manitoba (3). Data from this test road, as well as many others, have led to the development of methods to evaluate the cracking potential of asphalt pavements due to thermally induced stresses. One such method is known as the COLD program (computation of low temperature damage), developed for the NCHRP Project 1-10B (4,5). Lottman (6) has also developed a method using the indirect tensile test for identifying asphaltic concrete mixtures that are susceptible to moisture-induced damage. Extensive work has been done by Lottman and others but its application has not been included in this study.

This current study of the low temperature tensile properties of asphalt concrete mixtures, using both conventional and polymer modified asphalts, has employed the same method as reported by previous research in which the low temperature indirect tensile strength test method was used to evaluate the low temperature characteristics of asphalt cements (7,8). While the test results will be the major content of this chapter, a more detailed description of the testing procedure and apparatus has been included in Appendix A.

6.2 Summary of The Testing Method

The indirect tensile strength test method basically consists of loading an asphalt concrete cylinder via loading strips placed across the specimen diameter. The loading takes place in a compression testing frame chamber, maintained at a constant low temperature. Output signals from a load cell and three linear variable transducers are recorded on floppy diskette by means of a datalog card installed on a microcomputer. The layout of the equipment in the laboratory is shown in Figure VI-1. The Lotus 1-2-3 spread sheet program was used to process the raw data recorded on the diskette;

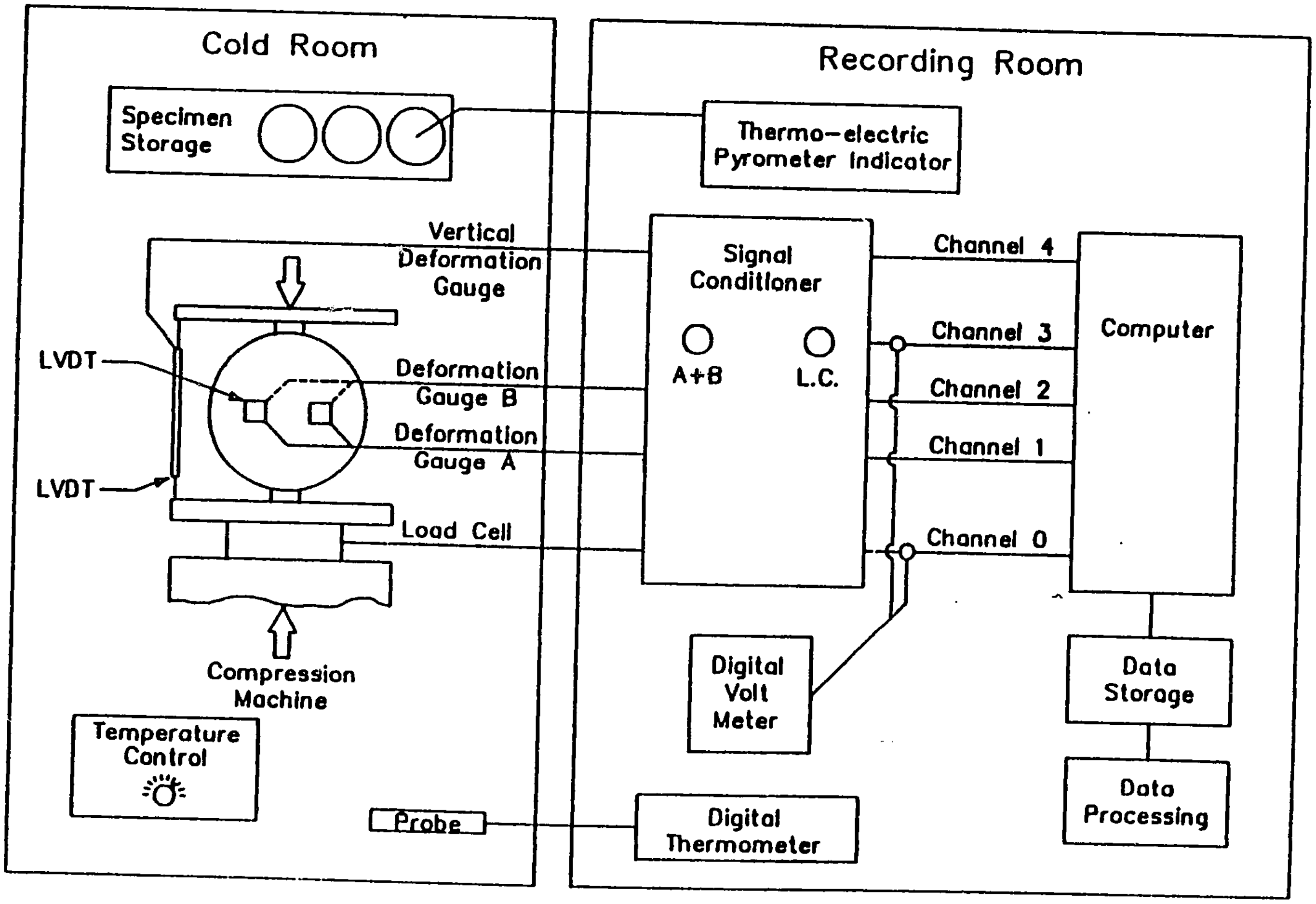

FIGURE VI-1 SCHEMATIC OF TEST EQUIPMENT LAYOUT

failure stress, strain, stiffness and the stress-strain relationship were obtained.

6.3 Theory

The indirect tensile strength test solution is based on the theory of elasticity. Briefly, when a cylindrical disc is subjected to a concentrated load (or a load strip of width less than d/10) in plane stress condition, the stress distribution is both compressive and tensile as shown in Figures VI-2 and VI-3.

The induced tensile stress at the centre is given by:

$$T = \frac{2 * P}{d\ t}$$

where:

T = Induced tensile stress (MPa)
P = Applied load (kN)
d = Diameter of specimen (m)
t = Thickness of specimen (m)

More discussion of the theory of the indirect tensile test can be found in References 2, 9, 10, and 11.

6.4 Laboratory Asphalt Concrete Specimens

Conventional and polymer modified asphalt cements supplied by

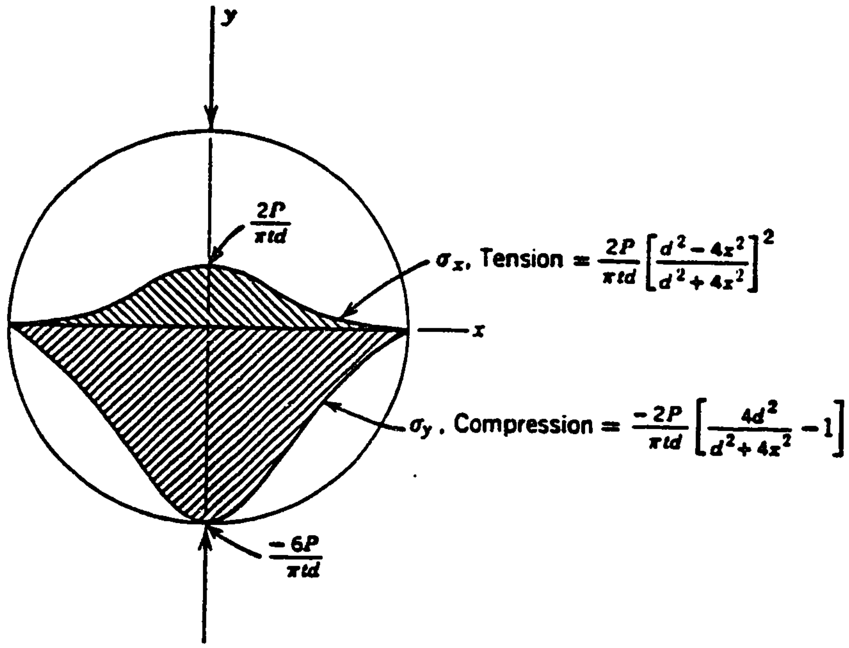

FIGURE VI-2 STRESS DISTRIBUTION ON X-AXIS

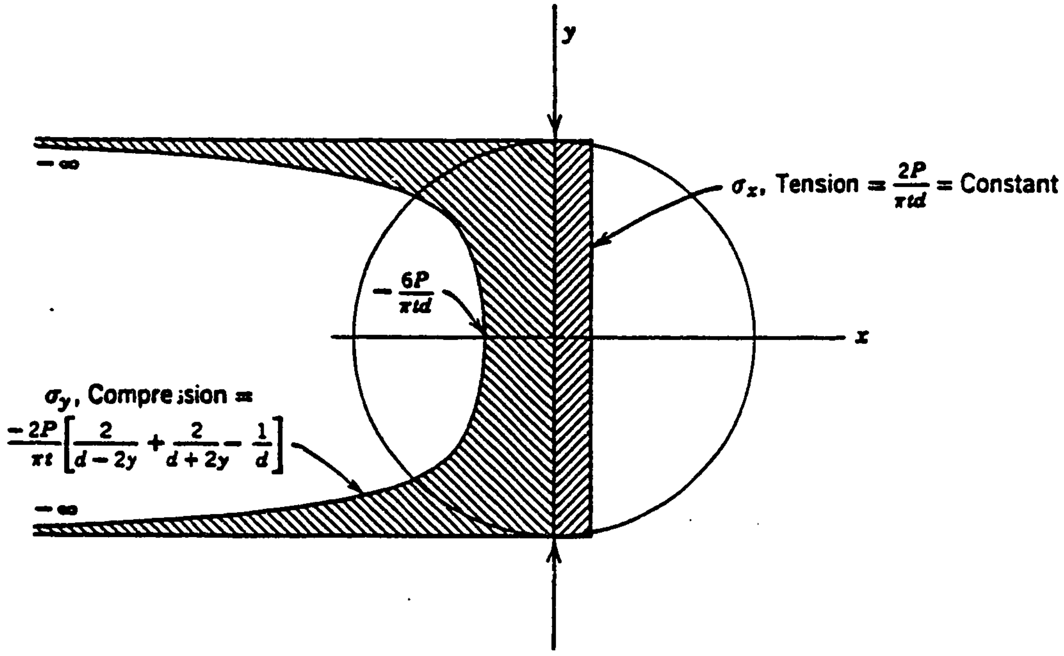

FIGURE VI-3 HORIZONTAL STRESS DISTRIBUTION ON Y-AXIS

Husky Oil and Imperial Oil Ltd. were used in preparing the laboratory specimens. The rheological properties of these asphalt cements have been described in Chapter 5. As described in Chapter 5, twenty-four specimens of each asphalt cement type were prepared, using aggregate from Lethbridge and Secondary Highway 794. The bulk specific gravity of each specimen was determined by weighing each specimen in air and then immersed in water. Groups of six specimens were arranged for testing at different temperatures according to a grouping program developed earlier at the University of Alberta and used by Leung (7) in his research. The specimens were grouped according to their bulk specific gravities, so that each group had a similar average density. The grouping of the specimens for low temperature evaluation is given in Appendix B.

The testing was carried out in accordance with the procedure described in Appendix A , at temperatures of 0 C, -10 C, -20 C, and -30 C. After the calibration of the equipment, the loading rate was set at a nominal value of 1.47 mm/min and remained unchanged throughout the testing.

6.5 Presentation And Discussion of Test Results

As discussed in Chapter 5, two different aggregates were used for the preparation of the specimens, so the results of both series shall be discussed separately.

6.5.1 Test Results

Table VI-1 summarizes the average stresses, strains, and stiffness moduli of the test specimens at failure, for the Lethbridge aggregate series. Appendix C contains the test results for the individual specimens, at different test temperatures. A major problem with undertaking tests of this type is the scatter of results, particularly at very low temperatures. It has been the practice in the past to test five specimens at each temperature, and to present the results based on the average values determined for the valid tests (7). Generally, strain values were rejected when they exceeded the coefficient of variation of 30 percent for temperature of 0 C and -10 C, and 40 percent for -20 C and -30 C new averages were calculated in such an instance.

6.5.1.1 Low Temperature Tensile Characteristics For The Lethbridge Aggregate

Figures VI-4 to VI-6 present plots of failure stress, failure strain, and failure stiffness, versus temperature for 150/200 and Husky PMA 2 asphalt cements, for direct visual comparison. Examination of these tabulated and plotted results leads to

Type of Binder	Test Temperature (C)	Failure Stress (KPa)	Failure Strain (0.0001)	Failure Stiffness (MPa)
150/200	0	1 120	96.0	210
Husky PMA 2	0	1 130	160.0	120
150/200	- 10	2 050	60.0	930
Husky PMA 2	- 10	2 790	95.0	420
150/200	- 20	3 880	18.0	4 710
Husky PMA 2	- 20	3 940	22.0	3 630
150/200	- 30	4 090	4.0	17 700
Husky PMA 2	- 30	4 650	7.0	12 000

TABLE VI-1 AVERAGE STRESS, STRAIN, AND STIFFNESS VALUES FOR LETHBRIDGE AGGREGATE

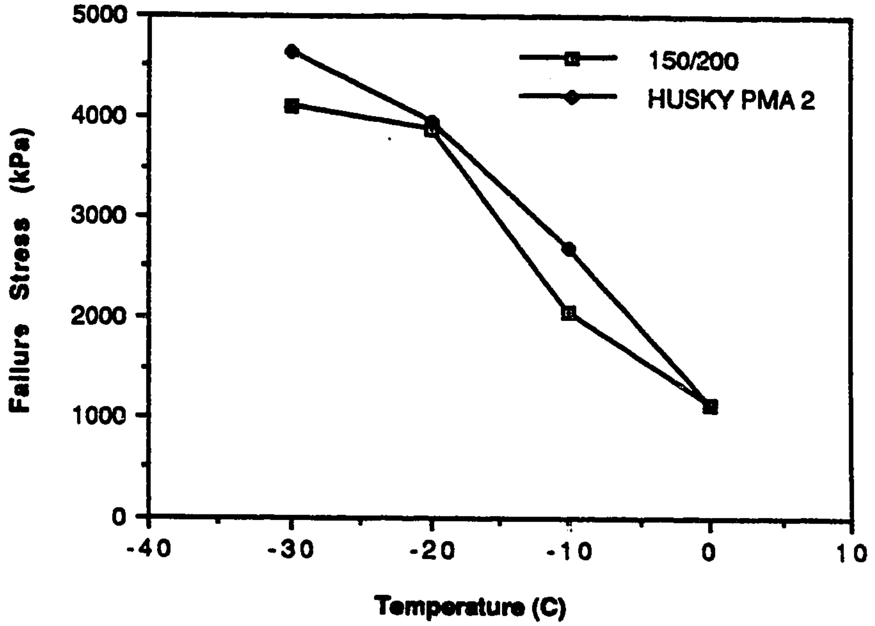

FIGURE VI-4 AVERAGE FAILURE STRESS-TEMPERATURE RELATIONSHIP FOR LETHBRIDGE AGGREGATE

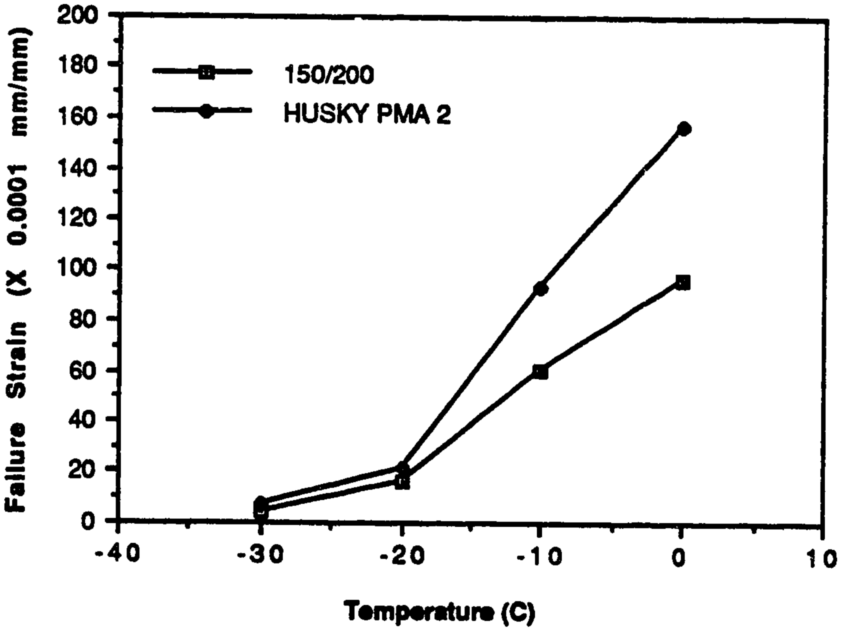

FIGURE VI-5 AVERAGE FAILURE STRAIN-TEMPERATURE RELATIONSHIP FOR LETHBRIDGE AGGREGATE

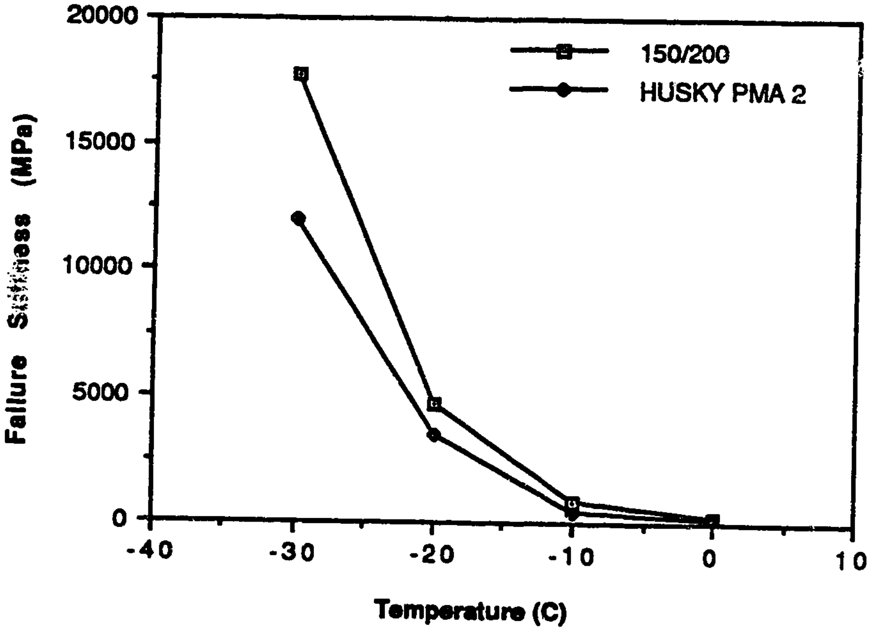

FIGURE VI-6 AVERAGE FAILURE STIFFNESS-TEMPERATURE RELATIONSHIP FOR LETHBRIDGE AGGREGATE

the following observation, for comparable temperatures and using 150/200 mixes as reference:

1. Husky PMA 2 exhibits higher failure stresses, observed at temperatures of -10 C and -30 C . The greatest change in the failure stress occurs when the temperature changed from -20 C to -30 C. In general, the failure stress increases as the test temperature decreases.

2. Husky PMA 2 exhibits higher failure strains, observed at temperatures of 0 C and -10 C. At temperatures of -20 C and colder the strains experienced by both mixes are nearly same. When the temperature changes from -10 C to -20 C, the strain decreases very rapidly. In general it is observed that the strain decreases as the temperature decreases.

3. Husky PMA 2 exhibits lower failure stiffness, especially observed at temperature of -20 C and colder. There is a very rapid change in the stiffness as the temperature decreases from -10 C and colder. In general it is observed that as the temperature decreases the failure stiffness increases.

These results support the statement of Arand (12), that polymers provide the asphalt concretes with higher tensile strength at low temperatures, in order to resist thermal and load-related stresses, with the additional advantage of being able to withstand greater strains without cracking.

Figures VI-7 to VI-10 present the average stress-strain curves for the test specimens fabricated with 150/200 and Husky PMA 2 asphalt cements at different test temperatures. The point on the graph are average of 6 samples tested at each temperature.

Generally, for the Husky PMA 2 asphalt, the average failure stress is higher than that for 150/200 Pen grade asphalt cement, except at 0 C where the failure stress is approximately the same for both mixes. However, the average failure strain is markedly higher for Husky PMA 2 at 0 C and -10 C.

6.5.1.2 Low Temperature Tensile Characteristics For Secondary Highway 794

Table VI-2 summarizes the average failure stresses, strains, and stiffnesses for specimens fabricated with Secondary Highway 794 aggregate two asphalts 150/200A and Imperial PMA. Appendix C contains the test results for the individual specimens at various test temperatures.

Figures VI-11 to VI-13 present the failure stress, failure strain and failure stiffness versus temperature for 150/200A and Imperial PMA asphalt cement mixes for direct visual comparison.

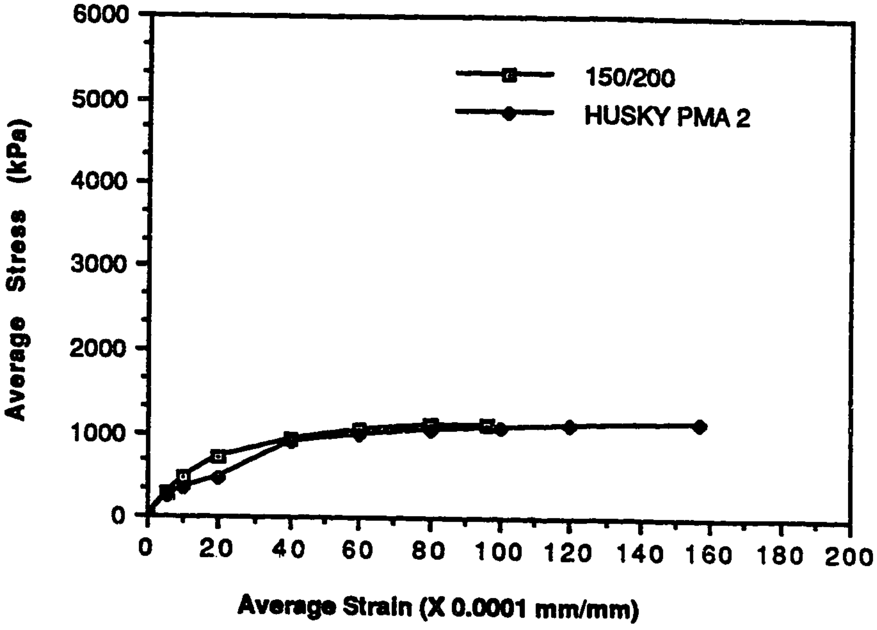

FIGURE VI-7 AVERAGE STRESS-STRAIN CURVES AT 0 C FOR LETHBRIDGE AGGREGATE

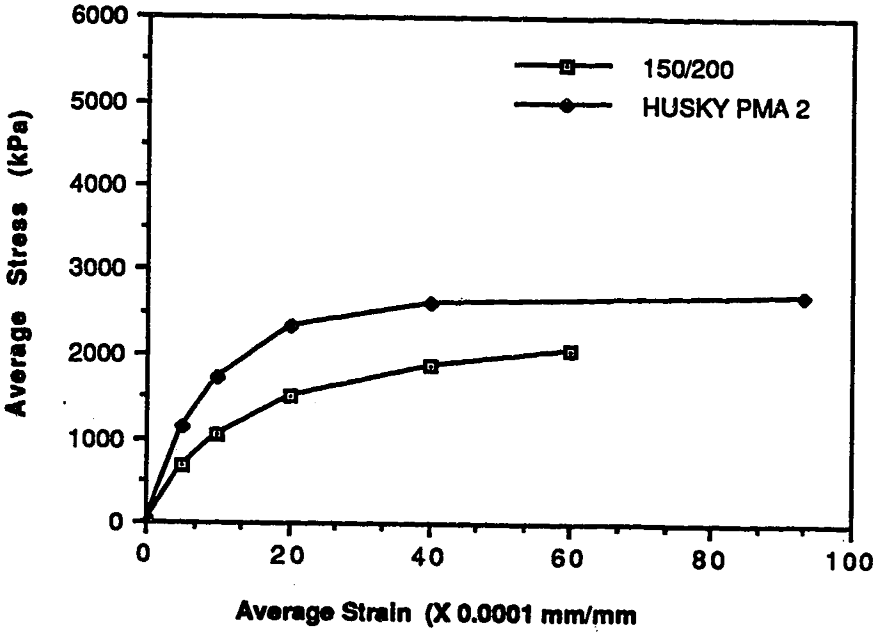

FIGURE VI-8 AVERAGE STRESS-STRAIN CURVES AT -10 C FOR LETHBRIDGE AGGREGATE

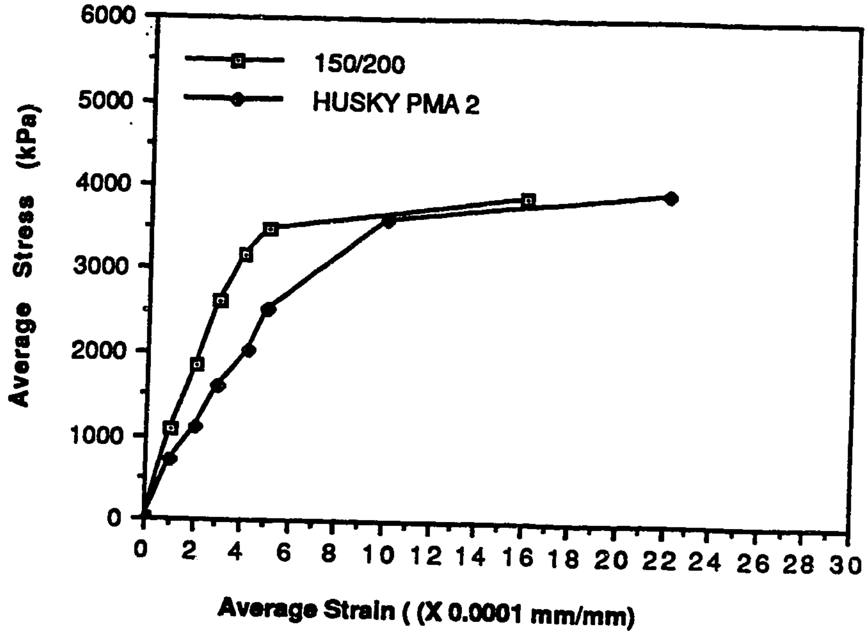

FIGURE VI-9 AVERAGE STRESS-STRAIN CURVES AT -20 C FOR LETHBRIDGE AGGREGATE

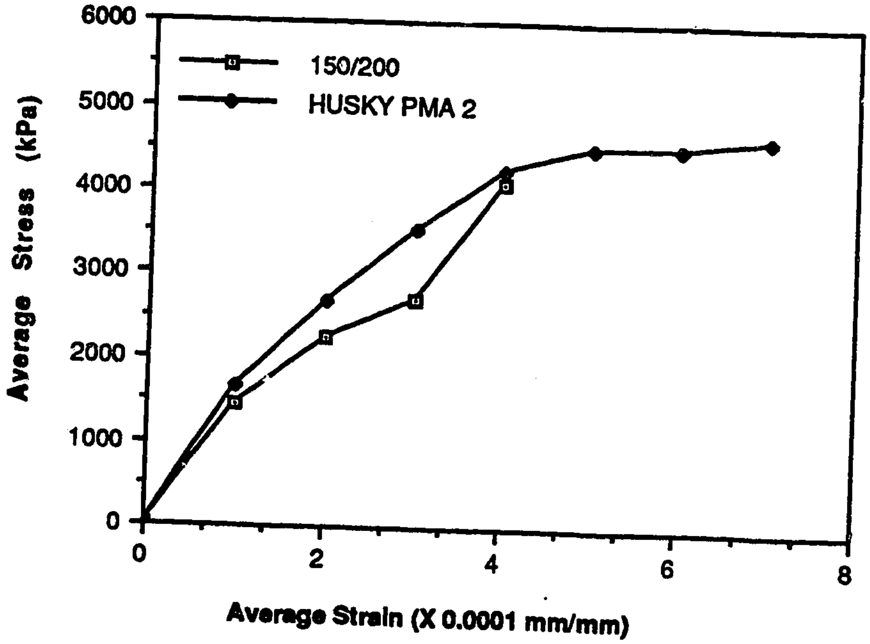

FIGURE VI-10 AVERAGE STRESS-STRAIN CURVES AT -30 C FOR LETHBRIDGE AGGREGATE

Type of Binder	Test Temperature (C)	Failure Stress (KPa)	Failure Strain (0.0001)	Failure Stiffness (MPa)
150/200A	0	1 400	110.0	210
Imperial PMA	0	1 060	127.0	140
150/200A	- 10	3 455	50.0	1 260
Imperial PMA	- 10	2 755	80.0	600
150/200A	- 20	4 200	5.0	153 50
Imperial PMA	- 20	4 415	14.0	58 35
150/200A	- 30	4 330	2.5	23 980
Imperial PMA	- 30	5 030	7.25	11 060

TABLE VI-2 AVERAGE STRESS, STRAIN AND STIFFNESS VALUES FOR SECONDARY HIGHWAY 794 AGGREGATE

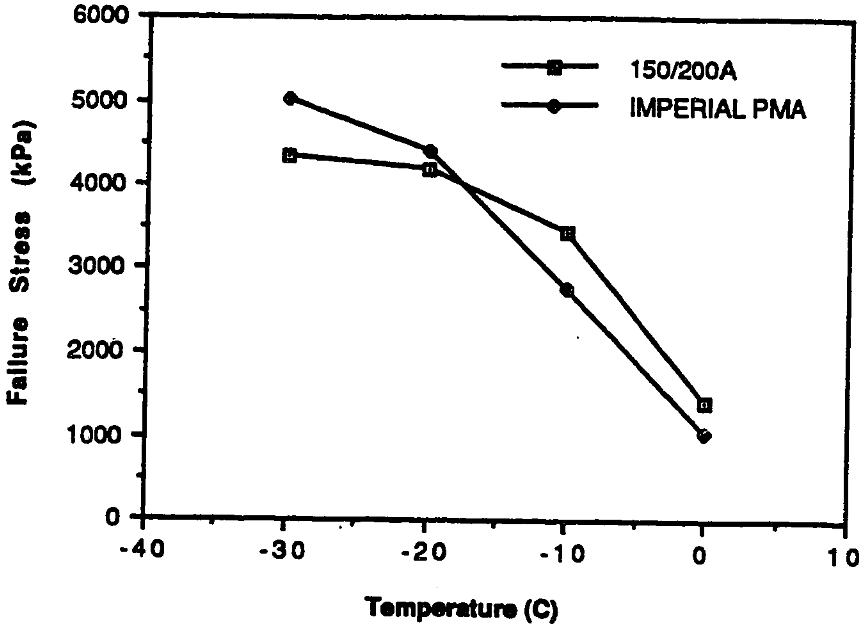

FIGURE VI-11 FAILURE STRESS-TEMPERATURE RELATIONSHIP FOR SECONDARY HIGHWAY 794 AGGREGATE

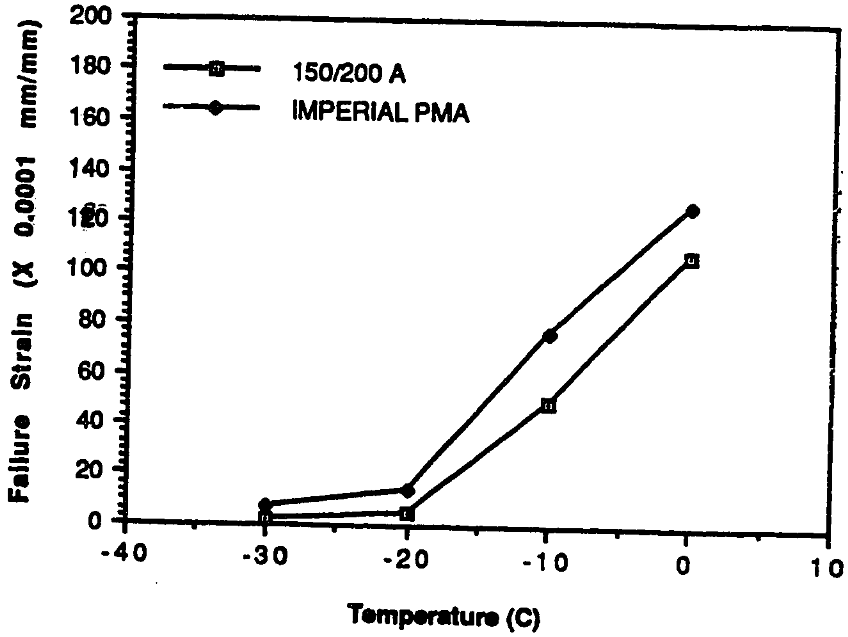

FIGURE VI-12 FAILURE STRAIN-TEMPERATURE RELATIONSHIP FOR SECONDARY HIGHWAY 794 AGGREGATE

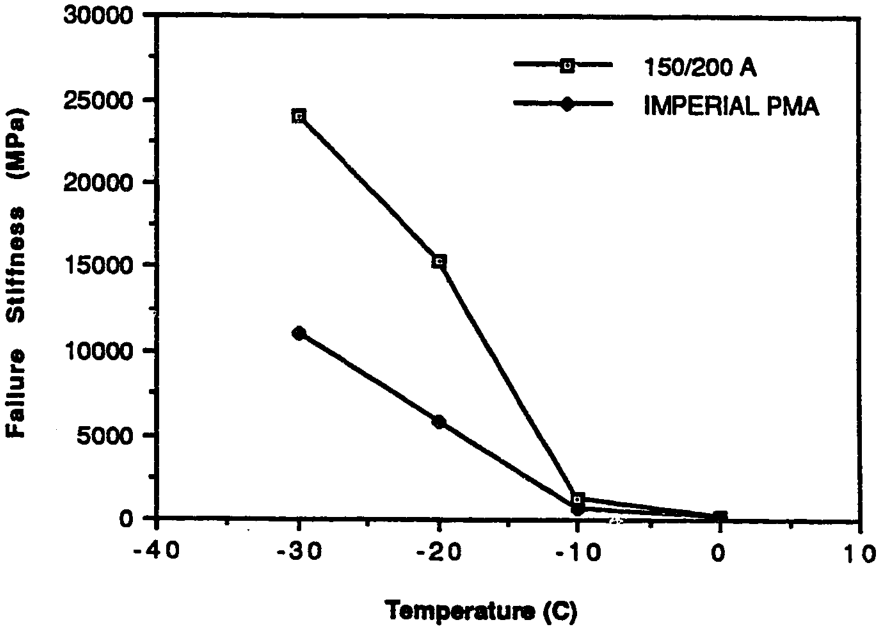

FIGURE VI-13 FAILURE STIFFNESS-TEMPERATURE RELATIONSHIP

FOR SECONDARY HIGHWAY 794 AGGREGATE

Examination of these tabulated and plotted results leads to the following observations, for comparable temperatures and using 150/200A mix as reference:

1. Imperial PMA exhibits lower failure stresses at temperatures of 0 C and -10 C, but at -20 C and colder temperatures, this trend reverses and an opposite trend is observed.

2. Imperial PMA exhibits higher failure strains. The difference is quite significant at all testing temperatures. The greatest decrease in the strain occurs when the temperature changes from -10 C to -20 C. Thus, Imperial PMA follows the same trend as previously reported in that, with a decrease in temperature, the failure strain decreases.

3. Imperial PMA exhibits lower failure stiffness. The stiffness at -20 C and colder temperature for 150/200A asphalt cement is very high as compared to Imperial PMA; thus, Imperial PMA shows a great improvement with respect to the factors that influence resistance to low temperature cracking.

Figures VI-14 to VI-16 present the average stress-strain curves of the test specimens fabricated with 150/200A and Imperial PMA asphalts, at different test temperatures. The failure stress for 150/200A is higher at temperatures of 0 C

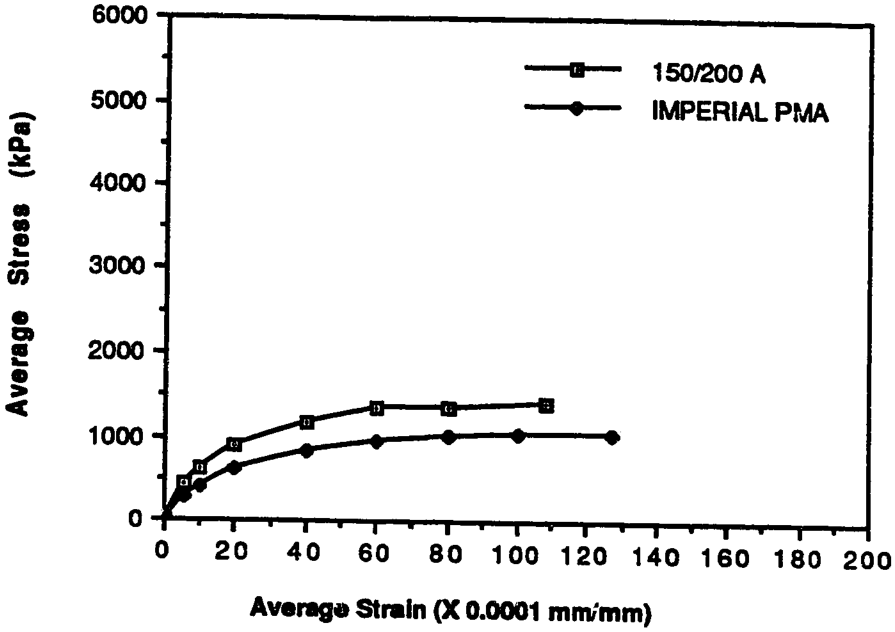

FIGURE VI-14 AVERAGE STRESS-STRAIN CURVES AT 0 C

FOR SECONDARY HIGHHWAY 794 AGGREGATE

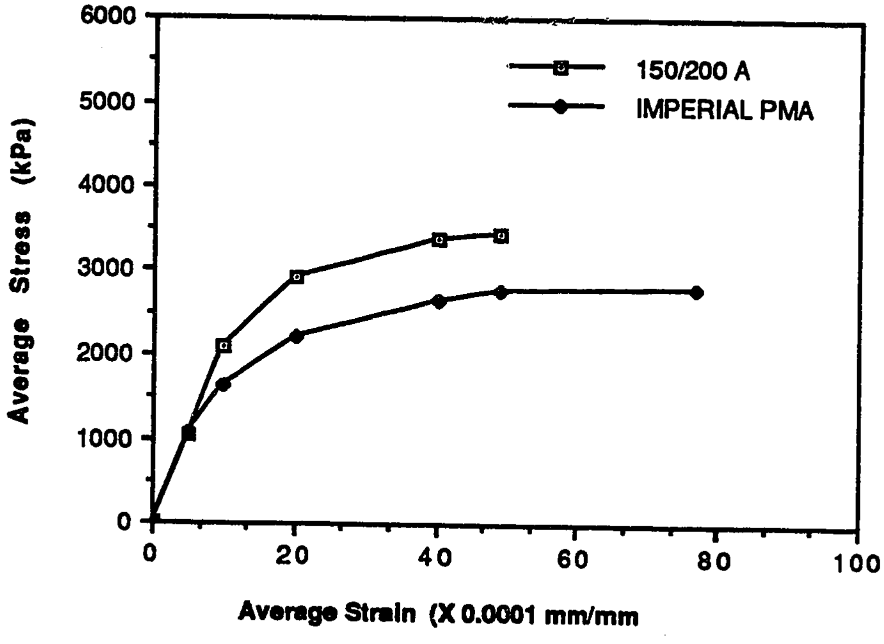

FIGURE VI-15 AVERAGE STRESS-STRAIN CURVES AT -10 C

FOR SECONDARY ROAD 794 AGGREGATE

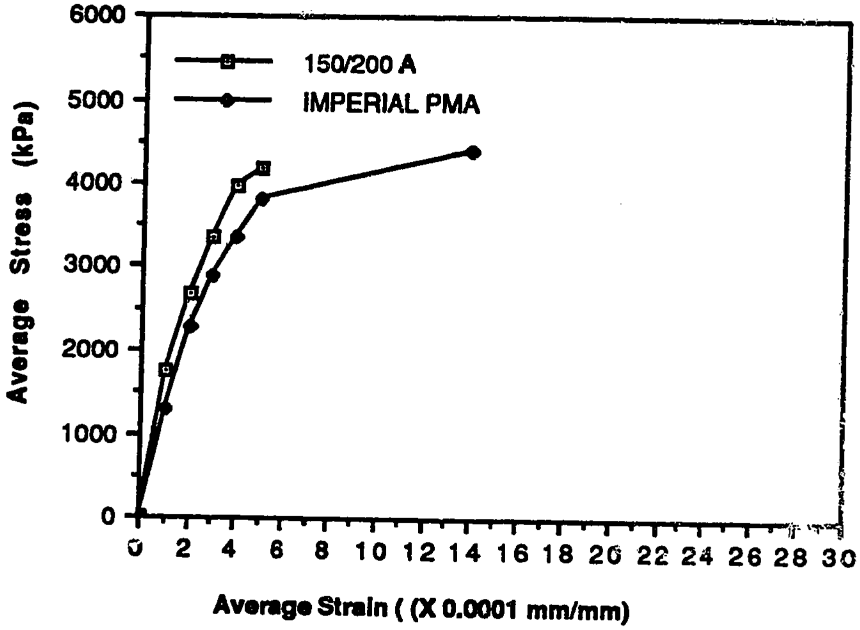

FIGURE VI-16 AVERAGE STRESS-STRAIN CURVES AT -20 C FOR SECONDARY HIGHWAY 794 AGGREGATE

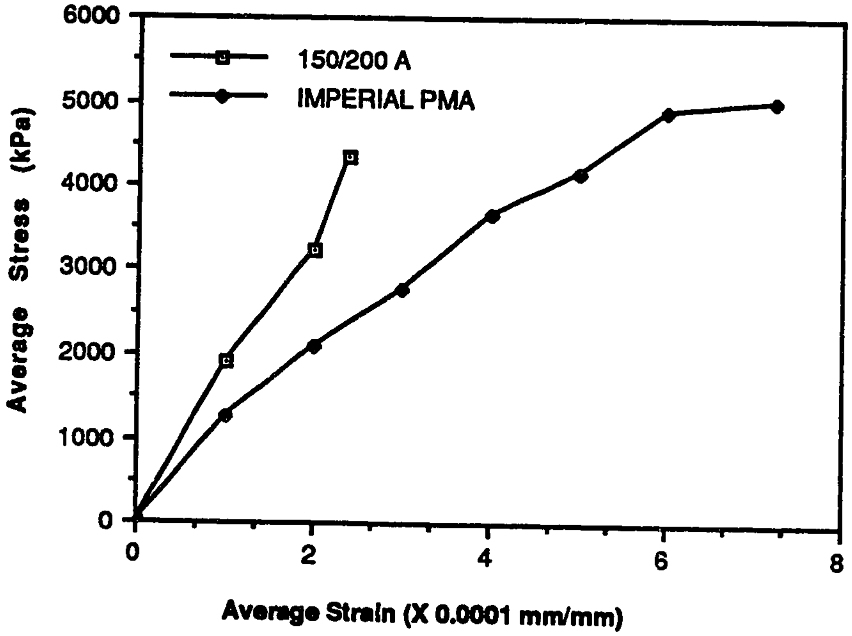

FIGURE VI-17 AVERAGE STRESS-STRAIN CURVES AT -30 C FOR SECONDARY HIGHWAY 794 AGGREGATE and -10 C, but at -20 C and colder temperatures, Imperial PMA exhibits a higher failure stress. However, the average failure strain of Imperial PMA is greater; showing toughness is enormously higher for Imperial PMA. Hence it would be able to withstand colder temperature before cracking.

6.6 Low Temperature Evaluation of Polymer Modified Asphalt Cements

The indirect tensile tests demonstrate that PMA asphalt mixtures sustain larger strains at failure; this is an important property to resist thermally induced cracking. Furthermore, the lower tensile stiffness of the polymer modified asphalt concrete mixtures implies that the induced tensile stresses, due to changing temperatures, will be smaller for these mixtures. Thus, the chance of thermal cracking is reduced. Also the toughness of both polymer modified asphalt cement is higher than conventional asphalt cement.

On the basis of the trends observed from laboratory testing to determine the characteristics of conventional and polymer modified asphalt concrete mixes, all point to the polymer modified mixes as being more resistant to thermally induced stresses at low temperatures and should show superior performance under these conditions.

The Lethbridge and Secondary Highway 794 aggregate series cannot be compared directly, due to the difference in the base asphalt cements. One important conclusion which can be drawn from the testing is that, in mixtures with different aggregates, both of these polymer modified asphalts exhibit higher failure strains and lower failure stiffnesses and therefore are expected to perform better than conventional asphalt cements.

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CHAPTER 7.0

PERMANENT DEFORMATION OF ASPHALT CONCRETE PAVEMENTS

7.1 Introduction

Barksdale (1) defines permanent deformation as the progressive accumulation of plastic strain in each layer of the pavement system, occurring under each load replication. Permanent deformation of asphalt concrete pavements causing is one of the primary factors influencing the serviceability and riding quality and can result in a need for rehabilitation to maintain acceptable levels. The hydroplaning and icing resulting from accumulated water in the rutted wheel paths cause additional safety concerns; thus, it is important to incorporate permanent deformation criteria into pavement designs in order to achieve the goal of improved pavement serviceability and safety.

According to Monismith (2) permanent deformation can result from both traffic and non traffic associated causes due to swelling or shrinkage of subgrade soil resulting in consolidation settlements. One of the earliest investigations of permanent deformation was conducted at AASHO Road Test (3); it was discovered that: 1) permanent deformation occurs in all layers of the pavement structure, and 2) is primarily due to lateral distortion of the pavement material. Although every layer of the pavement structure influences permanent deformation, this study will focus on permanent deformation in the conventional and polymer modified asphalt concrete layers, at different temperatures.

In this chapter, results are described of repeated load triaxial tests, carried out to investigate the behavior of conventional and polymer modified asphalt cements at high temperatures.

7.2 Factors Affecting Permanent Deformation of Asphalt Concrete Pavements

The most important factors affecting permanent deformation are:

1. Material properties,
2. Traffic loadings and volumes, and
3. Environmental conditions.

According to Huschek (4), aggregate gradation, asphalt content, degree of compaction, and softening point of the asphalt, are important factors influencing the resistance of asphalt pavements to permanent deformation. Recent studies (5,6) carried out at university of Alberta concluded that the type of asphalt, temperature, and gradation affect permanent deformation of asphalt concrete pavements. Softer asphalts may result in greater permanent deformation. Asphalt content influences the stability and durability of the mix. Temperature has a great influence on permanent deformation, because strains increase and stiffness decreases with an increase in the temperature, making the pavement less resistant to permanent deformation. Another important factor is the stress level imposed on the pavement, and its duration. Higher stresses result in greater permanent deformation. According to a study carried out by Haas et al. (7), the tire pressure has substantial effect on permanent deformation.

7.3 Laboratory Testing

As discussed in Chapter 1, the primary objective of this research program was to evaluate the permanent deformation behavior of conventional and polymer modified asphalt cements, at temperatures of 25 C, 35 C, and 45 C. Specimens prepared from conventional and polymer modified asphalt cements were tested using the repeated load triaxial test.

7.3.1 Testing Approach

The testing conducted in this research follows the same approach as Hadipour and McMillan (5,6), in which the repeated load triaxial test was utilized to attempt to simulate field conditions. An applied vertical stress of 350 kPa, and a lateral confining pressure of 35 kPa were used with a loading and rest time of 0.5 seconds. The load was applied through pneumatic cylinders, controlled by electric solenoids. The layout of the testing equipment is given in Figure VII-1. The signal to the solenoids (0.5 sec on/off) was provided by a

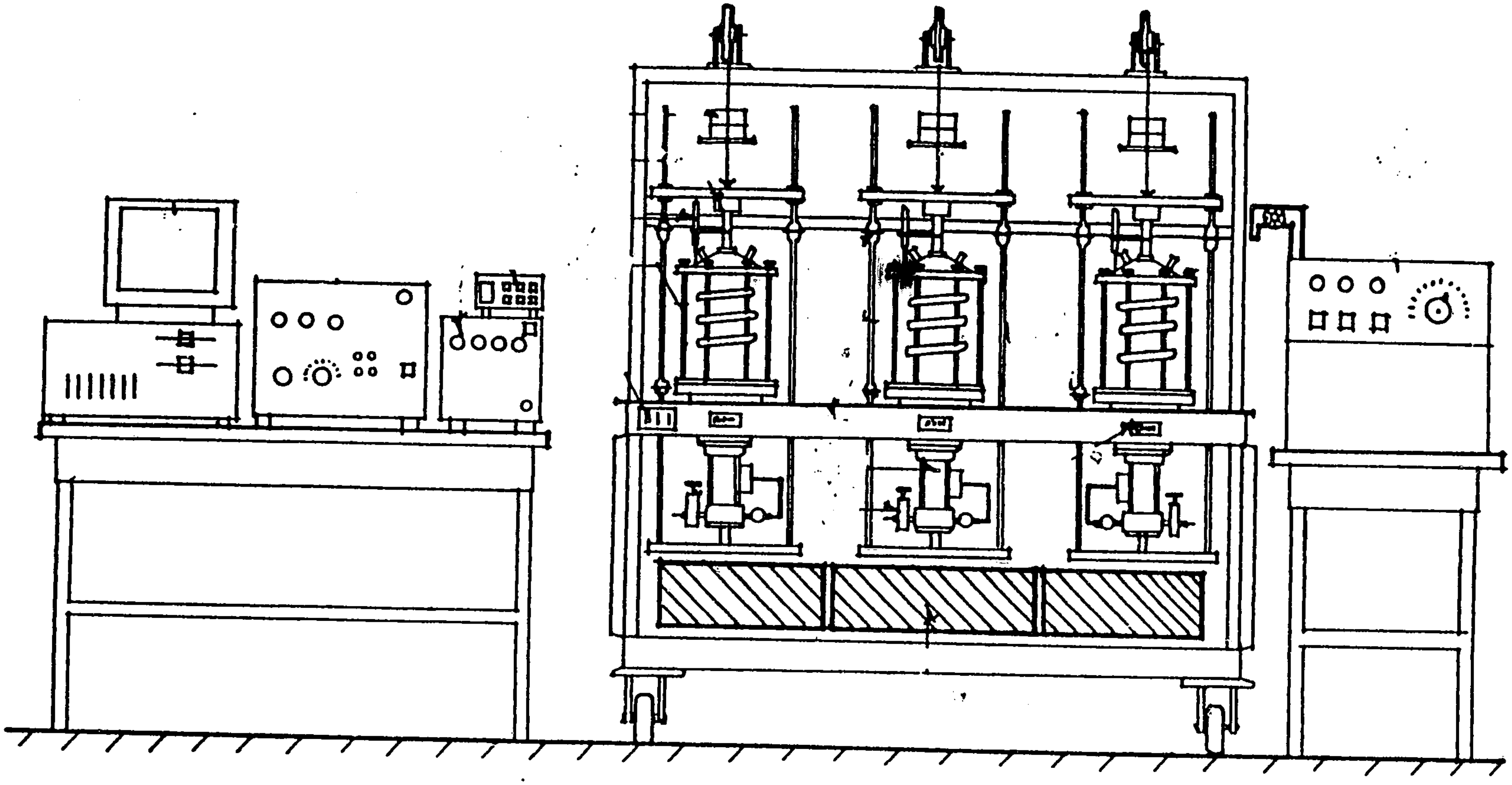


FIGURE VII-1 LAYOUT OF REPEATED LOAD TRIAXIAL TESTING EQUIPMENT square wave, the resulting loading curve, as felt by the load cell, consisted of an approximately 0.2 second load build up time, followed by approximately 0.3 second of constant load, followed by an immediate drop off. This loading rate attributable with this experiment simulates a vehicle speed of approximately 10 km/h, which is not a realistic approximation of highway traffic speeds, but it reduces the required number of loading cycles required to reach a specific level of deformation. According to Barksdale, a loading time of 0.04 seconds would correspond to a typical vehicle speed of approximately 90 km/h. However due to the limitations on testing equipment, the loading time had to be increased to 0.5 seconds which correspond to a vehicle speed of about 10 km/h for an element at depth of 102 mm. A detailed description of the repeated load triaxial test procedure is given in Appendix D.

7.4 Laboratory Asphalt Concrete Specimens

As discussed in Chapter 5, conventional and polymer modified asphalt cements were used to fabricate the specimens. The rheological properties of these asphalt cements have been discussed in Chapter 5. Eighteen specimens using each asphalt cement were fabricated, using aggregate from Lethbridge and Secondary Highway 794.

The bulk specific gravity of each specimen was determined by weighing each specimen in air and then immersed in water. Groups of six specimens were arranged for testing at different temperatures by a grouping program, according to their bulk specific gravities, so that the average density of each group was similar. The grouping of the specimens for high temperature testing is given in Appendix E. The testing was carried out in accordance with the procedure described in Appendix D and at temperatures of 25 C, 35 C, and 45 C.

7.5 Presentation And Discussion of Results

The repeated load triaxial tests measures the percent permanent strain for each sample, at various repetitions of the axial load. Results for each individual specimen were recorded, but for convenience, average strain values are reported at selected repetitions of 10, 50, 100, 1 000, 5 000, 10 000 and in increments of 10 000 up to 99 000 repetitions or failure.

As discussed in Chapter 5, two different types of aggregates were used in the fabrication of specimens, so the results for both series of test specimens will be discussed separately.

7.6 High Temperature Permanent Deformation Characteristics of Lethbridge Aggregate

Tables VII-1 and VII-2 summarize the percent permanent strain at each temperature for the two types of binder using

No of Repet (N)	Temperature (C)		
	25	35	45
0	0 (0.000)	0 (0.000)	0 (0.000)
10	0.152 (0.093)	0.217 (0.027)	0.386 (0.323)
50	0.278 (0.168)	0.394 (0.039)	0.629 (0.378)
100	0.458 (0.134)	0.489 (0.042)	0.659 (0.420)
1 000	0.614 (0.308)	0.983 (0.031)	1.594 (0.676)
5 000	1.188 (0.300)	1.776 (0.144)	4.015 (1.066)
10 000	1.211 (0.263)	2.331 (0.318)	4.761 (1.494)
20 000	1.391 (0.240)	2.917 (0.544)	7.081 (1.527)
30 000	1.560 (0.222)	3.579 (0.551)	7.975 (0.476)
40 000	1.698 (0.146)	4.183 (0.439)	9.661 (0.306)
50 000	1.811 (0.165)	4.970 (0.534)	
60 000	1.914 (0.247)	5.846 (0.716)	
70 000	2.037 (0.414)	6.106 (0.484)	
80 000	2.419 (0.693)	6.782 (0.241)	
90 000	2.779 (1.119)		
99 000			

( ) are standard deviations for the average strain values

TABLE VII-1 PERCENT PERMANENT STRAIN FOR 150/200

No of Rept. (N)	Temperature (C)		
	25	35	45
0	0 (0.000)	0 (0.000)	0
10	0.180 (0.085)	0.203 (0.024)	0.177 (0.020)
50	0.290 (0.091)	0.249 (0.028)	0.292 (0.028)
100	0.339 (0.094)	0.292 (0.028)	0.347 (0.013)
1 000	0.480 (0.105)	0.477 (0.058)	0.576 (0.059)
5 000	0.582 (0.131)	0.653 (0.072)	0.803 (0.144)
10 000	0.634 (0.117)	0.775 (0.092)	1.039 (0.211)
20 000	0.699 (0.128)	0.923 (0.113)	1.432 (0.340)
30 000	0.745 (0.141)	1.021 (0.133)	1.674 (0.403)
40 000	0.785 (0.141)	1.093 (0.147)	1.853 (0.450)
50 000	0.820 (0.158)	1.152 (0.159)	2.045 (0.489)
60 000	0.855 (0.173)	1.194 (0.166)	2.191 (0.525)
70 000	0.888 (0.213)	1.237 (0.177)	2.510 (0.740)
80 000	0.934 (0.238)	1.272 (0.185)	2.594 (0.663)
90 000	0.971 (0.278)	1.302 (0.189)	2.865 (0.749)
99 000	1.014 (0.325)	1.325 (0.192)	3.145 (0.837)

( ) are standard deviations for the average strain values

TABLE VII-2 PERCENT PERMANENT STRAIN FOR HUSKY PMA2

Lethbridge aggregate. Permanent strain values for the individual specimen tested were tabulated for a selected number of repetitions, i.e 10, 50, 100, 1 000, 5 000, and increments of 10 000 to failure or 99 000 repetitions. Average values for permanent strain are reported for convenience. Specimens which exhibited unusually large strains, for no apparent reason were removed prior to calculating the average.

Figures VII-2 and VII-3 present the permanent deformation curves for 150/200 pen grade mix, and Husky PMA 2 for three temperatures. Figures VII-4 to VII-6 present the two mixes side-by-side, for comparison at each test temperature of 25 C, 35 C, and 45 C.

Examinations of the data and plots lead to the following observations, for comparable temperatures, using 150/200 mix as a reference:

At 25 C, the strain for Husky PMA 2 is 1 percent compared to 150/200 pen grade asphalt which has a strain of about 2.8 percent at 99 000 repetitions under the same conditions.

2. At 35 C, the strain for Husky PMA 2 was 1.3 percent compared to 150/200 mix which has strain of about 6.8 percent at 80 000 repetitions under the same conditions.

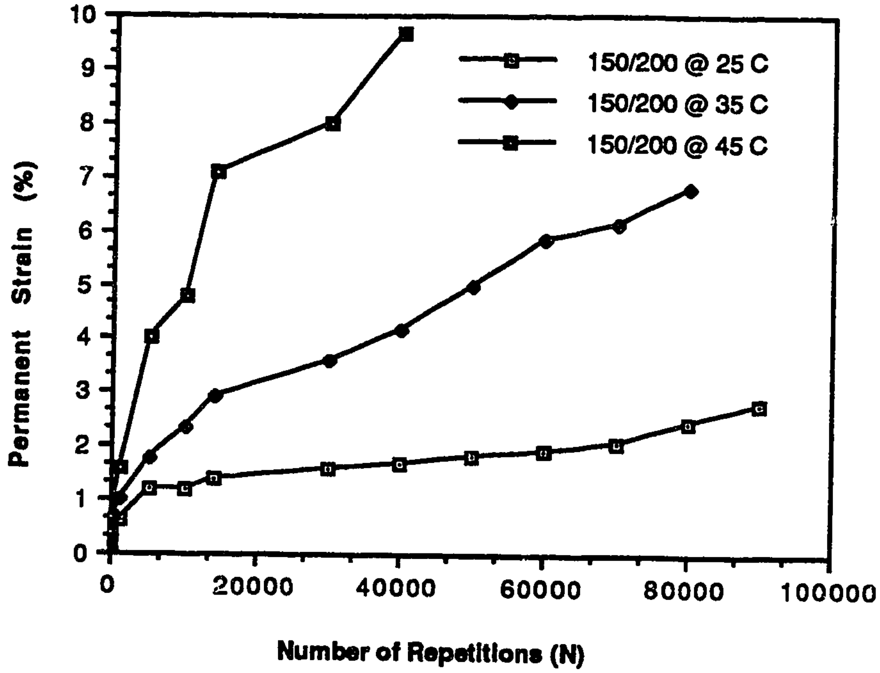


FIGURE VII-2 PERMANENT DEFORMATION CURVES FOR 150/200

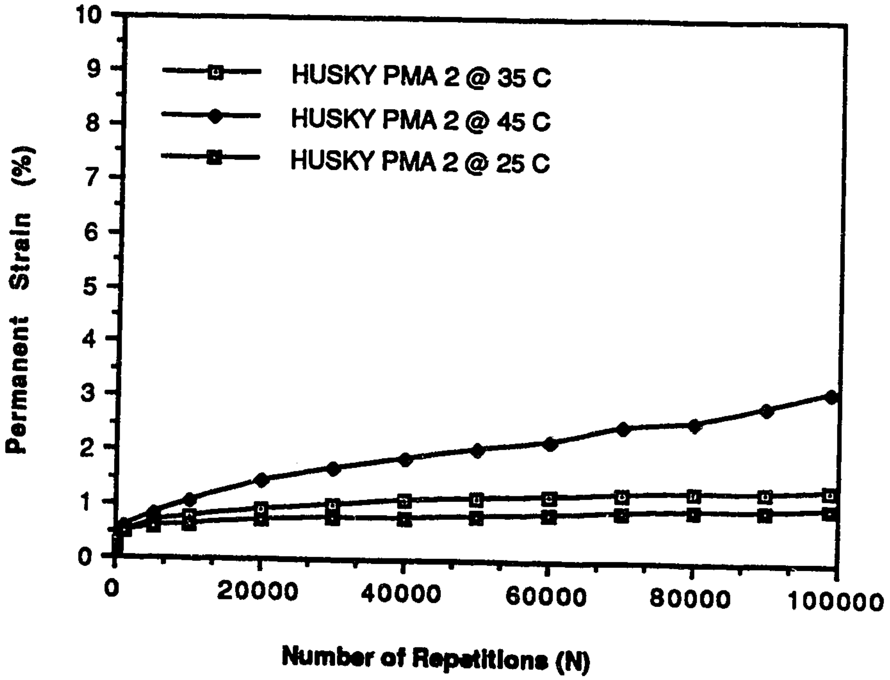


FIGURE VII-3 PERMANENT DEFORMATION CURVES FOR HUSKY PMA2

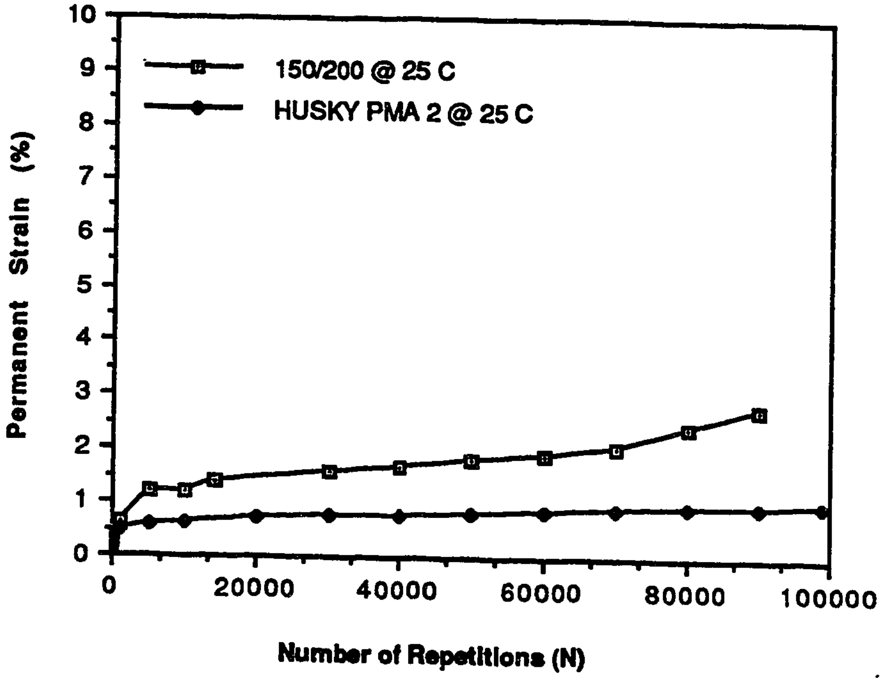


FIGURE VII-4 PERMANENT DEFORMATION CURVES @ 25 C

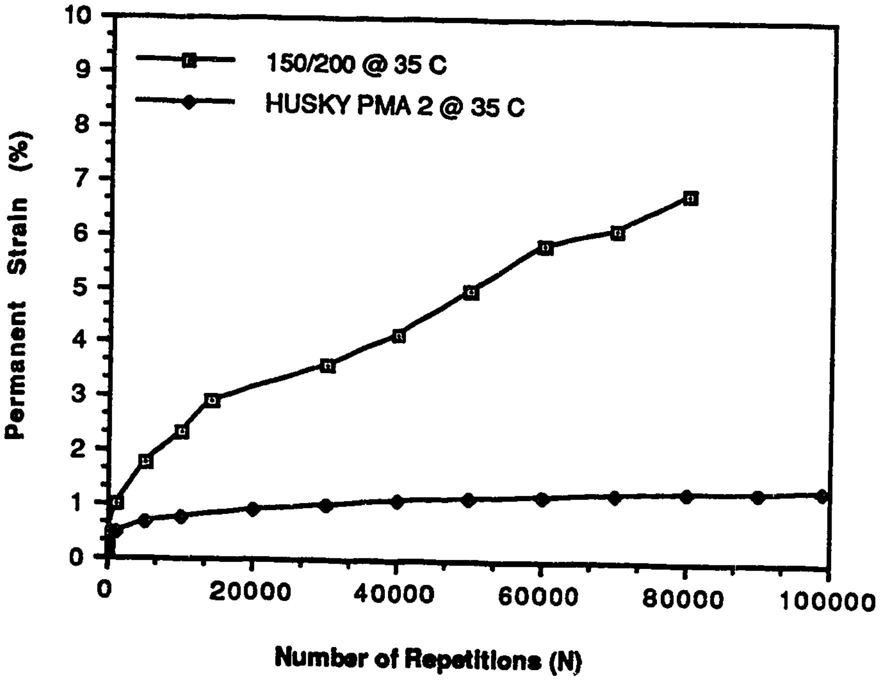


FIGURE VII-5 PERMANENT DEFORMATION CURVES @ 35 C

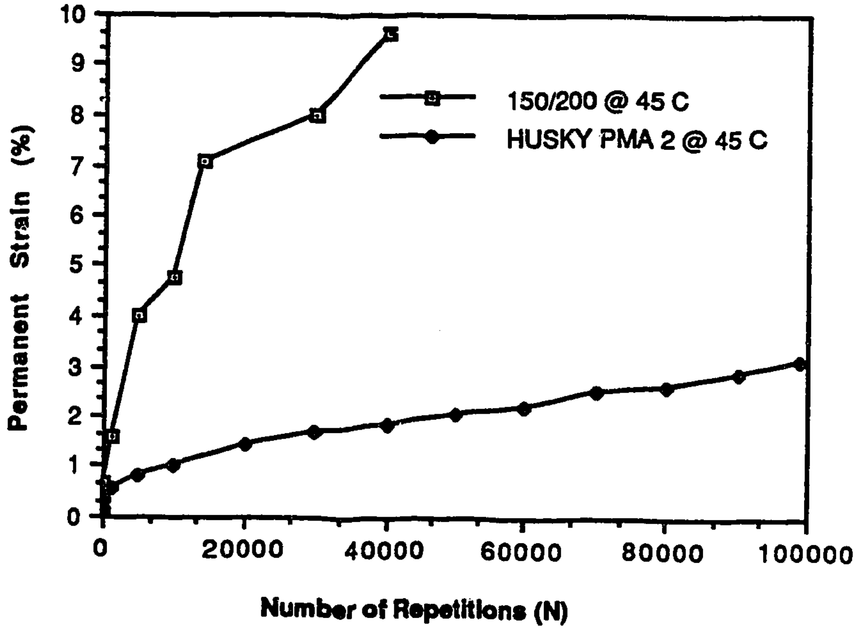


FIGURE VII-6 PERMANENT DEFORMATION CURVES @ 45 C

3. At 45 C the strain for Husky PMA 2 was 1.9 percent compared to 150/200 mix, which has strain of about 9.7 percent,40 000 repetitions, under the same testing conditions.

An overview of the results for the above mixes, shows that the strain increases as the temperature increases. This is due to the fact that, as the temperature increases, the binder stiffness decreases, making the mixes to be less resistant to permanent deformation.

In addition, from Figure VII-6, it can be observed that the Husky PMA 2, at 45 C, had a strain of 3.2 percent after 90 000 repetitions whereas the control mix (150/200) has strain of about 10 percent only after only 40 000 repetitions.

The data and plots points to the observation that the polymer modified mixes tested show improved resistance to permanent deformation under repeated loading condition and, thus, they could be expected to demonstrate superior performance under traffic loadings especially at high temperatures.

7.7 High Temperature Permanent Deformation Characteristic Of Secondary Highway 794 Aggregate

Tables VII-3 and VII-6 summarizes the percent permanent strains at each test temperature, for the two types of binders using secondary highway 794 aggregate. Average values

No of Repet. (N)	Temperature (C)		
	25	35	45
0	0 (0.000)	0 (0.000)	0 (0.000)
10	0.234 (0.099)	0.445 (0.403)	0.221 (0.169)
50	0.408 (0.154)	0.572 (0.407)	0.458 (0.160)
100	0.492 (0.196)	0.634 (0.408)	0.538 (0.160)
1 000	0.825 (0.438)	0.923 (0.402)	1.075 (0.247)
5 000	1.138 (0.733)	1.332 (0.347)	2.222 (0.486)
10 000	1.322 (0.924)	1.678 (0.261)	3.185 (0.712)
20 000	1.564 (1.168)	2.315 (0.202)	4.615 (1.015)
30 000	1.748 (1.397)	2.891 (0.512)	5.688 (1.186)
40 000	1.904 (1.519)	3.539 (0.995)	6.364 (0.950)
50 000	2.044 (1.666)	4.303 (1.646)	6.744 (0.718)
60 000	2.172 (1.802)	4.894 (2.065)	6.888 (0.550)
70 000	2.292 (1.926)	5.108 (1.940)	7.144 (0.542)
80 000	2.406 (2.037)	5.325 (1.806)	7.782 (0.640)
90 000	2.533 (2.137)	5.546 (1.672)	
99 000	2.628 (2.234)	5.742 (1.559)	

( ) are standard deviations for the average strain values

TABLE VII-3 PERCENT PERMANENT STRAIN FOR 150/200A

No of Repet. (N)	Temperature (C) 25		35		45	
0	0	(0.000)	0	(0.000)	0	(0.000)
10	0.133	(0.062)	0.307	(0.159)	0.142	(0.095)
50	0.292	(0.085)	0.408	(0.163)	0.225	(0.098)
100	0.340	(0.091)	0.449	(0.165)	0.263	(0.100)
1 000	0.357	(0.098)	0.593	(0.195)	0.425	(0.095)
5 000	0.418	(0.102)	0.728	(0.253)	0.626	(0.101)
10 000	0.452	(0.100)	0.795	(0.291)	0.750	(0.111)
20 000	0.495	(0.089)	0.862	(0.330)	0.911	(0.121)
30 000	0.575	(0.120)	0.890	(0.341)	1.023	(0.124)
40 000	0.608	(0.126)	0.912	(0.348)	1.115	(0.121)
50 000	0.647	(0.170)	0.929	(0.353)	1.194	(0.113)
60 000	0.678	(0.175)	0.944	(0.357)	1.268	(0.099)
70 000	0.707	(0.195)	0.961	(0.366)	1.346	(0.082)
80 000	0.734	(0.216)	0.970	(0.366)	1.431	(0.057)
90 000	0.760	(0.240)	0.985	(0.370)	1.534	(0.019)
99 000	0.783	(0.256)	0.956	(0.373)	1.635	(0.058)

( ) are standard deviations for the average strain values

TABLE VII-4 PERCENT PERMANENT STRAIN FOR IMPERIAL PMA

for the tested specimens at each temperature, are reported for convenience. Again, specimens which exhibited unusually large strains, for no apparent reason, were removed prior to calculating the averages.

Figures VII-7 and VII-8 present the percent permanent deformation curves for both 150/200A and Imperial PMA, at the three test temperatures. Figures VII-9 to VII-11 present the two mixes side-by-side for comparison, at test temperatures of 25 C, 35 C, and 45 C.

Examination of the data and the figures leads to the following observations, for comparable temperatures, using the 150/200A mix as reference:

1. At 25 C, the strain for Imperial PMA is 0.8 percent compared to 150/200A which has strain of 2.6 percent at 99 000 repetitions, under the same testing conditions.

2. At 35 C, the strain for Imperial PMA is 0.99 percent compared to 150/200A which has a strain of 5.7 percent after 99 000 repetitions, under the same testing conditions.

3. At 45 C, the strain for Imperial PMA is 1.4 percent compared to 150/200A which has a strain of 7.8 percent after 80 000 repetitions, under the same testing conditions.

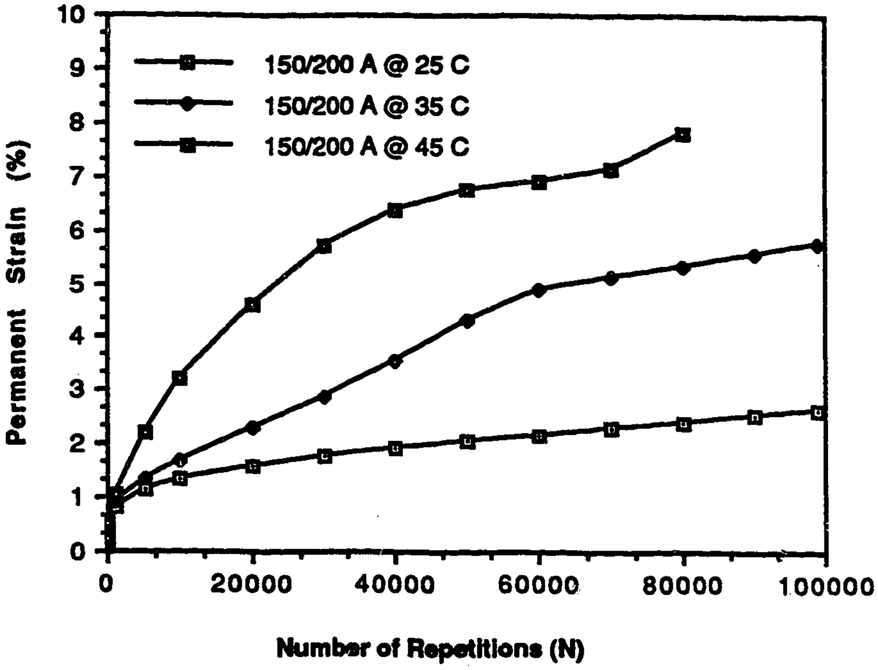


FIGURE VII-7 PERMANENT DEFORMATION CURVES FOR 150/200A AND SECONDARY HIGHWAY 794 AGGREGATE

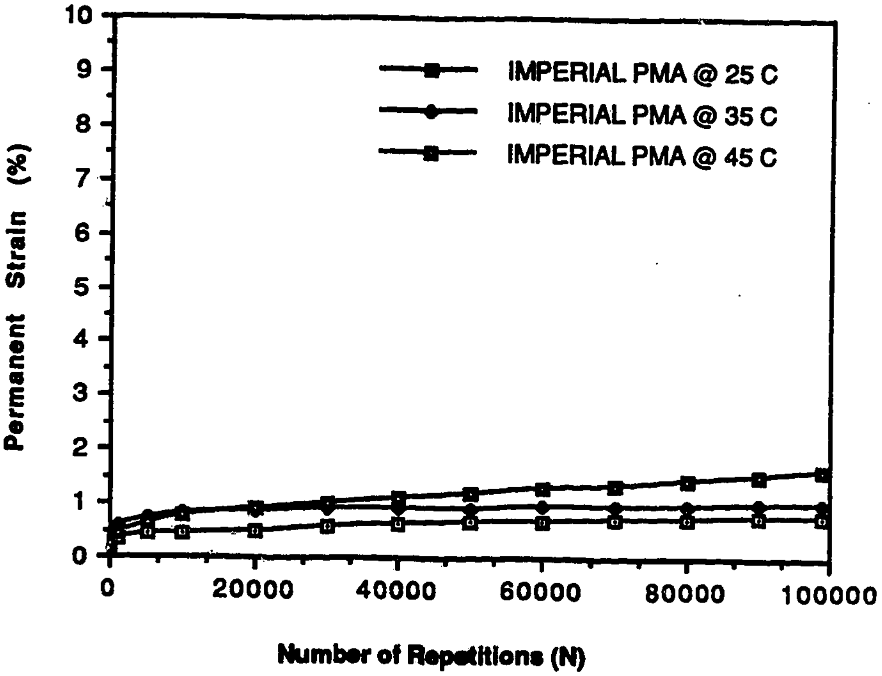


FIGURE VII-8 PERMANENT DEFORMATION CURVES FOR IMPERIAL PMA AND SECONDARY HIGHWAY 794 AGGREGATE

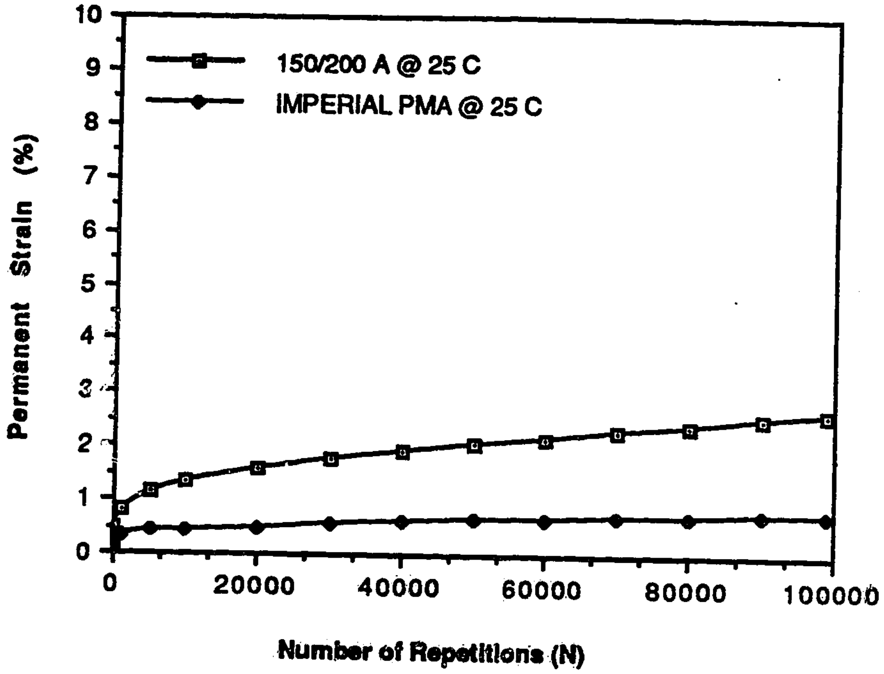


FIGURE VII-9 PERMANENT DEFORMATION CURVES @ 25 C

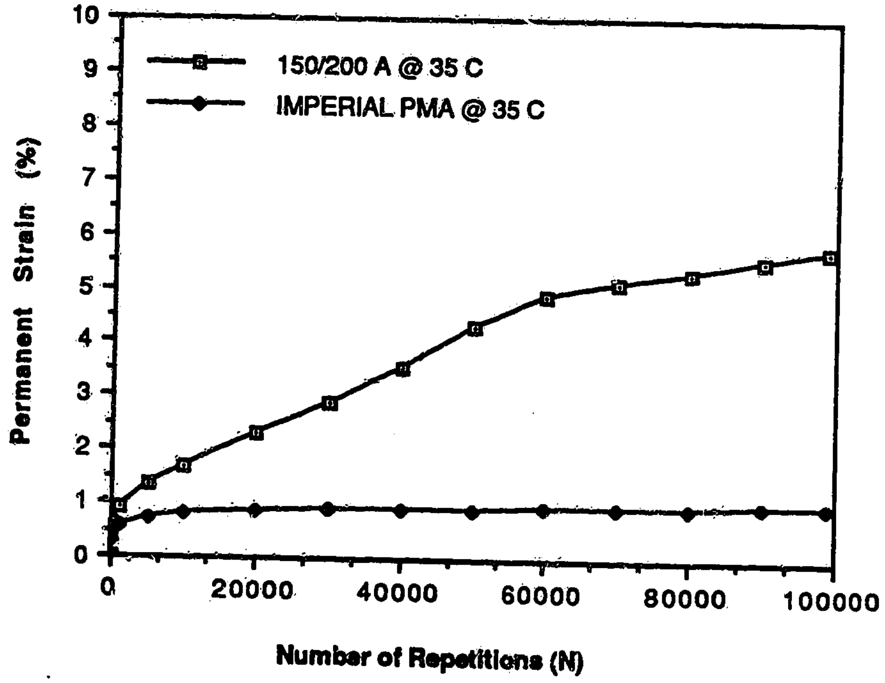


FIGURE VII-10 PERMANENT DEFORMATION CURVES @ 35 C

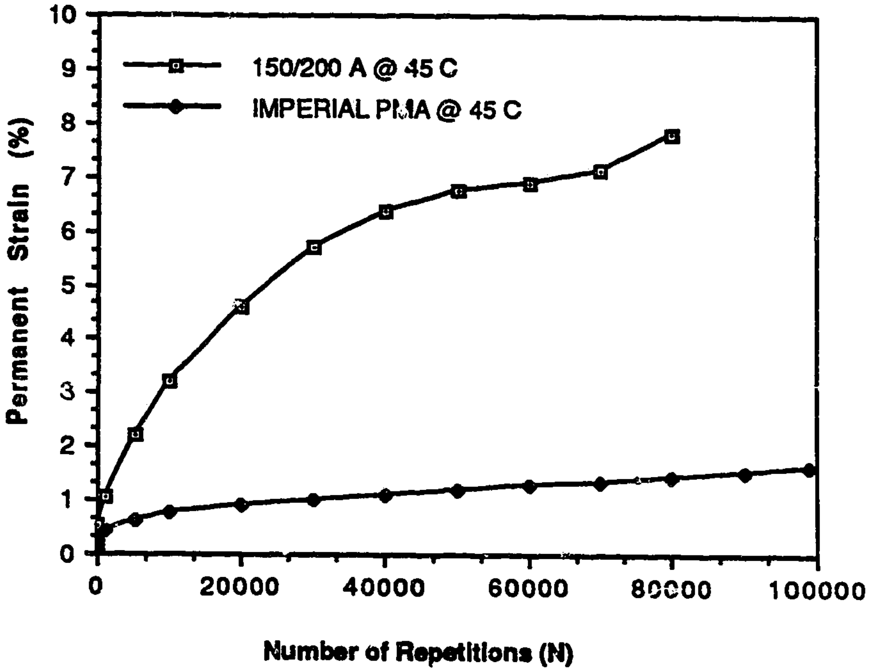


FIGURE VII-11 PERMANENT DEFORMATION CURVES @ 45 C

An overview of the the above data and plots again show that, as the temperature increases, the strain increases. Also from the Figure VII-11, it is observed that the Imperial PMA mix shows a strain of 1.6 percent after 99 000 repetitions whereas the control mix (150/200A) has a strain of 7.8 percent after 80 000 repetitions.

Again, the data indicates that the polymer modified mixes, as compared to conventional mixes show improved resistance to permanent deformation under repeated loading conditions, and thus could be expected to demonstrate superior performance nder traffic loading, especially at high temperatures.

7.8 High Temperature Performance of Conventional and Polymer Modified Asphalt Cements

According to the observed behavior of both conventional and polymer modified asphalt cements during repeated load triaxial testing, it is noted that, in general, polymer modified asphalt cement mixes perform better than the conventional asphalt cement mixes, especially at high temperatures, where the conventional mixes were seen to undergo large strains.

Although the types of aggregate used to fabricate the test specimens were different for the Husky PMA 2 and Imperial PMA mixes, it is observed from the data and the plotted results that both polymer modified asphalt cement mixes performed better than the mixes made with the conventional type of asphalt cements. The Imperial PMA showed better performance in terms of lower percent permanent strain, as compared to the Husky PMA 2. This may be due to the presence of higher amount of manufactured fines in the Secondary Highway 794 aggregate. Figures VII-12 and VII-13 show side by side comparison of the permanent strain at 25 C, 35 C, and 45 C for conventional and polymer modified asphalt cements. For comparable strain of 8 percent and conventional asphalt cements the Lethbridge aggregate reached this load at 30 00 repetitions. whereas the Secondary Highway 794 aggregate sustained 60 000 repetitions at 45 C. The effect of different types of aggregates on the characteristics of conventional and polymer modified asphalt cements is evident.

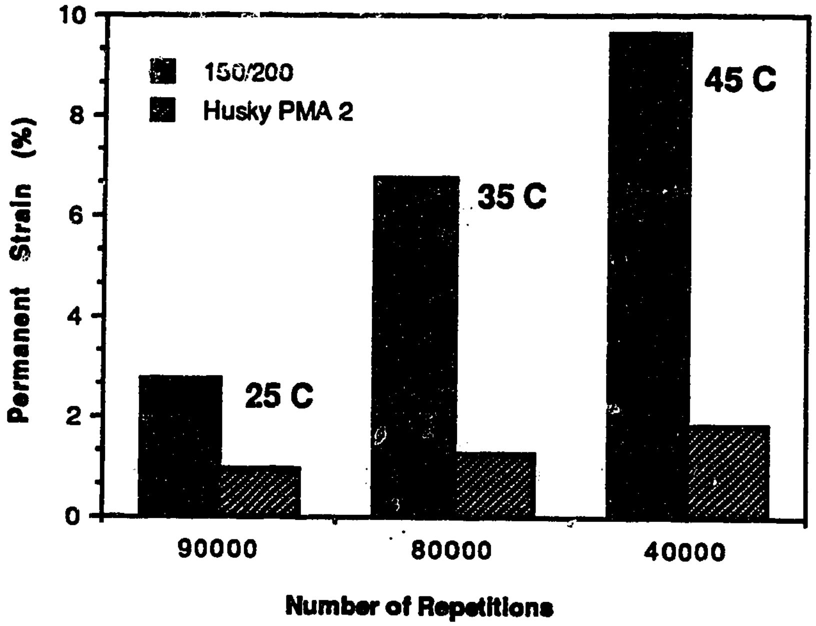
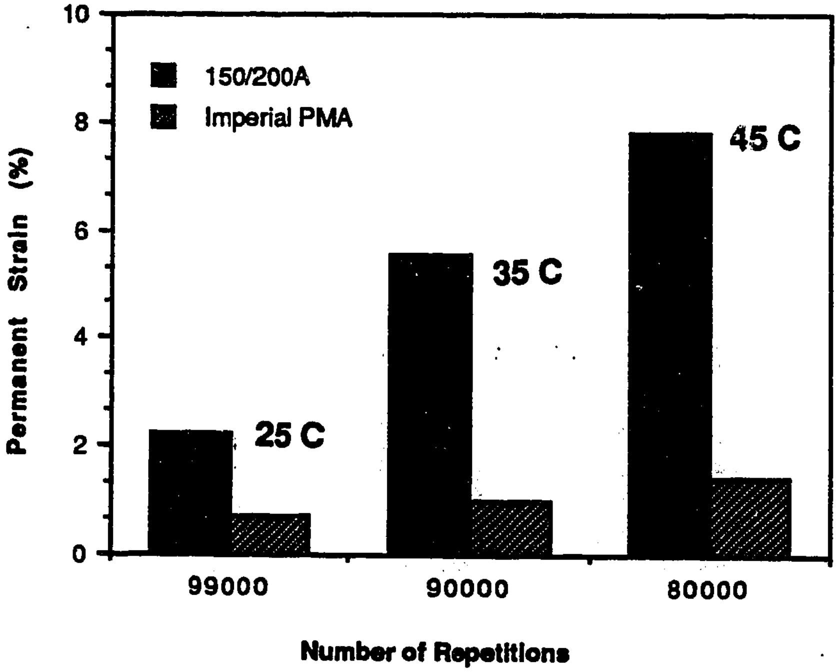


FIGURE VII-12 PERMANENT STRAIN AT 25 C, 35 C, AND 45 C FOR LETHBRIDGE AGGREGATE



IGURE VII-13 PERMANENT STRAIN AT 25 C, 35 C AND 45 C FOR SECONDARY HIGHWAY 794 AGGREGATE

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2. Monismith, C.L., 1976, "Rutting Prediction in Asphalt Concrete Pavements.", Transportation Research Board, Transportation Research Record 616, Washington D.C.

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6. McMillan, C.T., 1989, "A Study of Permanent Deformation Characteristics of Asphalt Concrete Pavements in Alberta.", M.Sc. Thesis University of Alberta.

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CHAPTER 8.0

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The main objective of this research was to evaluate and compare the behavior of conventional and polymer modified asphalts under both high and low temperatures. This has been achieved by laboratory testing of asphalt cement samples, and asphalt concrete specimens fabricated in the laboratory using these asphalt samples. Based on the laboratory test data for the conventional and polymer modified asphalt cements investigated in detail, the following conclusions can be drawn:

1. The indirect tensile strength test results show that the polymer modified mixes exhibit higher failure stresses, higher failure strains, and lower failure stiffness values, in the temperature range from 0 C to -30 C.

2. According to the above results, the polymer modified mixes are expected to be more resistant to thermally induced stresses at low temperatures.

3. For all mixes tensile failure stresses increase, failure

strains decreases, and failure stiffness increase with a decrease in temperature.

4. The laboratory test results showed that the polymer modified asphalt mixes exhibit less permanent strain than the conventional asphalt mixes, which demonstrate that the polymer modified asphalt mixes are more resistant to permanent deformation at high temperatures.

5. The repeated load triaxial test results show that the permanent strain of the various mixes was significantly affected by the test temperature.

6. The type of aggregate incorporated in the mix affects the resistance to permanent deformation at high temperatures.

7. From the trends observed at the low and high temperatures, the polymer modified asphalt mixes are expected to perform better under both low and high temperatures.

8.2 Recommendations

In order to carry out future work on polymer modified asphalt mixes, the following recommendations are presented:

1. The test sections constructed using the Husky PMA 2 and

Imperial PMA asphalt cements should be monitored for permanent deformation and traffic for possible correlation with laboratory test results.

2. There is a significant increase in the cost of producing asphalt concrete mixes with the polymer modified binders, so an economical justification study on life cycle costs for these mixes should be carried out.

3. Two types of aggregates were utilized in this research and they significantly affected the permanent strain of the mixes. Additional studies should be carried out to observe the effects of different aggregates available in Alberta, on the characteristics of the conventional and polymer modified asphalt mixes at both low and high temperatures.

4. Evaluation of characteristics of other polymer modified asphalts at both low and high temperatures is recommended.

5. Since no fundamental progress can be made at all without knowledge of the binder composition, future work should employ only samples whose polymer identity and characteristics and concentrations are known. The same is true for the asphalt component itself.

APPENDIX A

METHOD OF TEST AND ANALYSIS FOR THE LOW TEMPERATURE TENSILE PROPERTIES OF ASPHALT CONCRETE CYLINDERS USING THE INDIRECT TENSILE TEST

APPENDIX A

METHOD OF TEST AND ANALYSIS FOR THE LOW TEMPERATURE TENSILE PROPERTIES OF ASPHALT CONCRETE CYLINDERS USING THE INDIRECT TENSILE TEST

A.1 Scope

This method covers the procedure utilized for determining the low temperature tensile properties of asphalt concrete cylinders using the indirect tensile test. The test can be conducted on asphalt concrete laboratory specimens and cored pavement specimens.

A.2 Summary of Method

The indirect tensile test method consists of loading an asphalt concrete cylinder via loading strips across a diameter, in a compression testing frame and within a controlled temperature chamber maintained at a constant low temperature. Output signals from a load cell and three linear variable differential transducers are recorded on floppy diskette by means of a datalog card installed on a microcomputer. (Figure A.1)

By the use of the Lotus 1-2-3 spreadsheet program, the raw data recorded in the diskette is processed and the tensile

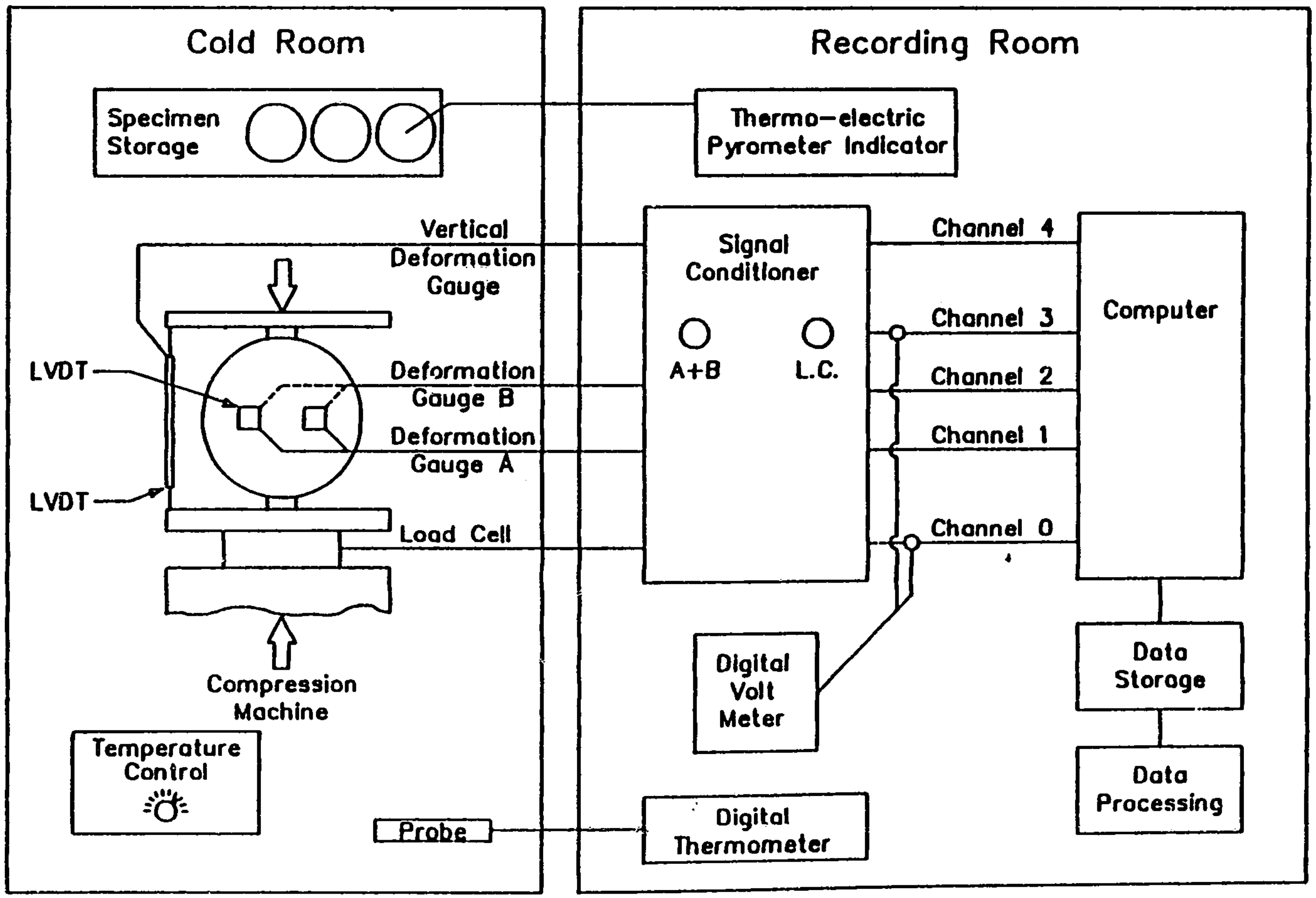


FIGURE A-1 SCHEMATIC OF TEST EQUIPMENT LAYOUT failure stress, failure strain, failure stiffness, and the stress-strain diagram can be obtained.

A.3 Significance

This method determines the tensile stress-strain and stiffness-strain characteristics of asphalt concrete at low temperatures and is primarily intended to assist in the design and evaluation of asphalt concrete with respect to low temperature thermal cracking.

A.4 Apparatus

A.4.1 Controlled Temperature Chamber

The controlled temperature chamber shall be capable of maintaining test specimens at a constant temperature +/-1 C within the range of +10 C to -30 C during the course of a test. A temperature monitoring device shall have its sensor embedded in a specimen of similar size and composition to the specimen which is to be tested and shall be capable of measuring temperature to +/-0.5 C.

A.4.2. Loading Apparatus

A.4.2.1 Compression Testing Frame

The compression frame shall have a minimum capacity of 5 tons and shall be capable of providing the rate of loading prescribed in Section 6.4.

A.4.2.2 Supplementary Bearing Bar or Plate

The supplementary bearing bar or plate shall conform to the specifications for this item in the Standard Methods of Test for indirect tensile strength of Molded Concrete Cylinders (ASTM Designation: C 496-85), except that the width of the bearing bar or plate shall not be less than 33 mm.

A.4.2.3 Bearing Strips

Two steel bearing strips of dimension as shown in Figure A-2 shall be placed between specimen and both the upper and lower bearing blocks of the testing machine or between the specimens and supplemental bars or plates, if used. (See Section A.4.2.2)

A.4.2.4 Load Cell

The load cell shall have a minimum capacity of 4.5 tonnes and shall be capable of measuring compressive loading to +/-1 per cent of true at the rate of loading prescribed in Section 6.4.

A.4.3 Gauge Points, and Marking and Mounting Apparatus

A.4.3.1 Gauge Points

The gauge points shall be 9.525 x 9.525 x 6.35 mm (0.025 mm from mean in any dimension) brass plates.

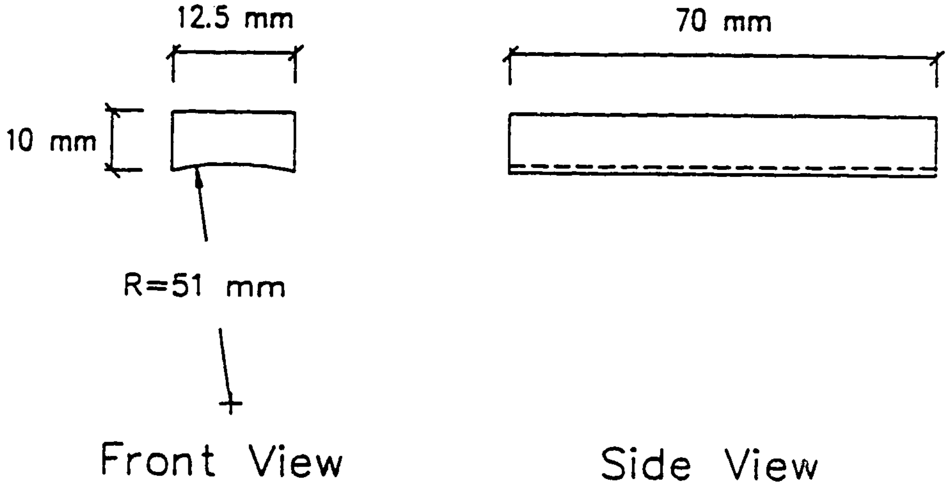


FIGURE A.2 LOAD BEARING STRIPS

A.4.3.2 Gauge Point Jig

The gauge point jig shall provide slots for marking the specimen and holes for mounting the Gauge Points. (Figure A-3)

A.4.4 Deformation Measurement Apparatus

A.4.4.1 Horizontal Displacement Gauges

The displacement gauges shall be two linear variable differential transducers of matched sensitivity (within 5%) and be capable of measuring displacements to within +/-0.00125 mm, and shall have a stroke of not less than +/-0.25 mm.

A.4.4.2 Displacement Gauge Core and Coil Assemblies

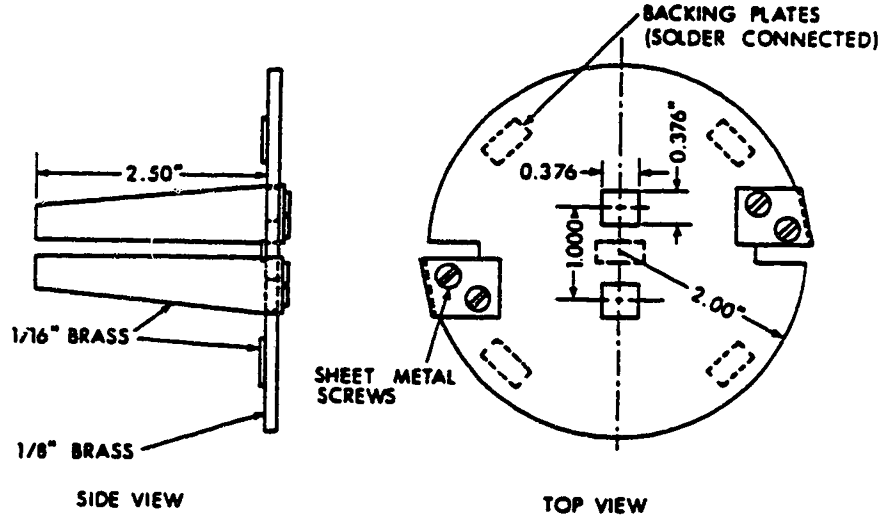
The two displacement gauge core and coil assemblies which hold the Horizontal Displacement Gauges shall be made of brass (Figure A-4)

A.4.4.3 Vertical Deformation Gauge

The displacement gauge shall be a linear variable differential transducer capable of measuring displacement to within 0.01 mm. The gauge shall be mounted on the compression frame and measures the movement of the loading plate.

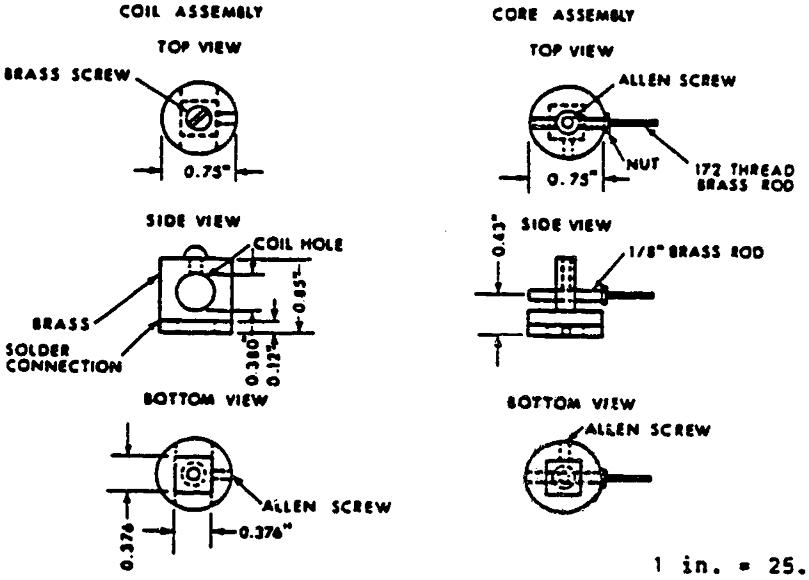
A.4.4.4 Displacement Gauge Calibration Jig

The displacement gauge calibration jig shall be made of



1 in. = 25.4 mm

FIGURE A-3 GAUGE POINT JIG



1 in. = 25.4 mm

FIGURE A-4 DISPLACEMENT GAUGE CORE AND COIL ASSEMBLIES brass and aluminum (Figure A-5) the dial gauge which comprises a portion of the displacement gauge calibration jig shall be a 0.0025 mm dial gauge.

A.4.5 Data Acquisition Apparatus

A.4.5.1 Computer Hardware

The computer hardware for acquiring and recording test data consists of the following:

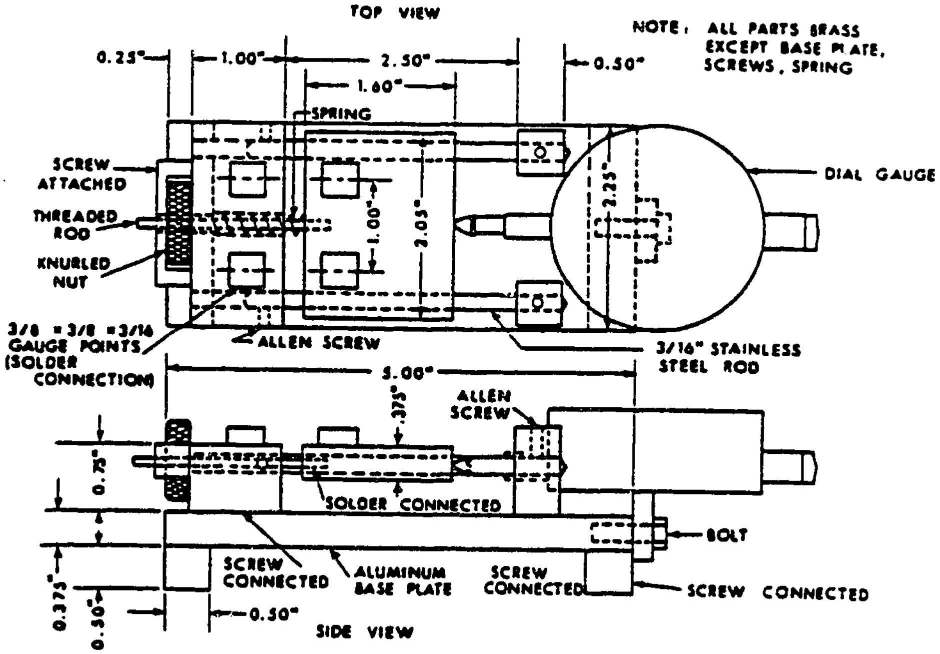
A microcomputer System with minimum 512K Ram is required although 640K Ram is preferred in order to provide a margin of safety for the computer operation.

Two double sided, double density disk drives are required in order to run the softwares. The first or "A" drive contains the operating system and the BASIC program. The second or "B" drive is used to store test data upon completion of the test.

A multifunction card is used for printer communication.

A clock card is used to note the time.

A Metra Byte Dash-8 Board is used to collect the test data in analog form and convert them into digital form for use by the computer. The Dash-8 board has 8 channels available for datalogging. Only five is needed. They are:



1 in. = 25.4 mm

FIGURE A-5 DISPLACEMENT GAUGE CALIBRATION JIG

a. Channel 0 ----- Load Cell
b. Channel 1 ----- LVDT A
c. Channel 2 ----- LVDT B
d. Channel 3 ----- Average of A and B
e. Channel 4 ----- Vertical LVDT

The Dash-8 board has a full scale input of + 5 volts on each channel with a resolution of 0.00244 volt.

A.4.5.2 Computer Software

Two software packages are required by the computer to acquire and record the test data. One is the IBM PC DOS version 3.1 and the other is the Dash-8 configuration package. A BASIC program written specifically for the indirect tensile test is also required.

The DOS disk operating system allows the establishment of a virtual disk on the computer for temporary data storage. When the test is finished, the contents of the virtual disk is transferred to the 'B' drive. The Dash-8 software package provides the input output driver routine which can be accessed from BASIC using the Call statement. The BASIC program defines various functions and operation in the use of the computer hardwares. The main function and operation defined in this program include the gathering of test data at designated intervals and duration; and the storing of the data in the computer and copying them to drive 'B', by using the Dash-8 software package. A listing of this program is enclosed in Section A.10.

A.4.5.3 Signal Conditioner

The signal conditioner is used to amplify, filter and condition the input signals from the test before sending the signals to the Dash-8 board. The conditioner also serially connects the input signals of the LVDT A and LVDT B resulting an average value for the horizontal deformation. In addition to the above functions, the conditioner is used to zero the signals of the load cell and the LVDTs, before sending them to the Dash-8 board.

A.5 Test Specimens

A.5.1 Asphalt Concrete Laboratory specimens

The specimens were fabricated according to procedure described in Chapter 5 using Asphalt Institute Manual Series MS-2 method.

A.6 Procedures

A.6.1 Calibration

A.6.1.1 Load Cell

The Load Cell shall be calibrated at room temperature (if temperature compensating) or at the test temperature (if non-temperatuire compensating), on a Compressing Tester whose load accuracy has been verified to + 1 percent in accordance with the Standard Methods of Verification of Testing Machines, ASTM Designation: E4-64.

A.6.2 Dial Gauge

The dial gauge shall be calibrated while on the Displacement Gauge Calibration Jig described in Section A.4.4.4, using machinist's gauge blocks.

A.6.2.1 Displacement Gauges

The two horizontal displacement gauges shall be calibrated when the two gauges are connected in series. They shall also be calibrated separately. The calibration shall be carried out on the Displacement Calibration Jig (using a 25.4 mm gauge length at null)

at the test temperature. Output signal (in terms of voltage) from the displacement gauges shall be measured by a digital voltmeter as well as by the computer data acquisition system.

A.6.3 Preparation of Specimen for Testing

A.6.3.1 Measurement

Determine the length and diameter of the test specimen to the nearest 0.25 mm by averaging four readings at each dimension.

A.6.3.2 Marking

Mark diametral loading points on each end of the specimen in the same axial plane using the Gauge Point Jig described in Section A.4.3.2.

A.6.3.3 Gauge Point Attachment

Cool the specimens to at least -10 C for about 2 hours before attaching the gauge points. Coat one side of each of two gauge points (described in Section A.4.3.1) with warm asphalt cement. (Use grade 200/300A asphalt cement for testing at temperature of -10 C or below. Use grade 85/100A asphalt cement for testing at temperature above -10 C). Warm the gauge points and insert the two coated Gauge Points through the holes in the aligned Gauge Point Jig and press firmly onto the specimen. Leave the specimen to cool horizontally for approximately 3 minutes to firmly affix the gauge points to the specimen. Invert the specimen (and prop in a manner that will not disturb the previously attached Gauge Points) and attach the other two Gauge Points in a similar manner.

A.6.3.4 Cooling

Immediately place the specimen into the Controlled Temperature Chamber.

A.6.4 Preparation for Loading of the Specimen

A.6.4.1 Specimen Inspection

After the specimen to be tested has reached equilibrium temperature, inspect it for Gauge Point slippage. If any slippage is evident remove the Gauge Points and repeat steps A.6.2.3 and A.6.2.4.

A.6.4.2 Positioning

Place the Load Cell on the loading ram platen of the Compression Testing Frame. Position the specimen so that the marked loading points are in a vertical plane passing through the center of thrust and so that the longitudinal axes of the Bearing Strips are in this vertical plane. Raise the loading ram of the Compression Testing Frame just enough to secure the specimen for Displacement Gauge attachment.

A.6.4.3 Displacement Gauge Attachment

Tie both of the Displacement Gauge Core and Coil Assemblies to some point on the Compression Testing Frame to obviate damage after specimen failure. Simultaneously place the rear Displacement Gauge Core and Coil Assembly onto the Gauge Points and then secure the assemblies by tightening the allen screws. Repeat the foregoing attachment procedure for the front Displacement Gauge Core and Coil Assembly.

A.6.5 Loading and Recording Procedure

A.6.5.1 Loading Rate

Set the Compression Testing Frame to a nominal loading rate of 1.47 mm/min. The actual loading rate many vary from the nominal loading rate by +/-10 percent but must be reproducible within +/-1 percent.

A.6.5.2 Loading

Engage the Compression Testing Frame and return to the recording area (Note: Loading will not begin until the power supply switch for the servo motor is closed. This switch should be located in the recording area, adjacent to the recorder).

A.6.5.3 Recording

Make sure all the wirings are hooked up correctly. Adjust the signal conditioner switches such that the voltage outputs from the load cell and the displacement gauges to the datalog card are conditioned close to +/-0.000 V. Run the computer program for datalogging. Input information as requested from the screen. This include the duration of recording data, the frequency of reading data and the name of channels to be used. (Channel 0 to Channel 4) The name of the sample will also be requested and will be used as the filename of the dataset. Press the run key and the computer will start to record data.

Record all other pertinent data such as date of test and test temperature (air and specimen) on the laboratory log book. The computer will stop recording data after the given period of time and copy the data set into floppy diskette.

A.6.5.4 Termination of Test

Upon failure of the specimen, turn off the power supply switch for the servo motor. Disengage the Compression Testing Frame and examine the fractured specimen. If the fracture surface passes under a Gauge Point the test shall be rejected.

A.7 Calculations

A.7.1 Tensile Stress

The tensile stress at any point to failure shall be calculated as follows:

$$T = \frac{2 * P}{P_i * t * d}$$

where:

t = specimen thickness, in m

d = specimen diameter, in m

T = tensile stress, in kPa

P = applied load, in kN, calculated as follows:

$P_i = 3.142$

$$P = \frac{N_p * k_1}{410}$$

where:

N_p = values, in binary bit form as recorded in channel 0 of the data file, 1 volt = 410 bits,

K_1 = conversion factor of load cell, in kilonewton per volt obtained from calibration.

A.7.2 Strain

The strain, at any point to failure is equal to the average deformation, in mm, as measured by the two horizontal deformation gauges, A and B, calculated as follows:

$$S = \frac{Nab * K_2}{410 * 25.4}$$

where:

S = average deformation of the strain gauges A and B, in mm/mm

Nab = value as recorded in binary bit form in channel 3 of the data file, 1 volt = 410 bits,

K_2 = conversion factor of the deformation gauges in mm per volt.

Due to the biaxial state of stress existing within the cylindrical specimen, the displacement measured between the gauge points is a result of both compressive stresses in the vertical direction and tensile stresses in the horizontal direction. The term strain is used without differentiation as to its cause. If tensile strain is desired, as for calculation of a stiffness modulus, use of equations applying the Generalized Hooke's Law is necessary.

A.7.3 Failure Strain

The failure Strain shall be considered as the strain corresponding to the first maximum stress reach during the test.

A.7.4 Tensile Strength

The tensile strength shall be considered as the maximum tensile stress.

A.7.5 Stiffness Modulus

The tensile stiffness modulus at any point to failure shall be calculated as follows:

$$S_t = \frac{0.912 * T}{0.5 * Sab}$$

where:

S_t = Tensile Stiffness Modulus in MPa,

T = Tensile stress in MPa,

Sab = Average strain of strain gauges A and B in mm/mm.

A.7.6 Data Processing

When the test is terminated, the raw test data stored in the disk is processed by an IBM XT microcomputer using the Lotus 1-2-3 spreadsheet program. A lotus 1-2-3 Macro program is written specifically to perform the calculations which are described earlier in this chapter. A listing of the Macro program and the instruction for using it are contained in Section A.10.

The printout of the processed data includes the stress, strain and stiffness of the specimen at each point of time during the test. The failure stress, failure strain and failure stiffness are determined by locating the maximum stress the specimen has first experienced. A sample printout is contained in Section A.10.

By selecting the appropriate pairs of stress-strain data, the stress strain diagram of the test specimen can be drawn by means of the Lotus 1-2-3 graph software or any other plotting programs.

A.8 Report

The report shall include the following:

1. Identification number, aggregate identification, asphalt cement penetration or viscosity, and asphalt cement supply,
2. Test temperature,
3. Rate of loading
4. Specimen diameter, and thickness,
5. A printout of the processed data of stress, strain and stiffness,
6. The failure strain,
7. The tensile strength,
8. A stress-strain diagram, and
9. Any abnormalities in the type of fracture.

A.9 Sources of Experimental Errors

The following are some of the sources of experimental errors that have been identified in the tensile splitting test method described in the previous chapters. Possible procedures to reduce these errors are also presented.

1. Shape of specimen may not be truly cylindrical. This may be caused by distortion during extraction in the case of

Marshall briquette or by poor quality coring in the field. This error will cause non-uniform loading of the specimen leading to erroneous results. To reduce this error, strict adherence to MS-2 procedure for preparation of Marshall briquettes and well supervised coring in the field are necessary.

2. The level of the loading platens of the compression machine may not be truly horizontal. This again will result in non-uniform loading of the specimen. To ensure that the loading platens are level, check and adjust the loading platens before each test.

3. The loading strips may be seated improperly. This will result in loading the specimen not in an axial plane which is assumed in the theory to calculate the stress distribution. To avoid this error to happen, align the diametral lines of the specimen with the centre of the loading strip and the line of thrust of the testing machine.

4. The compression machine may vibrate excessively, particularly at the start of a day's testing and/or at colder temperature. This will result in a large fluctuation of the readings of the LVDTs. To eliminate this problem, run the machine for a few minutes before starting the day's tests. Also check to ensure the driving belt of the servo motor is

tight.

5. The reading of the LVDTs may be moving before the test begins (very often at higher temperature). This indicates that either the LVDTs are not secured to the gauge points or the gauge points are slipping. To overcome this problem, tighten the allen screws of the core and coil assemblies and check the slippage of the gauge points. If slippage of the gauge points is identified, remove the gauge points and re-attach the gauge points using a harder asphalt. (Section 3.2.3)

6. The LVDTs may not at a horizontal position. This will result in inaccuracy in the strain reading. The problem may be caused by gauge point slippage, inaccuracy in marking the diametral lines or improper positioning of the specimen. To overcome this problem, check the position of the specimen and the accuracy of the diametral lines. Check the slippage of the gauge point. Make sure that the gauge points are firmly affixed (that is, the asphalt cement is cool) before inverting the specimen for another pair of gauge point.

7. The air temperature of the cold chamber may fluctuate, very often as much as 2 to 3 C during the course of the test. The temperature of the specimen also fluctuates, but to a lesser extent in the order of 1 to 2 C. This

fluctuation is caused by heat loss when opening the door of the cold chamber and the sensitivity of the thermostat which controls the activation of the compressor of the cold chamber. In general, provided the door of the cold chamber is closed tightly every time a person enters or leaves the chamber, a couple of adjustments of the thermostat is sufficient to bring the temperature of the specimen to within 1 C of the required test temperature.

8. The temperature of the cold chamber may be increasing though the thermostat is kept at the same temperature. This happens very often after a long duration of colder temperature being kept in the cold chamber because frost has been developed. To solve this problem, a half hour defrost operation is necessary.

9. The readings of a particular channel may stay constant at +2048. This happens when the input signal into the computer is exceeding +5V which is the extremes that the datalog card can read. This problem may be caused by either the LVDTs are not within their stroke range for example, the gauge points are not at a distance of 25.4 mm apart) or the signal conditioner is not used to condition the signal close to zero before starting test. To eliminate this problem, check that the LVDTs are positioned within their stroke range and that the signal conditioner is used to condition the signal to close to zero

volt with a voltmeter.

A.10 Listing of Computer Programs and Sample Printout

A.10.1 BASIC Program for Data Acquisition using the DASH-8 Card

```
120 OPEN "dash8.adr" FOR INPUT AS #1
130 INPUT #1, BASADR%
135 CLOSE #1
136 CLS
200 DIM DIO%(8),LT%(2)
210 INPUT "Enter length of stage #1(1 to 60 min.)":S1
220 INPUT "Enter interval(1 to 60 sec)":I1
230 INPUT "Enter length of stage #2(1 to 60 min.)":S2
240 INPUT "Enter interval(1 to 60 sec)":I2
250 TCOUNT=(S1*(60/I1))+(S2*(60/I2))
260 INPUT "Enter first channel":FC%
270 INPUT "Enter last channel":LC%
275 MD%=1:LT%(0)=FC%:LT%(1)=LC%:CALL DASH8 (MD%, LT%(0), FLAG%)
280 INPUT "Enter file name":F$:FF$="c:"+F$+".prn"
290 OPEN FF$ FOR OUTPUT AS 3
400 MD%=0:CALL DASH8 (MD%, BASADR%, FLAG%)
450 'enter stage #1
465 ON TIMER(I1) GOSUB 4000
470 ON KEY(1) GOSUB 2080:ON KEY(2) GOSUB 2500
480 KEY(1) ON:KEY(2) ON
485 PRINT"Press F1 to start test"
500 IF TEST=1 THEN GOTO 3000
510 GOTO 500
2000 TEST=1:RETURN
2500 OF=1:RETURN
3000 TIMER ON 'start datalogging
3010 IF OF=1 THEN GOTO 5000
3020 GOTO 3010
4000 IF READNO.=TCOUNT THEN GOTO 5000
4001 IF READNO.=S1*(60/I1) THEN ON TIMER(I2) GOSUB 4000
4003 MD%=2:CH%=FC%:CALL DASH8 (MD%, CH%, FLAG%)
4005 FOR I=FC% TO LC% 'a/d routine
4020 MD%=4:CALL DASH8 (MD%, DIO%(I), FLAG%):NEXT I
4030 READNO.=READNO.+1:TC=VAL(LEFT$(TIME$,2)+MID$(TIME$,4,2)+RIGHT$
4040 PRINT TC READNO.;:FOR I=FC% TO LC%:PRINT DIO%(I);:NEXT I:PRINT
4050 PRINT #3,TC READNO.;:FOR I=FC% TO LC%:PRINT #3,DIO%(I);:NEXT I
4060 RETURN
5000 CLOSE 3:SYSTEM
```

A.10.2 Lotus 1-2-3 Macro Program for Data Processing

The following is a listing of the LOTUS Macro that is used to perform the necessary calculations on the data from the tensile splitting tests. Along with the macro are included some comments to aid in future modifications of the macro. These comments DO NOT appear on the worksheet. The macro does not appear here in the same format as on the worksheet in order to facilitate the inclusion of comments.

This is the main macro which controls the selection of files to be processed. The files are to be listed under the headings of: "SAMPLE" and "TEMP" and "THICK". Under the "SAMPLE" heading input the name of the file that contains the test data. The "TEMP" requires the input of the temperature at which the sample was tested. The "THICK"ness is to be input in millimeters.

```
{goto}BEGIN¬         | this section          SAMPLE       TEMP     THICK
/rndIDA¬             | initializes
/rndTEMP¬            |  the macro            RW20          -20      69.6
/rndTHIK¬            |                       H12           -30      69.7
/rncIDA¬¬
{goto}IDA¬
/rndIDA¬
{down}
/rncIDA¬¬
{right}
/rncTEMP¬¬
{right}
/rncTHIK¬¬
/xiTHIK=0¬/xq¬
/cIDA¬
SAMNO¬
/cIDA¬                | this section copies the data
SAMNO2¬               | to other portions of the wks for
/cIDA¬                | subsequent use'by the following macros
FRET¬                 |
/cTEMP¬               |
SPTEMP¬               |
/cTHIK¬               |
THICK¬                |
/xcSTART¬             | this transfers control to the "START-UP" macro
/rndTEMP¬
/rndTHIK¬
/xgLOOP4¬             | this loops the macro back to the first line



START-UP MACRO

/wgrm                  | set the wks recalc to manual
/reALL¬                | erase old data
/rncTEST2¬¬
/rncTEST3¬¬
/rndTEST2¬
/rndTEST3¬
{goto}A5¬
/finUSR\GARYV\TENSILE\            | importing the data file
H12
¬{goto}TABLE1¬
+0.0000001¬
/c¬C250..J250¬                    | initializing the first value to
{goto}TABLE2¬                     | approx. zero (0) on calc table
{@ABS(C6-$C$5)+1.0000E-11)
/410*1000¬                        | calculations to convert the imported
{right}                           | data (bit format) into SI form of data
(@ABS(D6-$D$5)+1.0000E-11)  A     | ie. deflections, loads etc.
/410*0.01¬
```

A.10.3 Instructions for Using the Macro Program for Data Processing

INSTRUCTIONS FOR USING LOTUS 1-2-3 SPREADSHEETS

FOR TENSILE SPLITTING DATA CALCULATIONS

The computer is setup in such a way that LOTUS 1-2-3 can be called up from any directory in the computer. When you have turned the computer on and you are at the "C:\>' prompt type in the following command "123" and LOTUS will be loaded into the computer.

From there type in "/fr" (/ file retrieve) and a series of directory names will appear on the command line. Choose the directory named "USR" then another series of directories will appear, this time choose the one named "GARYV" and finally one more list of directories will appear, choose the one named "TENSILE". Then a file name called "TSPLIT" will appear and press the return key. The screen will blank out for a few seconds and then the worksheet will appear on screen.

On the command line a menu will appear with the following choices:

Enter Data   Process   Quit

Point to the operation you wish to perform and press the enter key or else press the first letter of the command (i.e. E, P, Q).

ENTER DATA

If you choose to enter or edit data the computer will move the cell pointer to the first line of data. In this case data refers to the "FILENAME", the "TEST TEMP." and the "THICKNESS". This data must be entered in order for the computer to know which files you wish to process. The files that are to be processed must have been copied into directory "\USR\GARYV \TENSILE" previous to starting the processing.

The data must be entered under the correct headings as follows:

FILENAME   TEST TEMP   THICKNESS

The filename does not require the ".PRN" at the end, the computer assumes this file designation. The test temp can be any number positive or negative. The thickness must be input in INCH !!!! The data must be entered in columnar form so to move from cell location to cell location use the cursor keys.

Once you have finished entering or editing the data press the "Alt" and "A" keys simultaneously to return to the command menu.

PROCESS

If you wish to process the data then use this command and the computer will automatically begin processing the data. The computer requires approximately 20 minutes to complete the calculations for each set of test data. Once the calculations are completed for a set of data the computer will write the results onto the hard disk for later retrieval. The computer will then erase the calculated data and begin calculations on the next data set. When the computer has finished processing all of the data sets the command menu will reappear on the screen.

QUIT

This command causes the computer to save the worksheet and exit from LOTUS 1-2-3.

Once you have exited from LOTUS you can print out any of the processed data by going to the directory named "C: USR GARYV TENSILE >" and typing in the following command:

```
PRINT FILENAME.PRN
```

A.10.4 Sample Printout of Processed Test Data

```
  TIME     READING    LOAD     LVDT       LVDT               VERTICAL   STRESS   STRAIN   STIFFNESS
(HHMMSS)   NUMBER     (KG)        A          B        A+B        LVDT    (kPa)     RATE      (MPa)
                                                                                 (mm/min)
9:34:52        1        .0         .0         .0         .0         .0        0        0          0
9:34:53        2        .0    0.00005     .00000     .00000    0.03831        0    2.299      105.0
9:34:54        3        .0    0.00002     .00000    0.00004    0.01915       .0   -1.149          0
9:34:55        4        .0     .00000     .00000     .00000    0.08620       .0    4.022      109.0
9:34:56        5        .0    0.00005     .00000     .00000    0.59379       .0   30.456      105.0
9:34:57        6      26.8    0.00002    0.00002    0.00004    0.63210     24.1    2.299     1155.1
9:34:58        7      56.1    0.00002    0.00005    0.00004    0.69914     50.4    4.022     2415.2
9:34:59        8      87.8    0.00007    0.00007    0.00006    0.62253     78.9   -4.597     1890.2
9:35:00        9     117.1    0.00007    0.00010    0.00004    0.68957    105.1    4.022     5040.5
9:35:01       10     143.8    0.00010    0.00010    0.00008    0.60337    129.2   -5.172     3097.8
9:35:02       11     170.7    0.00010    0.00012    0.00008    0.61295    153.3    0.575     3675.3
9:35:03       12     195.0    0.00012    0.00012    0.00011    0.26816    175.2  -20.687     2800.3
9:35:04       13     222.0    0.00012    0.00017    0.00011    0.29689    199.3    1.724     3185.3
9:35:05       14     248.8    0.00015    0.00017    0.00015    0.27774    223.4   -1.149     2677.7
9:35:06       15     276.8    0.00017    0.00022    0.00019    0.27774    248.7    0.000     2384.2
9:35:07       16     304.9    0.00017    0.00024    0.00019    0.26816    273.8   -0.575     2625.2
9:35:08       17     326.8    0.00022    0.00028    0.00023    0.27774    293.5    0.575     2345.2
9:35:09       18     353.7    0.00022    0.00029    0.00027    0.26816    317.6   -0.575     2175.2
9:35:10       19     378.0    0.00022    0.00034    0.00027    0.29689    339.5    1.724     2329.2
9:35:11       20     404.8    0.00027    0.00037    0.00030    0.27774    363.6   -1.149     2178.8
9:35:12       21     429.3    0.00027    0.00041    0.00030    0.30647    385.5    1.724     2310.2
9:35:13       22     453.7    0.00032    0.00041    0.00034    0.26816    407.4   -2.299     2170.2
9:35:14       23     480.5    0.00034    0.00046    0.00038    0.26816    431.5    0.000     2068.7
9:35:15       24     502.4    0.00037    0.00048    0.00046    0.27774    451.2    0.575     1803.7
9:35:16       25     526.8    0.00039    0.00056    0.00046    0.30647    473.1    1.724     1890.2
9:35:17       26     551.2    0.00044    0.00058    0.00049    0.28732    495.1   -1.149     1825.6
9:35:18       27     573.2    0.00048    0.00059    0.00053    0.32563    514.8    2.299     1762.7
9:35:19       28     597.6    0.00049    0.00066    0.00057    0.31605    536.7   -0.575     1715.2
9:35:20       29     619.5    0.00054    0.00068    0.00061    0.34478    556.4    1.724     1667.0
9:35:21       30     643.8    0.00056    0.00073    0.00065    0.30647    578.3   -2.299     1630.7
9:35:22       31     665.9    0.00061    0.00078    0.00068    0.27774    598.0   -1.724     1582.6
9:35:23       32     687.8    0.00063    0.00083    0.00072    0.32563    617.7    2.873     1558.6
9:35:24       33     712.2    0.00066    0.00088    0.00076    0.28732    639.6   -2.299     1533.1
9:35:25       34     734.1    0.00071    0.00093    0.00080    0.32563    659.3    2.299     1505.1
9:35:26       35     758.5    0.00076    0.00102    0.00088    0.31605    681.2   -0.575     1410.8
9:35:27       36     778.0    0.00080    0.00105    0.00091    0.34478    698.7    1.724     1395.8
9:35:28       37     800.0    0.00083    0.00112    0.00095    0.34478    718.5    0.000     1377.7
9:35:29       38     819.5    0.00086    0.00115    0.00098    0.33521    736.0   -0.575     1357.0
9:35:30       39     841.5    0.00093    0.00120    0.00103    0.31605    755.7   -1.149     1341.8
9:35:31       40     863.4    0.00098    0.00124    0.00110    0.34478    775.4    1.724     1281.8
9:35:32       41     882.9    0.00102    0.00134    0.00118    0.34478    793.0    0.000     1226.2
9:35:33       42     904.9    0.00107    0.00144    0.00122    0.33521    812.7   -0.575     1217.5
9:35:34       43     926.8    0.00112    0.00146    0.00129    0.34478    832.4    0.575     1173.6
9:35:35       44     946.3    0.00117    0.00154    0.00137    0.36394    849.9    1.149     1131.8
9:35:36       45     968.3    0.00124    0.00163    0.00145    0.36394    869.6    0.000     1087.1
9:35:37       46     987.8    0.00129    0.00168    0.00149    0.36394    887.2    0.000     1080.5
9:35:38       47    1007.3    0.00137    0.00178    0.00156    0.40225    904.7    2.299     1057.8
9:35:39       48    1024.4    0.00144    0.00185    0.00164    0.37352    920.0   -1.724 [illegible]
9:35:40       49    1041.5    0.00146    0.00193    0.00171    0.37352    935.3    0.000      996.4
9:35:41       50    1063.4    0.00154    0.00200    0.00178    0.40225    955.1    1.724      974.1
9:35:42       51    1078.0    0.00161    0.00212    0.00186    0.39267    968.2   -0.575      947.2
9:35:43       52    1095.1    0.00168    0.00220    0.00194    0.41182    983.5    1.149      924.8
9:35:44       53    1112.2    0.00176    0.00227    0.00202    0.38309    998.9   -1.724      903.8
9:35:45       54    1126.8    0.00183    0.00239    0.00213    0.41182   1012.0    1.724      866.3
9:35:46       55    1143.9    0.00193    0.00246    0.00221    0.43098   1027.3    1.149      849.1
9:35:46       56    1161.0    0.00202    0.00256    0.00228    0.42140   1042.7   -0.575      833.1
9:35:47       57    1178.0    0.00207    0.00266    0.00240    0.43098   1058.0    0.575      809.1
9:35:48       58    1192.7    0.00217    0.00280    0.00247    0.42140   1071.2   -0.575      790.0
9:35:49       59    1207.3    0.00229    0.00293    0.00259    0.42140   1084.3    0.000      764.4
9:35:50       60    1222.0    0.00237    0.00302    0.00266    0.44056   1097.4    1.149      751.6
9:35:51       61    1236.6    0.00246    0.00315    0.00282    0.42140   1110.6   -1.149      719.5
9:35:52       62    1251.2    0.00256    0.00329    0.00289    0.44056   1123.7    1.149      708.8
9:35:53       63    1261.0    0.00266    0.00339    0.00304    0.44056   1132.5    0.000      678.6
9:35:54       64    1278.0    0.00276    0.00351    0.00312    0.43098   1147.8   -0.575 67[illegible].0
9:35:55       65    1290.2    0.00290    0.00363    0.00327    0.45013   1158.8    1.149      649.8
9:35:56       66    1302.4    0.00302    0.00378    0.00342    0.46929   1169.7    1.149      623.1
9:35:57       67    1314.6    0.00312    0.00398    0.00354    0.45013   1180.7   -1.149      606.6
9:35:58       68    1324.4    0.00324    0.00410    0.00369    0.45013   1189.4    0.000      587.8
9:35:59       69    1336.6    0.00338    0.00424    0.00384    0.45971   1200.4    0.575      569.8
9:36:00       70    1346.3    0.00349    0.00439    0.00400    0.46929   1209.2    0.575      552.1
9:36:01       71    1356.1    0.00363    0.00461    0.00415    0.48844   1217.9    1.149      535.6
9:36:02       72    1365.8    0.00378    0.00476    0.00430    0.48844   1226.7    0.000      520.4
9:36:03       73    1375.6    0.00393    0.00490    0.00445    0.46929   1235.4   -1.149      506.2
9:36:04       74    1382.9    0.00410    0.00512    0.00460    0.48844   1242.0    1.149      492.1
9:36:05       75    1390.2    0.00424    0.00532    0.00479    0.47887   1248.6   -0.575      475.0
9:36:06       76    1402.4    0.00441    0.00546    0.00498    0.48844   1259.5    0.575      460.8
9:36:07       77    1407.3    0.00454    0.00566    0.00514    0.50760   1263.9    1.149      448.8
9:36:08       78    1414.6    0.00476    0.00590    0.00536    0.49802   1270.5   -0.575      432.0
9:36:09       79    1422.0    0.00493    0.00607    0.00552    0.51718   1277.1    1.149      422.2
9:36:10       80    1431.7    0.00510    0.00637    0.00575    0.49802   1285.8   -1.149      408.2
9:36:11       81    1436.6    0.00527    0.00656    0.00597    0.50760   1290.2    0.575      394.0
9:36:12       82    1441.5    0.00546    0.00680    0.00616    0.51718   1294.6    0.575      383.1
9:36:13       83    1446.3    0.00568    0.00707    0.00639    0.50760   1299.0   -0.575      370.7
9:36:14       84    1451.2    0.00585    0.00732    0.00662    0.51718   1303.4    0.575      358.1
9:36:15       85    1456.1    0.00600    0.00759    0.00685    0.51718   1307.7    0.000      348.3
9:36:16       86    1461.0    0.00620    0.00780    0.00708    0.54591   1312.1    1.724      338.2
9:36:17       87    1465.9    0.00634    0.00820    0.00731    0.54591   1316.5    0.000      328.7
9:36:18       88    1470.7    0.00651    0.00846    0.00753    0.55548   1320.9    0.575      319.8
9:36:19       89    1475.6    0.00668    0.00880    0.00776    0.55548   1325.3    0.000      311.4
9:36:20       90    1480.5    0.00685    0.00917    0.00803    0.53633   1329.6   -1.149      302.1
9:36:21       91    1485.4    0.00702    0.00946    0.00829    0.54591   1334.0    0.575      293.4
9:36:22       92    1487.8    0.00720    0.00986    0.00856    0.55548   1336.2    0.575      284.7
9:36:23       93    1487.8    0.00739    0.01027    0.00887    0.17239   1336.2  -22.986      274.9
9:36:24       94    1490.2    0.00761    0.01068    0.00917    0.17239   1338.4    0.000      266.2
9:36:25       95    1490.2    0.00778    0.01110    0.00951    0.16281   1338.4   -0.575      256.6
9:36:26       96    1492.7    0.00800    0.01154    0.00985    0.19155   1340.6    1.724      248.1
9:36:27       97    1490.2    0.00822    0.01202    0.01020    0.18197   1338.4   -0.575      239.4
9:36:28       98    1487.8    0.00846    0.01256    0.01054    0.17239   1336.2   -0.575      231.2
9:36:29       99    1485.4    0.00866    0.01315    0.01086    0.20112   1334.0    1.724      222.1
9:36:30      100    1482.9    0.00890    0.01371    0.01136    0.22986   1331.8    1.724      213.5
9:36:31      101    1482.9    0.00915    0.01434    0.01180    0.22986   1331.8    0.000      206.0
9:36:32      102    1480.5    0.00939    0.01495    0.01229    0.24901   1329.6    1.149      197.3
9:36:33      103    1478.0    0.00966    0.01559    0.01271    0.24901   1327.4    0.000      190.5
```

APPENDIX B

GROUPING OF THE INDIRECT TENSILE TEST SPECIMENS

APPENDIX B

GROUPING PROGRAM

B.1 Introduction

A grouping program developed previously was utilized for grouping of the test specimens. The weight of each specimen was determined by weighing each specimen in air, immersed in wat [illegible] n saturated surface dry weight, as discussed in [illegible] ese values were used as input in the program [illegible] culates the bulk specific gravity of each [illegible] sting to verify accuracy of input data. Also, [illegible] esented in numerical order of specimen [illegible] ication and another in order of decreasing specific gravity. Sorting is then done into possible groups according to their bulk specific gravities so that the difference in mean specific gravity is minimized. For this testing groups of six specimens were arranged for testing at different temperatures by the grouping program. A general description of the program is given in Section B.2

```
IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX B) HUSKY 150/200 AC (LOW TEMP)

NUMBER OF SAMPLES = 24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 0.000
THE STANDARD DEVIATION =   0.000
THE COEFFICIENT OF VARIATION (%) =   0.000

         SAMPLE   DRY WT.     SSDWT.      IM.WT.     VOL.    SP.GR.    NO. OF
          NAME      g.          g.          g.        cc.              ST.DEV.
                                                                      FROM MEAN
          150L1   1241.00     1241.90     714.66     714.66  0.000      +0.00
          150L2   1239.30     1239.60     715.40     715.40  0.000      +0.00
          150L3   1291.20     1291.30     745.00     745.00  0.000      +0.00
          150L4   1220.20     1220.60     702.31     702.31  0.000      +0.00
          150L5   1248.10     1248.30     721.00     721.00  0.000      +0.00
          150L6   1261.50     1262.00     726.86     726.86  0.000      +0.00
          150L7   1225.20     1226.10     705.50     705.50  0.000      +0.00
          150L8   1244.00     1244.50     716.30     716.30  0.000      +0.00
          150L9   1234.70     1235.10     711.31     711.31  0.000      +0.00
          150L10  1147.80     1149.30     661.84     661.84  0.000      +0.00
          150L11  1240.70     1241.30     714.64     714.64  0.000      +0.00
          150L12  1248.50     1249.30     718.29     718.29  0.000      +0.00
          150L13  1278.50     1278.90     738.44     738.44  0.000      +0.00
          150L14  1206.60     1207.30     694.91     694.91  0.000      +0.00
          150L15  1237.90     1238.80     715.03     715.03  0.000      +0.00
          150L16  1258.70     1259.30     725.10     725.10  0.000      +0.00
          150L17  1248.10     1249.10     718.72     718.72  0.000      +0.00
          150L18  1227.10     1228.90     707.56     707.56  0.000      +0.00
          150L19  1266.40     1266.90     731.43     731.43  0.000      +0.00
          150L20  1252.80     1253.30     721.20     721.20  0.000      +0.00
          150L21  1241.30     1242.30     715.07     715.07  0.000      +0.00
          150L22  1245.60     1246.10     718.58     718.58  0.000      +0.00
          150L23  1254.60     1254.70     722.89     722.89  0.000      +0.00
          150L24  1239.70     1240.70     714.32     714.32  0.000      +0.00
```

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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX B) HUSKY 150/200 AC (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.358
THE STANDARD DEVIATION =   0.005
THE COEFFICIENT OF VARIATION (%) =   0.203


      SAMPLE     DRY WT.     SSDWT.     IM.WT.     VOL.      SP.GR.    NO. OF
       NAME        g.          g.         g.        cc.                ST.DEV.
                                                                      FROM MEAN
      150L1      1241.00    1241.90     714.66    527.24     2.354     +0.82
      150L2      1239.30    1239.60     715.40    524.20     2.364     -1.35
      150L3      1291.20    1291.30     745.00    546.30     2.364     -1.22
      150L4      1220.20    1220.60     702.31    518.29     2.354     +0.72
      150L5      1248.10    1248.30     721.00    527.30     2.367     -1.93
      150L6      1261.50    1262.00     726.82    535.18     2.357     +0.12
      150L7      1225.20    1226.10     705.50    520.60     2.353     +0.89
      150L8      1244.00    1244.50     716.30    528.20     2.355     +0.53
      150L9      1234.70    1235.10     711.31    523.79     2.357     +0.10
      150L10     1147.80    1149.30     661.84    487.46     2.355     +0.64
      150L11     1240.70    1241.30     714.64    526.66     2.356     +0.40
      150L12     1248.50    1249.30     718.29    531.01     2.351     +1.36
      150L13     1278.50    1278.90     738.44    540.46     2.366     -1.64
      150L14     1206.60    1207.30     694.91    512.39     2.355     +0.60
      150L15     1237.90    1238.80     715.03    523.77     2.363     -1.20
      150L16     1258.70    1259.30     725.10    534.20     2.356     +0.31
      150L17     1248.10    1249.10     718.72    530.38     2.353     +0.94
      150L18     1227.10    1228.90     707.56    521.34     2.354     +0.83
      150L19     1266.40    1266.60     731.43    535.17     2.366     -1.80
      150L20     1252.80    1253.30     721.20    532.10     2.354     +0.68
      150L21     1241.30    1242.30     715.07    527.23     2.354     +0.70
      150L22     1245.60    1246.10     718.58    527.52     2.361     -0.74
      150L23     1254.60    1254.70     722.89    531.81     2.359     -0.29
      150L24     1239.70    1240.70     714.32    526.38     2.355     +0.54
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX B) HUSKY 150/200 AC

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.358
THE STANDARD DEVIATION =   0.005
THE COEFFICIENT OF VARIATION (%) =   0.203


        SAMPLE    DRY WT.    SSDWT.     IM.WT.     VOL.     SP.GR.    NO. OF
         NAME       g.         g.         g.        cc.               ST.DEV.
                                                                     FROM MEAN
        150L5     1248.10    1248.30    721.00     527.30    2.367     -1.93
        150L19    1266.40    1266.60    731.43     535.17    2.366     -1.80
        150L13    1278.50    1278.90    738.44     540.46    2.366     -1.64
        150L2     1239.30    1239.60    715.40     524.20    2.364     -1.35
        150L3     1291.20    1291.30    745.00     546.30    2.364     -1.22
        150L15    1237.90    1238.80    715.03     523.77    2.363     -1.20
        150L22    1245.60    1246.10    718.58     527.52    2.361     -0.74
        150L23    1254.60    1254.70    722.89     531.81    2.359     -0.29
        150L9     1234.70    1235.10    711.31     523.79    2.357     +0.10
        150L6     1261.50    1262.00    726.82     535.18    2.357     +0.12
        150L16    1258.70    1259.30    725.10     534.20    2.356     +0.31
        150L11    1240.70    1241.30    714.64     526.66    2.356     +0.40
        150L8     1244.00    1244.50    716.30     528.20    2.355     +0.53
        150L24    1239.70    1240.70    714.32     526.38    2.355     +0.54
        150L14    1206.60    1207.30    694.91     512.39    2.355     +0.60
        150L10    1147.80    1149.30    661.84     487.46    2.355     +0.64
        150L20    1252.80    1253.30    721.20     532.10    2.354     +0.68
        150L21    1241.30    1242.30    715.07     527.23    2.354     +0.70
        150L4     1220.20    1220.60    702.31     518.29    2.354     +0.72
        150L1     1241.00    1241.90    714.66     527.24    2.354     +0.82
        150L18    1227.10    1228.90    707.56     521.34    2.354     +0.83
        150L7     1225.20    1226.10    705.50     520.60    2.353     +0.89
        150L17    1248.10    1249.10    718.72     530.38    2.353     +0.94
        150L12    1248.50    1249.30    718.29     531.01    2.351     +1.36
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THESE ARE THE POSSIBLE GROUPS

       SAMPLE     SP.GR.     MEAN       GROUP       COEFF. OF
        NAME                 SP.GR.     ST.DEV.     VARIATION (%)

       150L5       2.367
       150L12      2.351
       150L22      2.361
       150L21      2.354
       150L8       2.355
       150L9       2.357
                             2.358      +0.0056        0.239


       150L19      2.366
       150L17      2.353
       150L23      2.359
       150L20      2.354
       150L24      2.355
       150L6       2.357
                             2.358      +0.0048        0.203


       150L13      2.366
       150L7       2.353
       150L16      2.356
       150L10      2.355
       150L14      2.355
       150L15      2.363
                             2.358      +0.0051        0.218


       150L1       2.354
       150L2       2.364
       150L3       2.364
       150L4       2.354
       150L11      2.356
       150L18      2.354
                             2.358      +0.0049        0.210
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX C) HUSKY PMA 2 (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 0.000
THE STANDARD DEVIATION =   0.000
THE COEFFICIENT OF VARIATION (%) =   0.000

         SAMPLE    DRY WT.    SSDWT.    IM.WT.    VOL.     SP.GR.    NO. OF
          NAME       g.         g.        g.       cc.               ST.DEV.
                                                                    FROM MEAN
         PMA/1     1196.37    1197.26   689.69    689.69   0.000     +0.00
         PMA/2     1256.33    1257.14   724.99    724.99   0.000     +0.00
         PMA/3     1254.28    1254.90   721.73    721.73   0.000     +0.00
         PMA/4     1224.96    1225.75   705.65    705.65   0.000     +0.00
         PMA/5     1263.95    1264.26   728.44    728.44   0.000     +0.00
         PMA/6     1215.96    1216.24   701.06    701.06   0.000     +0.00
         PMA/7     1274.65    1274.89   735.94    735.94   0.000     +0.00
         PMA/8     1225.28    1225.62   707.92    707.92   0.000     +0.00
         PMA/9     1266.93    1267.07   731.33    731.33   0.000     +0.00
         PMA/10    1236.20    1236.61   713.43    713.43   0.000     +0.00
         PMA/11    1257.54    1257.76   722.91    722.91   0.000     +0.00
         PMA/12    1245.02    1245.44   718.38    718.38   0.000     +0.00
         PMA/13    1206.30    1206.93   694.98    694.98   0.000     +0.00
         PMA/14    1236.11    1236.67   711.93    711.93   0.000     +0.00
         PMA/15    1290.32    1290.67   743.87    743.87   0.000     +0.00
         PMA/16    1237.15    1237.69   712.43    712.43   0.000     +0.00
         PMA/17    1226.71    1227.17   707.94    707.94   0.000     +0.00
         PMA/18    1244.37    1244.63   716.39    716.39   0.000     +0.00
         PMA/19    1248.79    1248.97   720.43    720.43   0.000     +0.00
         PMA/20    1249.19    1249.50   718.49    718.49   0.000     +0.00
         PMA/21    1240.81    1241.43   716.54    716.54   0.000     +0.00
         PMA/22    1242.83    1243.32   716.82    716.82   0.000     +0.00
         PMA/23    1244.57    1244.89   718.72    718.72   0.000     +0.00
         PMA/24    1236.83    1237.28   712.54    712.54   0.000     +0.00
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX C) HUSKY PMA 2 (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.359
THE STANDARD DEVIATION =   0.004
THE COEFFICIENT OF VARIATION (%) =   0.190

    SAMPLE     DRY WT.     SSDWT.     IM.WT.     VOL.     SP.GR.    NO. OF
     NAME        g.          g.         g.        cc.               ST.DEV.
                                                                   FROM MEAN
    PMA/1     1196.37     1197.26     689.69     507.57    2.357     +0.52
    PMA/2     1256.33     1257.14     724.99     532.15    2.361     -0.33
    PMA/3     1254.28     1254.90     721.73     533.17    2.352     +1.53
    PMA/4     1224.96     1225.75     705.65     520.10    2.355     +0.92
    PMA/5     1263.95     1264.26     728.44     535.82    2.359     +0.10
    PMA/6     1215.96     1216.24     701.06     515.18    2.360     -0.20
    PMA/7     1274.65     1274.89     735.94     538.95    2.365     -1.27
    PMA/8     1225.28     1225.62     707.92     517.70    2.367     -1.65
    PMA/9     1266.93     1267.07     731.33     535.74    2.365     -1.21
    PMA/10    1236.20     1236.61     713.43     523.18    2.363     -0.78
    PMA/11    1257.54     1257.76     722.91     534.85    2.351     +1.82
    PMA/12    1245.02     1245.44     718.38     527.06    2.362     -0.63
    PMA/13    1206.30     1206.93     694.98     511.95    2.356     +0.69
    PMA/14    1236.11     1236.67     711.93     524.74    2.356     +0.83
    PMA/15    1290.32     1290.67     743.87     546.80    2.360     -0.09
    PMA/16    1237.15     1237.69     712.43     525.26    2.355     +0.91
    PMA/17    1226.71     1227.17     707.94     519.23    2.363     -0.71
    PMA/18    1244.37     1244.63     716.39     528.24    2.356     +0.82
    PMA/19    1248.79     1248.97     720.43     528.54    2.363     -0.74
    PMA/20    1249.19     1249.50     718.49     531.01    2.352     +1.54
    PMA/21    1240.81     1241.43     716.54     524.89    2.364     -1.02
    PMA/22    1242.83     1243.32     716.82     526.50    2.361     -0.26
    PMA/23    1244.57     1244.89     718.72     526.17    2.365     -1.33
    PMA/24    1236.83     1237.28     712.54     524.74    2.357     +0.52
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX C) HUSKY PMA 2 (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.359
THE STANDARD DEVIATION =   0.004
THE COEFFICIENT OF VARIATION (%) =   0.190

         SAMPLE    DRY WT.    SSDWT.     IM.WT.     VOL.      SP.GR.    NO. OF
          NAME       g.         g.         g.        cc.               ST.DEV.
                                                                      FROM MEAN
         PMA/8     1225.28    1225.62    707.92     517.70    2.367     -1.65
         PMA/23    1244.57    1244.89    718.72     526.17    2.365     -1.33
         PMA/7     1274.65    1274.89    735.94     538.95    2.365     -1.27
         PMA/9     1266.93    1267.07    731.33     535.74    2.365     -1.21
         PMA/21    1240.81    1241.43    716.54     524.89    2.364     -1.02
         PMA/10    1236.20    1236.61    713.43     523.18    2.363     -0.78
         PMA/19    1248.79    1248.97    720.43     528.54    2.363     -0.74
         PMA/17    1226.71    1227.17    707.94     519.23    2.363     -0.71
         PMA/12    1245.02    1245.44    718.38     527.06    2.362     -0.63
         PMA/2     1256.33    1257.14    724.99     532.15    2.361     -0.33
         PMA/22    1242.83    1243.32    716.82     526.50    2.361     -0.26
         PMA/6     1215.96    1216.24    701.06     515.18    2.360     -0.20
         PMA/15    1290.32    1290.67    743.87     546.80    2.360     -0.09
         PMA/5     1263.95    1264.26    728.44     535.82    2.359     +0.10
         PMA/1     1196.37    1197.26    689.69     507.57    2.357     +0.52
         PMA/24    1236.83    1237.28    712.54     524.74    2.357     +0.52
         PMA/13    1206.30    1206.93    694.98     511.95    2.356     +0.69
         PMA/18    1244.37    1244.63    716.39     528.24    2.356     +0.82
         PMA/14    1236.11    1236.67    711.93     524.74    2.356     +0.83
         PMA/16    1237.15    1237.69    712.43     525.26    2.355     +0.91
         PMA/4     1224.96    1225.75    705.65     520.10    2.355     +0.92
         PMA/3     1254.28    1254.90    721.73     533.17    2.352     +1.53
         PMA/20    1249.19    1249.50    718.49     531.01    2.352     +1.54
         PMA/11    1257.54    1257.76    722.91     534.85    2.351     +1.82
```

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THESE ARE THE POSSIBLE GROUPS

         SAMPLE     SP.GR.     MEAN        GROUP       COEFF. OF
          NAME                 SP.GR.      ST.DEV.     VARIATION (%)

         PMA/8       2.367
         PMA/11      2.351
         PMA/19      2.363
         PMA/18      2.356
         PMA/15      2.360
         PMA/6       2.360
                               2.359       +0.0054       0.230

         PMA/23      2.365
         PMA/20      2.352
         PMA/17      2.363
         PMA/13      2.356
         PMA/5       2.359
         PMA/22      2.361
                               2.359       +0.0046       0.194

         PMA/7       2.365
         PMA/3       2.352
         PMA/12      2.362
         PMA/24      2.357
         PMA/1       2.357
         PMA/10      2.363
                               2.359       +0.0047       0.199

         PMA/2       2.361
         PMA/4       2.355
         PMA/9       2.365
         PMA/14      2.356
         PMA/16      2.355
         PMA/21      2.364
                               2.359       +0.0045       0.190
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN AUGUST/89
SH 794                             IMPERIAL OIL 150/200A ASPHALT (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 0.000
THE STANDARD DEVIATION =   0.000
THE COEFFICIENT OF VARIATION (%) =   0.000

           SAMPLE     DRY WT.     SSDWT.     IM.WT.     VOL.     SP.GR.    NO. OF
            NAME        g.          g.         g.        cc.               ST.DEV.
                                                                          FROM MEAN
           A/1        1208.60     1209.70    692.20     692.20    0.000     +0.00
           A/2        1239.90     1241.00    711.40     711.40    0.000     +0.00
           A/3        1234.60     1235.80    706.90     706.90    0.000     +0.00
           A/4        1234.40     1235.20    706.91     706.91    0.000     +0.00
           A/5        1253.80     1255.20    719.30     719.30    0.000     +0.00
           A/6        1274.10     1276.30    733.10     733.10    0.000     +0.00
           A/7        1231.50     1232.60    706.50     706.50    0.000     +0.00
           A/8        1222.80     1223.90    700.50     700.50    0.000     +0.00
           A/9        1248.30     1249.00    716.20     716.20    0.000     +0.00
           A/10       1248.30     1248.90    715.80     715.80    0.000     +0.00
           A/11       1224.50     1225.30    701.50     701.50    0.000     +0.00
           A/12       1238.00     1239.00    708.20     708.20    0.000     +0.00
           A/13       1241.20     1241.90    711.10     711.10    0.000     +0.00
           A/14       1254.30     1255.60    719.30     719.30    0.000     +0.00
           A/15       1251.80     1256.00    720.70     720.70    0.000     +0.00
           A/16       1229.00     1230.20    704.40     704.40    0.000     +0.00
           A/17       1241.00     1242.40    711.20     711.20    0.000     +0.00
           A/18       1229.90     1232.10    705.20     705.20    0.000     +0.00
           A/19       1243.50     1245.50    714.10     714.10    0.000     +0.00
           A/20       1273.10     1274.30    729.10     729.10    0.000     +0.00
           A/21       1241.40     1242.50    713.00     713.00    0.000     +0.00
           A/22       1230.40     1231.50    706.10     706.10    0.000     +0.00
           A/23       1241.60     1242.50    712.60     712.60    0.000     +0.00
           A/24       1237.30     1238.10    709.10     709.10    0.000     +0.00
```

```
IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN AUGUST/89
SH 794                                      IMPERIAL OIL 150/200A ASPHALT (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.339
THE STANDARD DEVIATION =   0.003
THE COEFFICIENT OF VARIATION (%) =   0.147

        SAMPLE    DRY WT.    SSDWT.     IM.WT.     VOL.      SP.GR.   NO. OF
         NAME       g.         g.         g.        cc.               ST.DEV.
                                                                     FROM MEAN
        A/1       1208.60    1209.70    692.20     517.50     2.335    +0.97
        A/2       1239.90    1241.00    711.40     529.60     2.341    -0.70
        A/3       1234.60    1235.80    706.90     528.90     2.334    +1.32
        A/4       1234.40    1235.20    706.91     528.29     2.337    +0.64
        A/5       1253.80    1255.20    719.30     535.90     2.340    -0.24
        A/6       1274.10    1276.30    733.10     543.20     2.346    -1.96
        A/7       1231.50    1232.60    706.50     526.10     2.341    -0.58
        A/8       1222.80    1223.90    700.50     523.40     2.336    +0.74
        A/9       1248.30    1249.00    716.20     532.80     2.343    -1.19
        A/10      1248.30    1248.90    715.80     533.10     2.342    -0.81
        A/11      1224.50    1225.30    701.50     523.80     2.338    +0.31
        A/12      1238.00    1239.00    708.20     530.80     2.332    +1.89
        A/13      1241.20    1241.90    711.10     530.80     2.338    +0.13
        A/14      1254.30    1255.60    719.30     536.30     2.339    +0.00
        A/15      1251.80    1256.00    720.70     535.30     2.339    +0.09
        A/16      1229.00    1230.20    704.40     525.80     2.337    +0.41
        A/17      1241.00    1242.40    711.20     531.20     2.336    +0.75
        A/18      1229.90    1232.10    705.20     526.90     2.334    +1.33
        A/19      1243.50    1245.50    714.10     531.40     2.340    -0.36
        A/20      1273.10    1274.30    729.10     545.20     2.335    +1.08
        A/21      1241.40    1242.50    713.00     529.50     2.344    -1.65
        A/22      1230.40    1231.50    706.10     525.40     2.342    -0.88
        A/23      1241.60    1242.50    712.60     529.90     2.343    -1.25
        A/24      1237.30    1238.10    709.10     529.00     2.339    -0.04
```

```
IDENTIFICATION OF THE PROJECT  **********  thesis hussain
SH 794                              IMPERIAL OIL 150/200A ASPHALT (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.339
THE STANDARD DEVIATION =   0.003
THE COEFFICIENT OF VARIATION (%) =   0.147

      SAMPLE     DRY WT.    SSDWT.     IM.WT.     VOL.     SP.GR.   NO. OF
       NAME        g.         g.         g.        cc.              ST.DEV.
                                                                    FROM MEAN
      A/6       1274.10    1276.30    733.10    543.20    2.346    -1.96
      A/21      1241.40    1242.50    713.00    529.50    2.344    -1.65
      A/23      1241.60    1242.50    712.60    529.90    2.343    -1.25
      A/9       1248.30    1249.00    716.20    532.80    2.343    -1.19
      A/22      1230.40    1231.50    706.10    525.40    2.342    -0.88
      A/10      1248.30    1248.90    715.80    533.10    2.342    -0.81
      A/2       1239.90    1241.00    711.40    529.60    2.341    -0.70
      A/7       1231.50    1232.60    706.50    526.10    2.341    -0.58
      A/19      1243.50    1245.50    714.10    531.40    2.340    -0.36
      A/5       1253.80    1255.20    719.30    535.90    2.340    -0.24
      A/24      1237.30    1238.10    709.10    529.00    2.339    -0.04
      A/14      1254.30    1255.60    719.30    536.30    2.339    +0.00
      A/15      1251.80    1256.00    720.70    535.30    2.339    +0.09
      A/13      1241.20    1241.90    711.10    530.80    2.338    +0.13
      A/11      1224.50    1225.30    701.50    523.80    2.338    +0.31
      A/16      1229.00    1230.20    704.40    525.80    2.337    +0.41
      A/4       1234.40    1235.20    706.91    528.29    2.337    +0.64
      A/8       1222.80    1223.90    700.50    523.40    2.336    +0.74
      A/17      1241.00    1242.40    711.20    531.20    2.336    +0.75
      A/1       1208.60    1209.70    692.20    517.50    2.335    +0.97
      A/20      1273.10    1274.30    729.10    545.20    2.335    +1.08
      A/3       1234.60    1235.80    706.90    528.90    2.334    +1.32
      A/18      1229.90    1232.10    705.20    526.90    2.334    +1.33
      A/12      1238.00    1239.00    708.20    530.80    2.332    +1.89
```

```
THESE ARE THE POSSIBLE GROUPS

         SAMPLE     SP.GR.     MEAN        GROUP       COEFF. OF
          NAME                 SP.GR.      ST.DEV.     VARIATION (%)

         A/6         2.346
         A/12        2.332
         A/2         2.341
         A/8         2.336
         A/15        2.339
         A/24        2.339
                               2.339       +0.0045        0.191


         A/21        2.344
         A/18        2.334
         A/7         2.341
         A/4         2.337
         A/13        2.338
         A/14        2.339
                               2.339       +0.0035        0.151


         A/23        2.343
         A/3         2.334
         A/19        2.340
         A/16        2.337
         A/11        2.338
         A/5         2.340
                               2.339       +0.0030        0.127


         A/1         2.335
         A/9         2.343
         A/10        2.342
         A/17        2.336
         A/20        2.335
         A/22        2.342
                               2.339       +0.0036        0.154
```

```
IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN
SH 794                                     IMPERIAL OIL PMA ASPHALT (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 0.000
THE STANDARD DEVIATION =   0.000
THE COEFFICIENT OF VARIATION (%) =   0.000


          SAMPLE     DRY WT.     SSDWT.     IM.WT.     VOL.      SP.GR.    NO. OF
           NAME        g.          g.         g.        cc.                ST.DEV.
                                                                          FROM MEAN
          I/1        1246.40     1247.70    715.20     715.20    0.000     +0.00
          I/2        1223.90     1225.60    701.90     701.90    0.000     +0.00
          I/3        1239.50     1240.40    710.37     710.37    0.000     +0.00
          I/4        1239.40     1244.60    715.50     715.50    0.000     +0.00
          I/5        1260.30     1264.30    725.80     725.80    0.000     +0.00
          I/6        1234.30     1235.30    707.30     707.30    0.000     +0.00
          I/7        1242.00     1243.40    713.20     713.20    0.000     +0.00
          I/8        1226.70     1228.10    705.20     705.20    0.000     +0.00
          I/9        1225.50     1227.20    704.50     704.50    0.000     +0.00
          I/10       1254.10     1255.40    720.90     720.90    0.000     +0.00
          I/11       1224.50     1227.50    703.40     703.40    0.000     +0.00
          I/12       1232.80     1235.50    709.30     709.30    0.000     +0.00
          I/13       1224.20     1225.30    701.80     701.80    0.000     +0.00
          I/14       1255.60     1258.80    721.40     721.40    0.000     +0.00
          I/15       1241.10     1244.70    714.10     714.10    0.000     +0.00
          I/16       1222.10     1225.40    702.50     702.50    0.000     +0.00
          I/17       1227.90     1231.00    705.70     705.70    0.000     +0.00
          I/18       1219.20     1221.00    700.20     700.20    0.000     +0.00
          I/19       1262.50     1265.10    726.10     726.10    0.000     +0.00
          I/20       1228.50     1229.40    704.80     704.80    0.000     +0.00
          I/21       1244.70     1247.20    714.20     714.20    0.000     +0.00
          I/22       1243.70     1246.50    715.30     715.30    0.000     +0.00
          I/23       1238.30     1239.90    710.80     710.80    0.000     +0.00
          I/24       1245.10     1250.70    718.20     718.20    0.000     +0.00
```

```
IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN
SH 794                                     IMPERIAL OIL PMA ASPHALT (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.340
THE STANDARD DEVIATION =    0.003
THE COEFFICIENT OF VARIATION (%) =    0.130


      SAMPLE     DRY WT.     SSDWT.      IM.WT.      VOL.       SP.GR.    NO. OF
       NAME        g.          g.          g.         cc.                 ST.DEV.
                                                                         FROM MEAN
      I/1        1246.40     1247.70     715.20     532.50      2.341     -0.16
      I/2        1223.90     1225.60     701.90     523.70      2.337     +1.04
      I/3        1239.50     1240.40     710.37     530.03      2.339     +0.54
      I/4        1239.40     1244.60     715.50     529.10      2.342     -0.75
      I/5        1260.30     1264.30     725.80     538.50      2.340     -0.07
      I/6        1234.30     1235.30     707.30     528.00      2.338     +0.82
      I/7        1242.00     1243.40     713.20     530.20      2.343     -0.77
      I/8        1226.70     1228.10     705.20     522.90      2.346     -1.90
      I/9        1225.50     1227.20     704.50     522.70      2.345     -1.44
      I/10       1254.10     1255.40     720.90     534.50      2.346     -2.02
      I/11       1224.50     1227.50     703.40     524.10      2.336     +1.25
      I/12       1232.80     1235.50     709.30     526.20      2.343     -0.87
      I/13       1224.20     1225.30     701.80     523.50      2.338     +0.55
      I/14       1255.60     1258.80     721.40     537.40      2.336     +1.23
      I/15       1241.10     1244.70     714.10     530.60      2.339     +0.37
      I/16       1222.10     1225.40     702.50     522.90      2.337     +0.99
      I/17       1227.90     1231.00     705.70     525.30      2.338     +0.87
      I/18       1219.20     1221.00     700.20     520.80      2.341     -0.28
      I/19       1262.50     1265.10     726.10     539.00      2.342     -0.70
      I/20       1228.50     1229.40     704.80     524.60      2.342     -0.53
      I/21       1244.70     1247.20     714.20     533.00      2.335     +1.61
      I/22       1243.70     1246.50     715.30     531.20      2.341     -0.37
      I/23       1238.30     1239.90     710.80     529.10      2.340     -0.07
      I/24       1245.10     1250.70     718.20     532.50      2.338     +0.65
```

```
IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN
SH 794                                     IMPERIAL OIL PMA ASPHALT (LOW TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.340
THE STANDARD DEVIATION =    0.003
THE COEFFICIENT OF VARIATION (%) =    0.130

          SAMPLE     DRY WT.    SSDWT.     IM.WT.     VOL.      SP.GR.    NO. OF
           NAME        g.         g.         g.        cc.                ST.DEV.
                                                                         FROM MEAN
          I/10       1254.10    1255.40    720.90     534.50    2.346     -2.02
          I/8        1226.70    1228.10    705.20     522.90    2.346     -1.90
          I/9        1225.50    1227.20    704.50     522.70    2.345     -1.44
          I/12       1232.80    1235.50    709.30     526.20    2.343     -0.87
          I/7        1242.00    1243.40    713.20     530.20    2.343     -0.77
          I/4        1239.40    1244.60    715.50     529.10    2.342     -0.75
          I/19       1262.50    1265.10    726.10     539.00    2.342     -0.70
          I/20       1228.50    1229.40    704.80     524.60    2.342     -0.53
          I/22       1243.70    1246.50    715.30     531.20    2.341     -0.37
          I/18       1219.20    1221.00    700.20     520.80    2.341     -0.28
          I/1        1246.40    1247.70    715.20     532.50    2.341     -0.16
          I/5        1260.30    1264.30    725.80     538.50    2.340     -0.07
          I/23       1238.30    1239.90    710.80     529.10    2.340     -0.07
          I/15       1241.10    1244.70    714.10     530.60    2.339     +0.37
          I/3        1239.50    1240.40    710.37     530.03    2.339     +0.54
          I/13       1224.20    1225.30    701.80     523.50    2.338     +0.55
          I/24       1245.10    1250.70    718.20     532.50    2.338     +0.65
          I/6        1234.30    1235.30    707.30     528.00    2.338     +0.82
          I/17       1227.90    1231.00    705.70     525.30    2.338     +0.87
          I/16       1222.10    1225.40    702.50     522.90    2.337     +0.99
          I/2        1223.90    1225.60    701.90     523.70    2.337     +1.04
          I/14       1255.60    1258.80    721.40     537.40    2.336     +1.23
          I/11       1224.50    1227.50    703.40     524.10    2.336     +1.25
          I/21       1244.70    1247.20    714.20     533.00    2.335     +1.61
```

```
THESE ARE THE POSSIBLE GROUPS

        SAMPLE     SP.GR.     MEAN       GROUP      COEFF. OF
         NAME                 SP.GR.     ST.DEV.    VARIATION (%)

        I/10       2.346
        I/21       2.335
        I/19       2.342
        I/6        2.338
        I/23       2.340
        I/15       2.339
                              2.340      +0.0038      0.164

        I/8        2.346
        I/11       2.336
        I/20       2.342
        I/24       2.338
        I/3        2.339
        I/5        2.340
                              2.340      +0.0034      0.144

        I/9        2.345
        I/14       2.336
        I/22       2.341
        I/13       2.338
        I/17       2.338
        I/12       2.343
                              2.340      +0.0032      0.137

        I/1        2.341
        I/2        2.337
        I/4        2.342
        I/7        2.343
        I/16       2.337
        I/18       2.341
                              2.340      +0.0025      0.106
```

B.2 General Description of the Program Grouping

The program can be called by typing the following. BLOCK LETTERS are the response of the computer, small letters are the characters that the user types. The program is on a diskette and hard drive of computer in Room 215 D.

```
A: USR> basica
OK
load"grouping"
OK
run
```

After running the program, the user types in,

```
system
```

The main operation of this program consists of the following three steps:

a. Calculating the specific gravities of the samples
b. Sorting the samples in accordance to their specific gravities, and
c. Grouping the samples to give a relatively constant group specific gravity.

Data can be put into the program either by input file or keyboard. To Calculate the specific gravity of a sample, the program requires the dry weight of the sample, saturated surface dry weight, and the immersed weight or volume of the sample. For the convenience of the user to identify samples, sample names are also required in the input data.

The program has the input data correction facility. Input data can be corrected simply by identifying the sample number, which data the user wants to correct and the correct value of the data. After the correction, the user have the choice of storing the data in a file.

The format of the input data is described as followed:

1. Identification of the project (up to 40 characters)
2. Number of samples in this run (up to 100 samples)
3. For each sample, enter
    The sample name (up to 6 characters)
    The initial dry weight
    The Saturated surface dry weight
    The immersed weight
    The volume

Enter 0 when any of the above sample data does not apply.

The specific gravity of each sample is then calculated using the above input data. The mean and the standard deviation of the specific gravities are also calculated. The number of standard deviation of each sample differ from the mean is then calculated and samples are sorted according to their number of standard deviations.

Sample are grouped into a size defined by the user. The criteria are to produce groups which have the same mean specific gravity and a similar population distribution. The user can exclude some of the samples from grouping. Usually the samples having the large number of standard deviation are excluded so as to produce a better distribution of the samples.

The program output, besides displays in the monitor which acts in the standard output, also can be produced in a printer and/or stored in a output file as the user requested. The output file can later be retrieved or transferred to the main frame and get a better print of the output.

APPENDIX C

INDIRECT TENSILE TEST RESULTS OF INDIVIDUAL SPECIMENS

HUSKY 150/200 AC (LETHBRIDGE AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
150L5	0	2367	1074	51	343
150L12	0	2351	1263	83	249
150L22	0	2361	954	98	160
150L21	0	2354	1137	123	152
150L8	0	2355	1120	95	202
150L9	0	2357	1164	125	153
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2358	1119	96	210
STANDARD DEVIATION			93	25	69
COEF. OF VAR (%)		0.2	8	26	33

HUSKY PMA 2 (LETHBRIDGE AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
PMA/8	0	2367	1241	163	130
PMA/6	0	2360	1051	180	96
PMA/11	0	2351	991	157	101
PMA/19	0	2363	1046	194	89
PMA/15	0	2360	1231	147	138
PMA/18	0	2356	1228	101	113
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2360	1131	157	111
STANDARD DEVIATION		5	104	29	18
COEF. OF VAR (%)		0.2	9	19	16

HUSKY 150/200 AC (LETHBRIDGE AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
150L19	-10	2366	2184	42	1295
150L17	-10	2353	2314	64	738
150L20	-10	2354	2837	45	1113
150L23	-10	2359	1897	48	973
150L24	-10	2355	1416	81	536
150L6	-10	2357	1642	86	434
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2357	2048	61	848
STANDARD DEVIATION		4	465	17	307
COEF. OF VAR (%)		0.17	23	28	36

HUSKY PMA 2 (LETHBRIDGE AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
PMA/23	-10	2365	3272	85	501
PMA/20	-10	2352	2872	67	567
PMA/17	-10	2363	3096	66	708
PMA/13	-10	2356	2053	144	217
PMA/5	-10	2359	2656	110	211
PMA/22	-10	2361	2262	83	327
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2359	2702	93	422
STANDARD DEVIATION		4	433	27	185
COEF. OF VAR (%)		0.17	16	29	44

HUSKY 150/200 AC (LETHBRIDGE AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
150L13	-20	2366	4129	12	5567
150L/7	-20	2353	3886	9	7291
150L/16	-20	2356	3597	29	2016
150L/10	-20	2355	3778	20	3075
150L/15	-20	2363	4008	12	5579
NUMBER OF SAMPLES		5	5	5	5
MEAN VALUE		2359	3880	16	4706
STANDARD DEVIATION		5	184	7	1902
COEF. OF VAR (%)		0.21	5	44	40

HUSKY PMA 2 (LETHBRIDGE AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
PMA/7	-20	2365	4261	37	1915
PMA/3	-20	2352	3807	35	1786
PMA/12	-20	2362	4101	21	3338
PMA/24	-20	2357	3282	12	4425
PMA/10	-20	2363	4116	12	4448
PMA/1	-20	2357	4078	13	5028
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2359	3941	22	3490
STANDARD DEVIATION		4	324	10	1263
COEF. OF VAR (%)		0.16	8	45	36

HUSKY 150/200 AC (LETHBRIDGE AGGREGA) MODIFIEID

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
150L13	-20	2366	4129	12	5567
150L16	-20	2356	3597	29	2016
150/15	-20	2363	4008	12	5579
150L10	-20	2355	3778	20	3075
NUMBER OF SAMPLES		4	4	4	4
MEAN VALUE		2360	3878	18	4059
STANDARD DEVIATION		5	205	7	1559
COEF. OF VAR (%)		0.2	9	39	38

HUSKY 150/200 AC (LETHBRIDGE AGGREGA) MODIFIEID

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
150L13	-20	2366	4129	12	5567
150L7	-20	2353	3886	9	7291
150/15	-20	2363	4008	12	5579
150L10	-20	2355	3778	20	3075
NUMBER OF SAMPLES		4	4	4	4
MEAN VALUE		2359	3950	13	5378
STANDARD DEVIATION		5	131	4	1503
COEF. OF VAR (%)		0.21	6	31	28

HUSKY 150/200 AC (LETHBRIDGE AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
150L4	-30	2354	3799	5	11709
150L11	-30	2356	3468	2	29931
150L18	-30	2354	3217	5	11565
NUMBER OF SAMPLES		3	3	3	3
MEAN VALUE		2355	3495	4	17735
STANDARD DEVIATION		0.9	238	1	8624
COEF. OF VAR (%)		0.04	7	25	49

HUSKY PMA 2 (LETHBRIDGE AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
PMA/9	-30	2365	4426	7	11234
PMA/14	-30	2356	4135	10	6861
PMA/16	-30	2355	4852	5	16103
PMA/21	-30	2364	5175	6	13954
NUMBER OF SAMPLES		4	4	4	4
MEAN VALUE		2360	3504	7	12038
STANDARD DEVIATION		5	397	2	3451
COEF. OF VAR (%)		0.19	11	29	29

IMPERIAL 150/200A (SH794:02/:04 AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
A/6	0	2346	1704	110	225
A/15	0	2332	1524	138	180
A/2	0	2341	1345	90	245
A/8	0	2336	1133	100	186
A/12	0	2339	1172	97	199
A/24	0	2339	1528	115	218
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2339	1401	108	209
STANDARD DEVIATION		4	204	16	23
COEF. OF VAR (%)		0.19	15	15	11

IMPERIAL PMA (SH794:02/:04 AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
I/10	0	2346	1232	143	142
I/21	0	2335	983	125	129
I/19	0	2342	992	138	118
I/15	0	2338	1005	95	173
I/6	0	2340	1048	143	120
I/23	0	2339	1083	118	151
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2340	1057	127	139
STANDARD DEVIATION		4	85	17	19
COEF. OF VAR (%)		0.17	8	13	14

IMPERIAL 150/200A (SH794:02/:04 AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
A/18	-10	2344	3374	57	971
A/21	-10	2334	3146	61	849
A/14	-10	2341	3680	46	1323
A/13	-10	2337	3752	33	1860
A/7	-10	2338	3411	62	898
A/4	-10	2339	3368	34	1652
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2339	3455	49	1259
STANDARD DEVIATION		3	204	12	388
COEF. OF VAR (%)		0.13	6	24	30

IMPERIAL PMA (SH794:02/:04 AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
I/8	-10	2346	2537	73	573
I/11	-10	2336	2919	70	688
I/20	-10	2342	2692	86	517
I/5	-10	2338	2812	74	629
I/3	-10	2339	2803	88	524
I/24	-10	2340	2769	70	650
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2340	2755	77	597
STANDARD DEVIATION		3	118	7	64
COEF. OF VAR (%)		0.13	4	9	11

IMPERIAL 150/200A (SH794:02/:04 AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
A/23	-20	2343	4749	6.8	11385
A/19	-20	2334	3584	2.3	25776
A/5	-20	2340	3657	5.3	11272
A/16	-20	2337	4294	5.1	12352
A/11	-20	2338	5185	5.9	14916
A/3	-20	2340	3724	3.5	16375
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2339	4199	5	15346
STANDARD DEVIATION		3	603	1.49	5021
COEF. OF VAR (%)		0.13	14	30	33

IMPERIAL PMA (SH794:02/:04 AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
I/17	-20	2338	4445	17	4355
I/9	-20	2345	4522	9	8869
I/14	-20	2336	4361	24	2990
I/12	-20	2343	4374	11	6741
I/13	-20	2338	4462	13	6219
I/22	-20	2341	4326	12	5833
NUMBER OF SAMPLES		6	6	6	6
MEAN VALUE		2340	4415	14	5835
STANDARD DEVIATION		3	67	5	1847
COEF. OF VAR (%)		0.13	1.51	36	32

IMPERIAL 150/200A (SH794:02/:04 AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
A/22	-30	2342	3588	1.4	31356
A/20	-30	2335	4524	2.5	20593
A/9	-30	2343	4583	2.3	26138
A/1	-30	2335	4619	3.4	17839
NUMBER OF SAMPLES		4	4	4	4
MEAN VALUE		2339	4329	2.4	23982
STANDARD DEVIATION		4	429	0.71	5202
COEF. OF VAR (%)		0.16	10	30	22

IMPERIAL PMA (SH794:02/:04 AGGREGATE)

SAMPLE NUMBER	TEST TEMP (C)	SAMPLE DENSITY Kg/m3	FAILURE STRESS KPa	FAILURE STRAIN X0.0001	FAILURE STIFFNESS MPa
I/7	-30	2343	5000	7.2	11356
I/4	-30	2342	5131	7.8	11120
I/18	-30	2341	4965	6.5	10535
I/1	-30	2341	5018	7.5	11235
NUMBER OF SAMPLES		4	4	4	4
MEAN VALUE		2341	5029	7.25	11061
STANDARD DEVIATION		0.83	62	0.48	315
COEF. OF VAR (%)		0.035	1.23	7	2.85

APPENDIX D

UNIVERSITY OF ALBERTA REPEATED LOAD TRIAXIAL TEST APPARATUS PROCEDURES AND COMPUTER PROGRAMS

APPENDIX D

REPEATED LOADING TRIAXIAL TEST APPARATUS, PROCEDURES AND COMPUTER PROGRAMS

D.1 Introduction

One of the major objectives of the testing program undertaken in this investigation was to determine the permanent deformation characteristics of the conventional and polymer modified asphalt concrete mixtures. A repeated load triaxial test apparatus together with a dynamic recording system were needed to fulfill this purpose.

This appendix describes the testing apparatus and the recording system as well as the computer programs for the recording and processing of the data. The testing procedures are included here.

D.2 Repeated Load Triaxial Test Apparatus

D.2.1 Description of the Test Apparatus

The layout for the repeated load triaxial test apparatus is shown in Figure D-1. The essential features and functions of the various components are described below. Corresponding reference letters are included on Figure D.1.

A Counterbalance For The Loading Yoke

This unit consists of a weight and pulley system used to counterbalance the weight of the loading yoke on the piston and ram.

B Load Cell

This device is used to measure the axial stress applied to the specimen. It has an operating range of 0 to 910 kg.

C (LVDT) Linear Variable Differential Transducer

This is an electrical displacement transducer which measures the specimens axial deformation.

D Triaxial Cell

The triaxial cell used in this experiment was of standard size for the testing of 102 mm diameter by 204 mm high cylindrical specimen. The central area of the base of the triaxial cell is supported by the testing machine frame. This configuration allows the loading yoke to pass by the

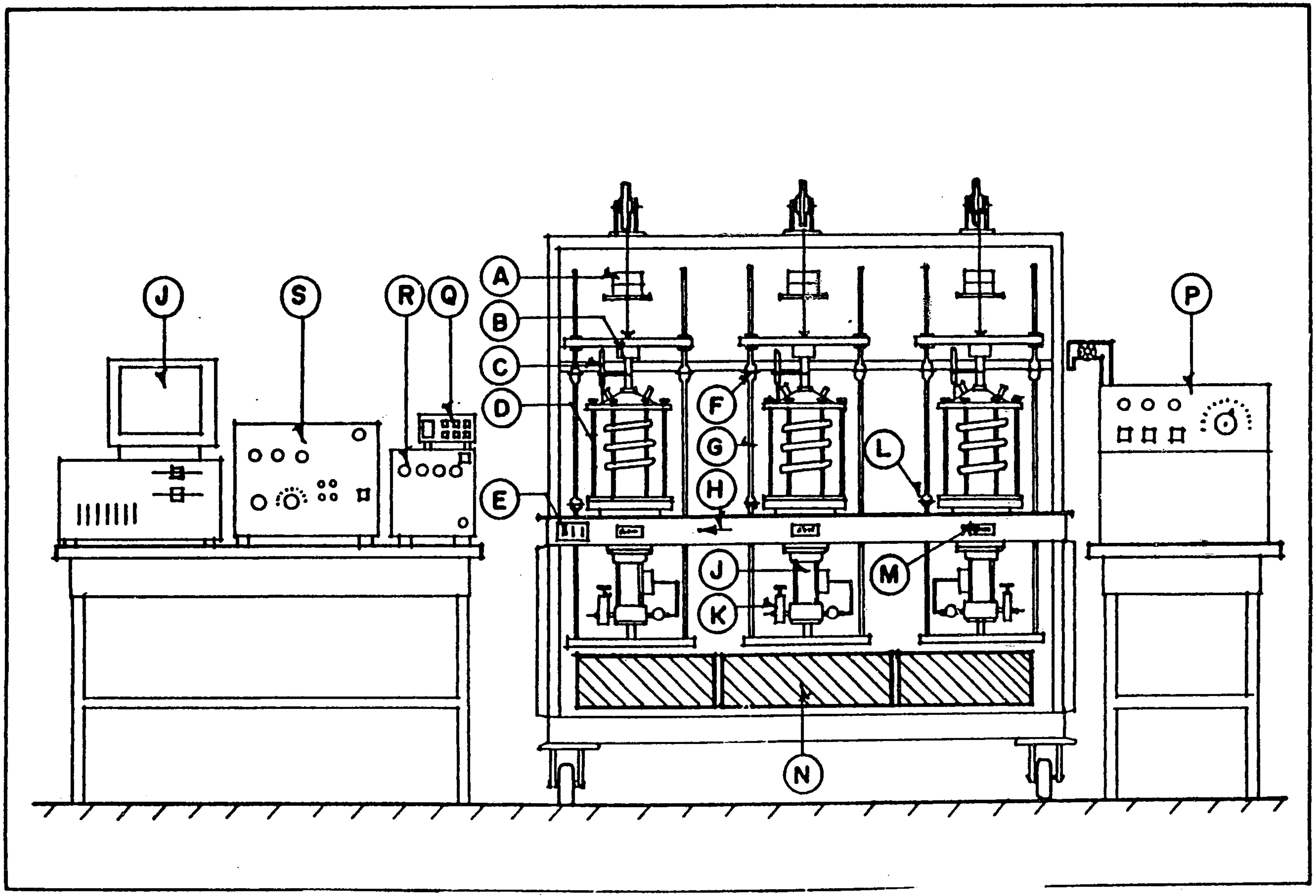

FIGURE D-1 SCHEMATIC OF EQUIPMENT LAYOUT FOR REPEATED LOAD TRIAXIAL TEST cell without obstruction. The clear removable cylinder is made of 9.5 mm thick perspex. The loading ram is a 19 mm diameter ground stainless steel rod with a hemispherical and designed to fit into the depression in the loading cap. The top cap of the cell contains entrance and exit spouts for the temperature control lines which continue as copper coils within the cell body. The top cap also contains a threaded hole for the seating of the LVDT core. The base of the triaxial cell contains valves for the connection of the confining pressure as well as the pressure transducer line. The axial load capacity of the loading ram is 2700 kg and pressure capacity of the triaxial cell is 1000 KPa. The detailed description of the triaxial cell is given in section D.2.2.

E Bay Operation Switches These switches supply the on-off control for the operation of their respective bays.

F Guide Frame for the Loading Yoke

This unit is designed to restrict the horizontal movement of the loading yoke. The apparatus consists of a slotted plate bolted to the frame and a smooth sided annular cylinder which threads onto the loading yoke rods. The annular cylinder is positioned such that it fits within the slot in the plate ensuring that the load is applied vertically to the load cell.

G Loading yoke

This is a rectangular frame which transfers the load to the loading ram of the triaxial cell from the piston at the bottom of the frame through the load cell located at the top of the frame.

H Pressure Transducer

This is a gauge used to measure the confining pressure in the three triaxial cells. In order to measure the confining pressure in each of the three triaxial cells, a four way valve is used. The transducer is connected to one of the arms while the other three arms are connected to the triaxial cells. By using a three-way valve switch, the pressure from two triaxial cells is shut off and pressure from the third triaxial cell is measured by transducer. The pressure transducer has an operating range of 0 to 2070 KPa.

J Air Pressure Cylinder and Piston

This unit transforms air pressure from the reservoir tank into mechanical energy which is then transferred to the loading yoke.

K Air Pressure regulators

These units are installed at various tappings on the air pressure reservoir tank to regulate the air pressure to the triaxial cells. The operating range of the regulators is 14 to 1000 KPa.

L Safety Microswitches

These units are designed such that when a pre-set maximum axial deformation is reached a steel bar will come in contact with a microswitch, shutting down the bay operation. This system avoids damage to the test apparatus in the event of sample failure. The switches are installed in each bay on the frame close to the loading yoke. A steel bar is mounted between two nuts on the threaded loading yoke. The location of the bar can be adjusted by rotating the nuts to obtain the correct gap width between the microswitch and the contact bar.

M Counter

This is a six digit electric counter connected to the solenoid valve in order to record the number of load applications to the specimen.

N Air Pressure Reservoir Tank

This is a cylindrical tank for the storage of the compressed air. It has sufficient capacity to provide the pressure requirements for the three triaxial cells. The maximum pressure capacity of the tank is 850 KPa.

P Temperature Control Bath

This unit is used to provide the required test temperature inside the three triaxial cells. By circulating the pre-set temperature controlled fluid through the heating coils within the triaxial cell, the temperature of the specimen can be kept at a desired constant test temperature throughout the experiment.

Q Voltmeter

This unit reads the voltage in millivolts from the pressure transducer. It is calibrated for the pressure range of the transducer, making it possible to read the confining pressures.

R Electrical Timing Unit

This consists of an electrical network of resistors, capacitors and inductance coils, which act to form a pulsating signal. By adjusting the properties of the components in the network, the frequency and duration of loading can be controlled. For this unit the minimum on-load time is 0.25 seconds.

S Signal Conditioner

This signal conditioner is used to amplify and condition the signals from the load cells, LVDTs and pressure transducer. An Exp-16 board which acts as a multiplexer is built into the signal conditioner. This card collects the signals from the load cells and amplifies the required signals, which are then sent to the Dash-8 card installed inside the computer. The Dash-8 card transforms the signals from the analog format into digital format. The LVDTs and pressure transducer signals are also amplified inside the signal conditioner and sent to the Dash-8 card. They, however, do not pass through the Exp-16 card.

T Computer and Data Logger

The computer collects data from the LVDTs and load cells from each of the triaxial cells. The computer used is an OPERAND with 640 K of RAM and two disc drives. The operating system used was DOS version 3.1. The data logging card, Dash-8 is installed in the computer. This card collects and converts the output voltages from LVDTs and load cells into "bits" for storage in the computer. Computer programs were written using "BASICA" to initialize the computer and collect the data.

Solenoid Valve (Not shown in the figure)

This valve controls the flow of pressurized air from the air-pressure reservoir to the air pressure cylinder and piston unit. The unit also provides the exhaust vent for air from the pressure cylinder and piston unit. The unit is controlled by the electric timing unit which electrically opens and closes a three-way solenoid operated valve.

Air Pressure Gauges (Not shown in the figure)

These gauges are installed after the air pressure regulators and indicate the air pressure being supplied by that particular line. The operating range of the gauges used are 0 to 1100 KPa for the axial pressure.

D.3. Operational Procedures

D.3.1 Sample Preparation

Level the top and bottom of the 102 mm diameter by 204 mm high specimen, ensuring that the surface and edges are free from protruding pieces of aggregate. If the specimen's surface cannot be levelled it can be sawed to produce an even surface.

D.3.2 Setting up the Sample in the Triaxial Cell

1. Place the specimen on the 102 mm diameter base plate of the triaxial cell.

2. Enclose the specimen and base plate with a 102 mm diameter rubber membrane.

3. Place the loading cap on top of the sample and enclose it with the rubber membrane.

4. Install the rubber O-rings over the membrane at the base

plate and the loading cap, fold the excess membrane material over the o-rings.

5. Align the specimen for verticality with the base plate and the loading cap.

6. Mount the top of the triaxial cell over the centered specimen. The loading ram should fit smoothly into the depression in the top of the loading cap. If a rotation of the loading ram causes lateral movement in the loading cap, there will be eccentricity in the positioning of the sample. In this case remove the top of the triaxial cell and realign the sample. Repeat this procedure until there is no eccentricity present.

7. Tighten the mounting screws, sealing the top of the triaxial cell of the base. Applying high vacuum grease to the surface of the loading ram was found to be helpful in stopping the leaks from the rubber gaskets and the loading ram channel.

D.3.3 Preparation for Testing

1. Insert the triaxial cell into loading bay 1, ensure that the specimen is not disturbed from its aligned position. Adjust the loading yolk so that the calibrated load cell sits properly on the loading ram.

2. Close all connection valves to the test cell.

3. Fill the air-pressure reservoir tank with compressed air.

4. Connect and start the heat circulation unit which has been previously set at the test temperature.

5. Fill the cell by pumping distilled water, of the proper test temperature, through the confining pressure valve.

6. Connect the pressure transducer and confining pressure lines to the triaxial cell.

7. Switch on the (a) electric timing unit, (b) signal conditioning unit, (c) computer and (d) volt meter.

8. Set the electric timing unit at the desired on load and off-load times.

9. Mount the LVDT core in the threaded hole in the top cap of the triaxial cell.

10. Insert the LVDT unit onto the core and lightly clamp the unit to the clamp bar attached to the loading ram of the triaxial cell.

11. Balance the calibrated LVDT with the aid of the computer program and then firmly clamp it into place.

12. Place a "U" shaped bar across the top of the triaxial cell, this will act as a dummy sample during the adjustment of the axial load.

13. Using the axial air pressure regulator, set the axial required pressure on the "U" shaped bar, fine tune the setting with the aid of the computer.

14. Open the pressure transducer and confining pressure

valves.

15. Using the lateral air pressure regulator, set the confining pressure to the required valve, fine tune the adjustment using the voltmeter.

16. Remove the "U" shaped bar from the top of the triaxial cell.

17. Set counter to zero.

18. Adjust the guides on the loading yoke by turning them on the threaded rod so that they come within the guide frame.

19. Determine the anticipated maximum deflection the sample is likely to undergo.

20. Adjust the gap between the safety microswitch and the steel bar according to the anticipated maximum sample deflection.

21. Bay 1 is ready for testing.

22. Set bay 2 and bay 3 by repeating the same procedure undertaken for bay 1.

23. The system is now ready for operation.

24. Initialize the computer.

25. Give proper name to the current test.

26. Start the test on the bay 1 by turning on the bay 1 operation switch and F1 button on the computer keyboard simultaneously.

27. After bay 1 has completed the first 1000 cycles, start the test on bay 2 by turning on simultaneously the bay 2 operating switch and F2 button on the computer keyboard.

28. Likewise, when bay 2 has completed 1000 cycles, switch on the bay 3 operating switch and F3 button to start the test on bay 3.

D.4 Data Acquisition System

A data acquisition system was used to collect the data from the triaxial test. The raw data which was recorded by computer using several programs was then processed and percent permanent strain and resilient modulus were computed. Following is the description of the hardware and software used for the data logging system including programs for collecting and processing the data.

D.4.1 Computer Hardware Used in the Data Acquisition System

The that was used to gather the test data was an IBM clone that was distributed by operand Electronics. The computer contained a number of features beyond the normal base system. The computer hardware consisted of the following:

(a) 640 K RAM

The absolute minimum amount of RAM that was required by the software was 512 K but it was preferable to use 640 K in order to provide a margin of safety for computers operation. 640 K is the maximum amount of RAM that can be accessed by current versions of DOS.

(b) Disk Drives

Two disk drives were required in order to run the software. The first or "A" drive contained the operating system and the basic program. The second or "B" drive was the drive to which the data would be sent upon completion of the test. Saving the data on the separate drive prevents the loss of any of the computer programs due to overwriting by test data. Before the data was written to a floppy it was stored in a RAM disk drive as explained later in the software section.

(c) Multifunction Card

The multifunction card was used in place of a parallel port because the card contains both a serial and parallel port which was used for printer communications. This card also has a clock on board.

D.4.2 Data Acquisition Hardware

There were two pieces of equipment that actually formed the repeated loading triaxial test data acquisition hardware system:

(a) MetraByte EXP-16 Board

The EXP-16 board was used in conjunction with the DASH-8 card in order to accommodate all of the data inputs from the test. The EXP-16 board can accommodate up to 16 channels of analog information. The board amplifies, filters and conditions the input signal from the test. The EXP-16 board multiplexs the signals into one channel that is fed into the DASH-8 board. This board was installed in the signal conditioner and was connected to the DASH-8 board in the computer by means of a ribbon cable. For further information regarding the EXP-16 board refer to the manual as published by the manufacturer, MetraByte corp.

(c) Dash-8 Board

The DASH-8 board was used to collect the data in analog form and convert it into digital form for use by the computer. The data was passed from the EXP-16 board to the DASH-8 board. The EXP-16 board collected the data because it had 16 channels available for data acquisition as opposed to the 8 channels available on the DASH-8 board. The DASH-8 board has a full scale input of +/- 5 volts on each channel with a resolution of 2.44 millivolts (0.00244 volts).

The DASH-8 board comes with a programmed software package that allows the user to configure the board to his own requirements. This software plus additional technical information can be found in the DASH-8 manual that is published by the manufacturer, MetraByte corp.

D.4.3 Data Acquisition Software

There were two prepackaged software packages used by the computer to record the test data. One was DOS version 3.1 and the other was the DASH-8 configuration package. There was also a program written in BASIC specifically for use in the repeated loading triaxial test. The detailed description of each program is given below:

(a) DOS 3.1

DOS 3.1 was used because it was the most up to date operating system available and it allowed the establishment of a "virtual disk" on the computer. When the computer "booted up" there was command in the "config.sys" file that created a 200 K virtual disk in RAM. A virtual disk has a very quick access time so that it is possible for the computer to store the gathered information on this "disk". When the test was finished the contents of the virtual disk was automatically transferred to the diskette in drive"B".

(b) DASH-8 Software

The DASH-8 board was supplied with a software package that provides the I/O driver routine. This routine is called "DASH8.BIN" and can be accessed from BASIC using call statements. Using the DASH8.BIN software in conjunction with a BASIC program provided considerable flexibility in the use of the computer hardware. Various functions and operations were defined from within the BASIC program by using the DASH8.BIN file. The DASH-8 operations manual can be used for further information.

(c) Triaxial Test Control and Datalogging Program

A BASIC program was written to collect the test data from the repeated loading triaxial test and store it in the computer. This program made use of the DASH-8 software and therefore any attempt to analyze the program should be done with the DASH-8 manual as reference.

This program uses the timer built into the DASH-8 board and therefore does not require any internal clock in the computer. The timer controls the data acquisition portion of the board so that there are two hundred measurements made per second. The computer takes the maximum and minimum values. The board timer also sends one pulse per second to the external timer. This external timing unit controls the operation of the air rams that load the specimens.

The limitations due to the hardware allowed only one reading per second to be recorded. Because only one reading per second could be recorded and there were three samples being tested the start-ups were staggered. Test one would commence and readings would be taken every one second for the first 1000 seconds. Upon completion of the first 1000 second test two would begin and its first 1000 readings would be recorded and test three would start after test two completed the first one thousand cycles.

The information was recorded as follows: every second for the first 1000 seconds, every 100 seconds until 10,000 seconds and then every 1000 seconds until the end of the test.

The BASIC program written for the repeated loading triaxial test is illustrated in section D.4.4.1. It contains all the information and comments regarding the test which makes it self-explanatory.

(d) Programs for Processing the Raw Data

The data which have been collected by computer were in binary form. Computer programs were necessary to convert the collected data from the binary formats into permanent deformation and resilient modulus values by introducing the various parameters and necessary calculations.

The percent permanent strain was computed as follows:

$$Ep = \frac{100\ Nmin\ Kp}{410\ t}$$

Where

Ep = percent permanent strain,

Nmin = deformation values in binary bit as recorded by computer (minimum values at each pulse),

1 volt = 410 bits,

Kp = calibration factor for LVDT, mm/volt, and

t = thickness of the specimen, mm.

A Lotus 1-2-3 Macro program was written specifically converting the raw data from binary to real format and performing the percent deformation and resilient modulus computations. This program is presented in section D.4.4.2.

D.4.4 Listing of the computer Program for the Repeated Load Triaxial Test

D.4.4.1 Triaxial Test Control and Datalogging program

```
50 '**********************************************************
60 '*                 Repeated Loading Triaxial Test         *
70 '*                 Control and Datalogging System         *
80 '**********************************************************
100 'def seg=&h1700 'Setup load segment
110 'bload "dash8.bin",0 'Loads at 1700:0000
111 '---------------------------------------------------------
112 ' above requried for interpertive version
113 '---------------------------------------------------------
115 '
116 '    Load dash8 address
117 '........................................
120 OPEN "dash8.adr" FOR INPUT AS #1
130 INPUT #1, BASADR%
135 CLOSE #1
136 '........................................
137 '     Setup variables
138 'the number of reading are modified using max and diff
139 '........................................
150 MAX1=1000: DIFF1=100: MAX2=1000: DIFF2=100: MAX3=1000: DIFF3=100
151 DIM DAH%(2),DAL%(2),LCH%(2),LCL%(2),DA%(199),DIO%(2),LT%(2),TRAN%(2)
152 '          Definations
153 '    DAH=Maxium load cell reading DAL=low load cell reading DA=readings
154 '    LCH=Maxium lvdt reading      LCL=low lvdt reading
155 '........................................
156 '    Initialize dash8 with mode 0
157 '........................................
160 DASH8=0 : FLAG%=0 : MD%=0
170 CALL DASH8 (MD%, BASADR%, FLAG%)
175 '........................................
180 '........................................
185 '    Setup of function keys
186 '    --------------------
187 '
188 '      Function Key#              Desription
189 '
190 '           1             start test sample #1
191 '           2             stop test sample #1(cursor down at same time)
192 '           3             start test sample #2
193 '           4             stop test sample #2(cursor down at same time)
194 '           5             start test sample #3
195 '           6             stop test sample #3(cursor down at same time)
196 '           10            stops program
197 KEY(1) ON : KEY(2) ON : KEY (3) ON: KEY (4) ON : KEY (5) ON
198 KEY(6) ON : KEY(14) ON : KEY (10) ON
199 '........................................
200 '      Setup files for data to be sent to c:drive
201 '........................................
201 INPUT "enter file name";F$:FFO$="c:"+F$+"0.prn":FF1$="c:"+F$+"1.prn"
202 FF2$="c:"+F$+"2.prn"
203 OPEN FFOS FOR OUTPUT AS 3 :OPEN FF1$ FOR OUTPUT AS 1
204 OPEN FF2S FOR OUTPUT AS 2
205 '........................................
206 '      Subroutine pointers for defined keys
207 '........................................
210 ON KEY(1) GOSUB 400 '  function key 1
215 ON KEY(2) GOSUB 500 '               2
220 ON KEY(3) GOSUB 600 '               3
225 ON KEY(4) GOSUB 700 '               4
230 ON KEY(5) GOSUB 800 '               5
```

```
233 ON KEY(6) GOSUB 850 '               6
234 ON KEY(14) GOSUB 550 ' down cursor
235 ON KEY(11) GOSUB 360 ' up cursor
236 ON KEY(10) GOSUB 450 ' function key 10
237 '.........................................
238 '      Set dasn8 time/counter configuation use mode 10
239 '.........................................
240 MD%=10 : DIO%(0)=2 : DIO%(1)=3 ' use counter 2
250 CALL DASH8 (MD%. DIO%(0). FLAG%) 'configuation 3(square wave generator)
251 '.........................................
252 '      Load the timer/counter use mode 11
253 '.........................................
260 MD%=11 : DIO%(0)=2 : DIO%(1)=23868/4 ' 23868/4=5967  one period=.4190 us
270 CALL DASH8 (MD%. DIO%(0). FLAG%) ' 5967*.4190=2500 us or 2.5 msec
271 '.........................................
272 '    Enable/disable data channel tag use mode 17
273 '.........................................
280 MD%=17 : EN%=0 '0=off , 1=on
290 CALL DASH8 (MD%. EN%. FLAG%)
291 '.........................................
300 GOSUB 1000 ' goto title page
301 '.........................................
302 '      Wait for function keys to start tests
303 '.........................................
305 IF S1=1 OR S2=1 OR S3=1 THEN GOTO 900
310 GOTO 305
315 '.........................................
316 '       Restart test
317 '.........................................
360 IF STP1=1 THEN S1=0:SR1=0:STT1=0:ST1=0:NT1=0:RETURN 'restart #1
370 IF STP2=1 THEN S2=0:SR2=0:STT2=0:ST2=0:NT2=0:RETURN 'restart #2
380 IF STP3=1 THEN S3=0:SR3=0:STT3=0:ST3=0:NT3=0:RETURN 'restart #3
385 '.........................................
386 '      Subroutine-Start test #1
400 S1=1 : SR1=0 :RETURN
450 STOP
475 '.........................................
476 '       Subroutine to stop or restart test #1
477 '.........................................
500 STP1=1 : KEY (14) ON:KEY (11) ON: KEY (14) STOP:KEY (11) STOP:STP1=0:RETURN
525 '.........................................
526 '      Subruotine-Stop tests
527 '.........................................
550 IF STP1=1 THEN S1=0 : SR1=0 : RETURN 'stop test #1
560 IF STP2=1 THEN S2=0 : SR2=0 : RETURN 'stop test #2
570 IF STP3=1 THEN S3=0 : SR3=0 : RETURN 'stop test #3
580 RETURN
585 '.........................................
586 '  .   Subroutine-Start test #2
587 '.........................................
600 S2=1 : SR2=0 : RETURN
605 '.........................................
606 '      Subroutine-stop or restart test #2
607 '.........................................
700 STP2=1 : KEY (14) ON:KEY (11) ON:KEY (14) STOP:KEY (11) STOP:STP2=0 :RETURN
705 '.........................................
706 '      Subroutine-Start test #3
707 '.........................................
800 S3=1 : SR3=0 : RETURN
805 '.........................................
807 '      Subroutine-stop or restart test #3
808 '.........................................
850 STP3=1 : KEY (14) ON:KEY (11) ON:KEY (14) STOP:KEY (11) STOP:STP3=0 :RETURN
852 '.........................................
875 '      Sync with control pulse supplied externally
876 '=========================================================================
900 GOSUB 1500 'input i/o
910 IF IP% AND 1 THEN GOTO 900 'is bit 1 high?
920 GOSUB 1500 'input i/o
930 IF IP% AND 1 THEN GOTO 970 'is bit 1 high
940 GOTO 920
970 GOSUB 1500:IF IP% AND 1 THEN GOTO 970 'check again
```

```
975 GOTO 3000 'goto control routine
980 '=====================================================================
1000 RETURN 'reserved for title page
1100 '.................................
1110 '     Subroutine-input dash8 i/o with mode 13
1120 '.................................
1500 MD%=13
1510 CALL DASH8 (MD%, IP%, FLAG%):RETURN
1520 '.................................
1900 '=====================================================================
1910 '                  Dash8 datalogging routine
1920 '                  ------------------------
1930 '.........................
1940 '     Determine which test to sample
1950 '.........................
2000 IF SR1=1 THEN SR1=0 : STT1=STT1+1 : R=STT1 : T=0 : GOTO 2050 'do #1
2010 IF SR2=1 THEN SR2=0 : STT2=STT2+1 : R=STT2 : T=1 : GOTO 2100 'do #2
2020 IF SR3=1 THEN SR3=0 : STT3=STT3+1 : R=STT3 : T=2 : GOTO 2200 'do #3
2040 NR=1:GOTO 2060 'do none
2045 '.........................
2046 '.........................
2047 '     set exp16 channel no. and output
2048 '.........................
2050 MD%=14 : OP%=0 :C1=STT1:C2=ST1:TO=3:NR=0
2060 CALL DASH8 (MD%, OP%, FLAG%)
2065 '..........................
2066 ' -    Set first and last channel use mode 1
2067 '...........................
2070 MD%=1 : LT%(0)=0 : LT%(1)=3
2080 CALL DASH8 (MD%, LT%(0), FLAG%)
2081 '...........................
2082 '      log data use mode 5
2083 '...........................
2085 C=0
2090 MD%=5 : TRAN%(0)=VARPTR(DA%(C)): TRAN%(1)=199
2095 CALL DASH8 (MD%, TRAN%(0), FLAG%):IF NR=1 THEN FOR NI=0 TO 100:NEXT NI:GOTO 970
2096 C=0 : STA=8 : FIN=196 : GOSUB 4500 'get max and min
2097 HTEMP1=HTEMP : LTEMP1=LTEMP 'store max and min
2098 C=T+1 : STA=T+9 : FIN=T+197 : GOSUB 4500
2099 PRINT #TO,C1 C2 HTEMP LTEMP HTEMP1 LTEMP1:GOTO 970 'output to data file
2100 MD%=14 : OP%=1 :C1=STT2:C2=ST2:TO=1:NR=0: GOTO 2060 'set exp16
2200 MD%=14 : OP%=2:C1=STT3:C2=ST3:TO=2:NR=0: GOTO 2060 'set exp16
2300 '==================================================================
2310 '                         control routines
2320 '                         ----------------
3000 PRINT ST1 STT1 "   " ST2 STT2 "   "ST3 STT3"  "HTEMP"  "LTEMP" "HTEMP1"  "LTEMP1
3001 '+++++++ turn function keys on ++++++++
3002 KEY(1) ON : KEY(2) ON : KEY (3) ON: KEY (4) ON:KEY (5) ON:KEY (6) ON
3003 IF DON1=1 AND DON2=1 AND DON3=1 GOTO 4000 'is test done
3004 KEY (1) STOP:KEY (2) STOP:KEY (3) STOP:KEY (4) STOP:KEY (5) STOP:KEY (6) STOP
3005 IF S1=1 THEN ST1=ST1+1 : NT1=NT1+1 'test 1 on?,set conditions
3006 IF NT1=DIFF1 THEN SRS1=1 : NT1=0 'diff1 reached,do reading on test 1
3010 IF S2=1 THEN ST2=ST2+1 : NT2=NT2+1 'test 2 on?,set conditions
3011 IF NT2=DIFF2 THEN SRS2=1 : NT2=0 'diff2 reached,do reading on test 2
3020 IF S3=1 THEN ST3=ST3+1 : NT3=NT3+1 'test 3 on?,set conditions
3021 IF NT3=DIFF3 THEN SRS3=1 : NT3=0 'diff reached,do reading on test 3
3025 '..........................
3026 '      Do 100 readings on test 1 if on
3027 '..........................
3030 IF ST1>99 THEN GOTO 3200 'goto test 2 if more then 100 readings
3040 IF S1=0 THEN GOTO 3200 '0=off,1=on,is test 1 on?
3050 SR1=1 'do a reading
3060 GOTO 2000 'goto dataloging routine
3065 '...............................
3070 '      do 100 readins on test 2 if on
3075 '.................................
3200 IF ST2>99 THEN GOTO 3300 'goto test 3 if more then 100 readings
3205 IF SRS1=1 THEN SR1=1:SRS1=0:GOTO 2000 'if on read test 1
3210 IF S2=0 THEN GOTO 3300 'is test 2 on?
3220 SR2=1 'do a reading on test 2
3230 GOTO 2000 'go to datalogging routine
```

```
3235 '...................................
3236 '        Do 100 readings on test 3 if on
3237 '...................................
3300 IF ST3>99 THEN GOTO 3400 'goto adjustments of control program
3305 IF SRS1=1 THEN SR1=1:SRS1=0:GOTO 2000 'if on read test 1
3307 IF SRS2=1 THEN SR2=1:SRS2=0:GOTO 2000 ' if on read test 2
3310 IF S3=0 THEN GOTO 3400 ' is test 3 on
3320 SR3=1 ' do a reading on test 3
3330 GOTO 2000 ' go to datalogging routine
3335 '...................................
3336 '      Counter adjustment routines
3337 '....................................
3338 '            counter 1
3339 '..................................
3400 IF S1=0 THEN GOTO 3600 'skip if off
3410 IF ST1=MAX1 THEN GOTO 3500 'check for max total readings
3420 IF SRS1=1 THEN SR1=1 : SRS1=0 : GOTO 2000 'go to datalog routine
3430 GOTO 3600 'goto test 2 counter
3500 IF ST1=100000! THEN DON1=1:CLOSE 3 :S1=0: GOTO 2000 'max reached close file
3505 NT1=0
3510 MAX1=MAX1*10 : DIFF1=DIFF1*10 : GOTO 3410 'reset max and diff
3575 '            counter 2
3576 '..................................
3600 IF S2=0 THEN GOTO 3800  'skip if off
3610 IF ST2=MAX2 THEN GOTO 3640 'check for max readings
3620 IF SRS2=1 THEN SR2=1 : SRS2=0 : GOTO 2000 'goto datalog routine
3630 GOTO 3800 'goto test 3 counter
3640 IF ST2=100000! THEN DON2=1:CLOSE 1:S2=0:GOTO 2000 ' max reached close file
3700 NT2=0 : MAX2=MAX2*10 : DIFF2=DIFF2*10 : GOTO 3610 'reset max and diff
3750 '            counter 3
3755 '..................................
3800 IF S3=0 THEN GOTO 2000 'skip if off
3810 IF ST3=MAX3 THEN GOTO 3840 'check for max readings
3820 IF SRS3=1 THEN SR3=1 : SRS3=0 : GOTO 2000 'goto datalog routine
3830 GOTO 2000
3840 IF ST3=100000! THEN DON3=1:CLOSE 2 :S3=0: GOTO 2000
3900 NT3=0 : MAX3=MAX3*10 : DIFF3=DIFF3*10 : GOTO 3810
3950 '..................................
3955 '       return to system
3960 '..................................
4000 PRINT "done":SYSTEM
4100 '...................................
4400 '....................................
4410 '       Subroutine-max and min
4500 IF DA%(C)>DA%(C+4) THEN HTEMP=DA%(C):LTEMP=DA%(C+4): GOTO 4520
4510 HTEMP=DA%(C+4) : LTEMP=DA%(C)
4520 FOR C=STA TO FIN
4530 IF DA%(C)>HTEMP THEN HTEMP=DA%(C) : GOTO 4550
4540 IF DA%(C)<LTEMP THEN LTEMP=DA%(C)
4550 C=C+3 : NEXT C :C=0 : RETURN
 10000 STOP
```

D.4.4.2 Lotus 1-2-3 Macro Program for Triaxial Test Data Processing

The following is a listing of the LOTUS macro that controls the spreadsheet for the triaxial test data calculations. The macro does not appear in the spreadsheet in the same format as it is presented here. As well the comments found here are not found in the spreadsheet they are placed here to assist in future modifications of the spreadsheet.

INITIALIZING SUBROUTINE

```
/wgrm                    | this macro initializes         INITIAL    NUMBER
/reOLDRAW¬               | the worksheet                                 1
{goto}A11¬               |                                   4
/finUSR\GARYV\TRIAX\     | the test data is retrieved
12APBCAO                 |
¬                        |
/dqiINPUT¬               |
cCRITERION¬              |
ddq                      | the cell pointer is moved to the
{goto}A11¬               | correct locatin as specified
/df{esc}.                |
{end}{down}¬             |
0¬1¬¬                    |
/xgCALC¬                 |
```

CALCULATION SUBROUTINE (performs all necessary calculations)

```
{goto}BIT1¬                                                   FACTOR    THICK
+0.00000001¬                                                  2.8504    8.156
/cBIT1¬H11..J11¬
{goto}BIT2¬
(@ABS(D12-$D$11))¬
{goto}PERMDEF¬
((BIT2*2.44*100*$FACTOR)/(1000*$THICK*25.4))¬          | % permanet strain
{goto}DIFFER¬                                          | claculation
@ABS(C12-D12)¬
{goto}RESMOD¬
+(310.26405/((($H12-1)*2.44*$FACTOR)/(1000*$THICK*25.4)))¬   | resilient
/cG12..L12¬                                                  | modulus
G12..L1205¬                                                  |calculation
/cB9.B1205¬
I9¬
/rncTEST¬¬                  |    this section determines where the
/rndTEST¬                   |    pertinent data is and then passes control
{goto}A1203¬                |    to the ERASE macro
/rncTEST¬¬                  |
/xiTEST<>0¬/xgERASE¬        |
/rndTEST¬                   |
{up}                        |
/rncTEST¬¬                  |
/xgLOOP¬                    |
```

DATA INPUT SUBROUTINE

```
{goto}BEGIN¬          | this subroutine allows the file names,
/rndIDAS¬             | sample data, and starting points to be entered
/rndIDAF¬             | entered into the worksheet.
/rndTEMP¬             |
/rndTHIK¬             |
/rndSTINT¬            |
```

```
/rndFACT1¬
/rncIDAS¬¬
{goto}IDAS¬
/rndIDAS¬
{down}
/rncIDAS¬¬
{right}
/rncIDAF¬¬
{right}
/rncTEMP¬¬
{right}
/rncTHIK¬¬
{right}
/rncSTINT¬¬
{right}                         C8
/rncFACT1¬¬
{right}
/xiTHIK=0¬/xq¬
/cIDAS¬
SAMNO¬
/cIDAS¬
PRINTID¬
/cIDAF¬
FRET¬
/cIDAF¬
FILID¬
/cTEMP¬
SPTEMP¬
/cTHIK¬
THICK¬
/cTHIK¬
THIK1¬
/cSTINT¬
INITIAL¬
/cSTINT¬
INIT2¬
/cFACT1¬
FACTOR¬
/cFACT1¬
FACT2¬
/xcSTART¬
/rndIDAF¬
/rndTEMP¬
/rndTHIK¬
/rndSTINT¬
/rndFACT1¬
/xgLOOP4¬
```

PRINT SUBROUTINE

```
{goto}I1¬
/pfUSR\GARYV\TRIAX\
B4
¬
crr.
{end}{down}
{end}{down}
{end}{down}
{end}{right}
{end}{right}¬
gq
/xr
```

this is the print macro which prints out all of the calculated data

ERASE

```
{down}
/re.
{right}
{right}
{right}
```

this is the erase macro which deletes all extraneous data

```
{right}
{right}
{right}
{right}
{right}
{right}
{right}
{right}
{right}
{end}
{down}~
/xgPRINT~
```

AUTOEXEC MACRO

```
{goto}a1500~            |this macro starts the menu macro when the wks.
/xg\Q~                  | is called up.
```

MAIN MENU MACRO

```
/xmMMenu~                                      | this is the menu macro
Enter     Process  Quit                        | which has overall control
Enter or Begin proLeave LOTUS 1-2-3            | of the spreadsheet
/xc\W~    /xc\Z~   /fs~r/qy
```

```
{goto}E1308~          |  this sets up titles for the data input
{down}                |
{down}
{down}
{down}
{down}
{down}
/wth
```

(BELOW IS AN EXAMPLE OF DATA THAT MUST BE INPUT BEFORE MACRO EXECUTION

USE THE CURSOR KEYS TO MOVE AND PRESS "Alt" "Q" TO RETURN TO MENU

SAMPLE NAME	FILE ID	TEMP DEG C	THICK (INCHES)	START	FACTOR
B4	12APBCAO	25	8.156	4	2.8504
B1S	26MABECO	25	8.182	15	3.022
E8S	26MABEC1	25	8.143	15	3.241
C1S	26MABEC2	25	8.137	15	2.7304
A5	10APAFDO	25	8.175	11	2.8504

APPENDIX E

GROUPING OF HIGH TEMPERATURE SPECIMENS

```
IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN
CITY OF LETHBRIDGE AGGREGATE (MIX B) HUSKY 150/200 AC (HIGH TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 0.000
THE STANDARD DEVIATION =   0.000
THE COEFFICIENT OF VARIATION (%) =   0.000

      SAMPLE     DRY WT.     SSDWT.     IM.WT.      VOL.     SP.GR.    NO. OF
       NAME        g.          g.         g.         cc.               ST.DEV.
                                                                      FROM MEAN
      150/1      3907.20     3909.10    2248.50    2248.50    0.000     +0.00
      150/2      3935.90     3937.50    2264.30    2264.30    0.000     +0.00
      150/3      3952.10     3954.00    2277.00    2277.00    0.000     +0.00
      150/4      3922.10     3923.00    2263.50    2263.50    0.000     +0.00
      150/5      3928.10     3928.80    2267.70    2267.70    0.000     +0.00
      150/6      3916.50     3917.60    2254.30    2254.30    0.000     +0.00
      150/7      3902.80     3903.60    2244.80    2244.80    0.000     +0.00
      150/8      3938.60     3939.60    2273.60    2273.60    0.000     +0.00
      150/9      3965.00     3965.90    2288.50    2288.50    0.000     +0.00
      150/10     3915.90     3918.00    2258.00    2258.00    0.000     +0.00
      150/11     3976.10     3977.60    2288.50    2288.50    0.000     +0.00
      150/12     3929.20     3929.90    2269.40    2269.40    0.000     +0.00
      150/13     3935.50     3936.80    2265.20    2265.20    0.000     +0.00
      150/14     3903.00     3903.60    2245.80    2245.80    0.000     +0.00
      150/15     3890.40     3891.80    2243.60    2243.60    0.000     +0.00
      150/16     3864.50     3865.60    2231.80    2231.80    0.000     +0.00
      150/17     3995.50     3998.30    2305.20    2305.20    0.000     +0.00
      150/18     3893.00     3894.10    2239.60    2239.60    0.000     +0.00
      150/19     3961.10     3962.00    2286.00    2286.00    0.000     +0.00
      150/20     3987.20     3987.80    2296.40    2296.40    0.000     +0.00
      150/21     3933.30     3934.30    2263.60    2263.30    0.000     +0.00
      150/22     3999.50     4000.80    2309.00    2309.00    0.000     +0.00
      150/23     3954.80     3956.20    2280.30    2280.30    0.000     +0.00
      150/24     3963.30     3965.30    2287.50    2287.50    0.000     +0.00
```

```
IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN
CITY OF LETHBRIDGE AGGRAGATE (MIX B) 150/200 AC (HIGH TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.359
THE STANDARD DEVIATION =   0.005
THE COEFFICIENT OF VARIATION (%) =   0.203

         SAMPLE    DRY WT.    SSDWT.    IM.WT.     VOL.    SP.GR.    NO. OF
          NAME       g.         g.        g.        cc.              ST.DEV.
                                                                    FROM MEAN
         150/1     3907.20    3909.10   2248.50   1660.60   2.353     +1.25
         150/2     3935.90    3937.50   2264.30   1673.20   2.352     +1.37
         150/3     3952.10    3954.00   2277.00   1677.00   2.357     +0.46
         150/4     3922.10    3923.00   2263.50   1659.50   2.363     -0.95
         150/5     3928.10    3928.80   2267.70   1661.10   2.365     -1.23
         150/6     3916.50    3917.60   2254.30   1663.30   2.355     +0.88
         150/7     3902.80    3903.60   2244.80   1658.80   2.353     +1.27
         150/8     3938.60    3939.60   2273.60   1666.00   2.364     -1.09
         150/9     3965.00    3965.90   2288.50   1677.40   2.364     -1.02
         150/10    3915.90    3918.00   2258.00   1660.00   2.359     -0.02
         150/11    3976.10    3977.60   2288.50   1689.10   2.354     +1.02
         150/12    3929.20    3929.90   2269.40   1660.50   2.366     -1.54
         150/13    3935.50    3936.80   2265.20   1671.60   2.354     +0.95
         150/14    3903.00    3903.60   2245.80   1657.80   2.354     +0.95
         150/15    3890.40    3891.80   2243.60   1648.20   2.360     -0.32
         150/16    3864.50    3865.60   2231.80   1633.80   2.365     -1.35
         150/17    3995.50    3998.30   2305.20   1693.10   2.360     -0.21
         150/18    3893.00    3894.10   2239.60   1654.50   2.353     +1.23
         150/19    3961.10    3962.00   2286.00   1676.00   2.363     -0.95
         150/20    3987.20    3987.80   2296.40   1691.40   2.357     +0.32
         150/21    3933.30    3934.30   2263.60   1670.70   2.354     +0.96
         150/22    3999.50    4000.80   2309.00   1691.80   2.364     -1.08
         150/23    3954.80    3956.20   2280.30   1675.90   2.360     -0.20
         150/24    3963.30    3965.30   2287.50   1677.80   2.362     -0.69
```

```
IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN
CITY OF LETHBRIDGE AGGREGATE (MIX B) (HIGH TEMP)

NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.359
THE STANDARD DEVIATION =   0.005
THE COEFFICIENT OF VARIATION (%) =   0.203

      SAMPLE    DRY WT.     SSDWT.      IM.WT.      VOL.      SP.GR.    NO. OF
       NAME       g.          g.          g.         cc.               ST.DEV.
                                                                      FROM MEAN
      150/12    3929.20     3929.90     2269.40     1660.50    2.366     -1.54
      150/16    3864.50     3865.60     2231.80     1633.80    2.365     -1.35
      150/5     3928.10     3928.80     2267.70     1661.10    2.365     -1.23
      150/8     3938.60     3939.60     2273.60     1666.00    2.364     -1.09
      150/22    3999.50     4000.80     2309.00     1691.80    2.364     -1.08
      150/9     3965.00     3965.90     2288.50     1677.40    2.364     -1.02
      150/19    3961.10     3962.00     2286.00     1676.00    2.363     -0.95
      150/4     3922.10     3923.00     2263.50     1659.50    2.363     -0.95
      150/24    3963.30     3965.30     2287.50     1677.80    2.362     -0.69
      150/15    3890.40     3891.80     2243.60     1648.20    2.360     -0.32
      150/17    3995.50     3998.30     2305.20     1693.10    2.360     -0.21
      150/23    3954.80     3956.20     2280.30     1675.90    2.360     -0.20
      150/10    3915.90     3918.00     2258.00     1660.00    2.359     -0.02
      150/20    3987.20     3987.80     2296.40     1691.40    2.357     +0.32
      150/3     3952.10     3954.00     2277.00     1677.00    2.357     +0.46
      150/6     3916.50     3917.60     2254.30     1663.30    2.355     +0.88
      150/13    3935.50     3936.80     2265.20     1671.60    2.354     +0.95
      150/14    3903.00     3903.60     2245.80     1657.80    2.354     +0.95
      150/21    3933.30     3934.30     2263.60     1670.70    2.354     +0.96
      150/11    3976.10     3977.60     2288.50     1689.10    2.354     +1.02
      150/18    3893.00     3894.10     2239.60     1654.50    2.353     +1.23
      150/1     3907.20     3909.10     2248.50     1660.60    2.353     +1.25
      150/7     3902.80     3903.60     2244.80     1658.80    2.353     +1.27
      150/2     3935.90     3937.50     2264.30     1673.20    2.352     +1.37
```

```
THESE ARE THE POSSIBLE GROUPS

          SAMPLE     SP.GR.     MEAN        GROUP       COEFF. OF
           NAME                 SP.GR.      ST.DEV.     VARIATION (%)

          150/12      2.366
          150/2       2.352
          150/19      2.363
          150/14      2.354
          150/10      2.359
          150/20      2.357
                                2.359       +0.0053       0.226


          150/16      2.365
          150/7       2.353
          150/4       2.363
          150/13      2.354
          150/3       2.357
          150/15      2.360
                                2.359       +0.0051       0.214


          150/5       2.365
          150/1       2.353
          150/24      2.362
          150/6       2.355
          150/21      2.354
          150/22      2.364
                                2.359       +0.0054       0.230


          150/9       2.364
          150/11      2.354
          150/17      2.360
          150/18      2.353
          150/8       2.364
          150/23      2.360
                                2.359       +0.0047       0.200
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX C) HUSKY PMA 2 (HIGH TEMP)

NUMBER OF SAMPLES = 24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 0.000
THE STANDARD DEVIATION = 0.000
THE COEFFICIENT OF VARIATION (%) = 0.000


 SAMPLE     DRY WT.     SSDWT.     IM.WT.     VOL.     SP.GR.    NO. OF
  NAME        g.          g.         g.        cc.               ST.DEV.
                                                               FROM MEAN
 PMA/1      3804.60    3805.90    2189.50    2189.50    0.000     +0.00
 PMA/2      3851.90    3853.30    2216.10    2216.10    0.000     +0.00
 PMA/3      3917.20    3918.40    2241.80    2241.80    0.000     +0.00
 PMA/4      3868.70    3869.90    2225.00    2225.00    0.000     +0.00
 PMA/5      3846.00    3846.70    2212.30    2212.30    0.000     +0.00
 PMA/6      3893.40    3894.50    2240.20    2240.20    0.000     +0.00
 PMA/7      3859.70    3860.70    2223.90    2223.90    0.000     +0.00
 PMA/8      3847.80    3848.70    2215.60    2215.60    0.000     +0.00
 PMA/9      3841.90    3842.60    2210.20    2210.20    0.000     +0.00
 PMA/10     3930.40    3932.10    2268.30    2268.30    0.000     +0.00
 PMA/11     3876.90    3877.50    2230.00    2230.00    0.000     +0.00
 PMA/12     3901.70    3902.40    2249.90    2249.90    0.000     +0.00
 PMA/13     3962.60    3963.50    2283.50    2283.50    0.000     +0.00
 PMA/14     3954.50    3955.70    2282.50    2282.50    0.000     +0.00
 PMA/15     3894.50    3895.80    2239.50    2239.50    0.000     +0.00
 PMA/16     3993.40    3995.00    2301.90    2301.90    0.000     +0.00
 PMA/17     3917.70    3918.30    2252.00    2252.00    0.000     +0.00
 PMA/18     3883.60    3886.40    2240.40    2240.40    0.000     +0.00
 PMA/19     3930.90    3932.10    2265.80    2265.80    0.000     +0.00
 PMA/20     3976.50    3979.60    2294.70    2294.70    0.000     +0.00
 PMA/21     3919.20    3921.80    2257.40    2257.40    0.000     +0.00
 PMA/22     3767.40    3768.80    2167.50    2167.50    0.000     +0.00
 PMA/23     3899.40    3901.50    2244.10    2244.10    0.000     +0.00
 PMA/24     3874.50    3875.50    2233.30    2233.30    0.000     +0.00
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX C) PMA 2 (HIGH TEMP)
NUMBER OF SAMPLES =  24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.355
THE STANDARD DEVIATION =   0.006
THE COEFFICIENT OF VARIATION (%) =   0.236

  SAMPLE    DRY WT.    SSDWT.    IM.WT.     VOL.     SP.GR.   NO. OF
   NAME       g.         g.        g.        cc.               ST.DEV.
                                                              FROM MEAN
  PMA/1     3804.60   3805.90   2189.50   1616.40    2.354     +0.29
  PMA/2     3851.90   3853.30   2216.10   1637.20    2.353     +0.47
  PMA/3     3917.20   3918.40   2241.80   1676.60    2.336     +3.41
  PMA/4     3868.70   3869.90   2225.00   1644.90    2.352     +0.61
  PMA/5     3846.00   3846.70   2212.30   1634.40    2.353     +0.39
  PMA/6     3893.40   3894.50   2240.20   1654.30    2.354     +0.33
  PMA/7     3859.70   3860.70   2223.90   1636.80    2.358     -0.49
  PMA/8     3847.80   3848.70   2215.60   1633.10    2.356     -0.14
  PMA/9     3841.90   3842.60   2210.20   1632.40    2.354     +0.33
  PMA/10    3930.40   3931.10   2268.30   1662.80    2.364     -1.50
  PMA/11    3876.90   3877.50   2230.00   1647.50    2.353     +0.39
  PMA/12    3901.70   3902.40   2249.90   1652.50    2.361     -1.03
  PMA/13    3962.60   3963.50   2283.50   1680.00    2.359     -0.60
  PMA/14    3954.50   3955.70   2282.50   1673.20    2.363     -1.45
  PMA/15    3894.50   3895.80   2239.50   1656.30    2.351     +0.72
  PMA/16    3993.40   3995.00   2301.90   1693.10    2.359     -0.59
  PMA/17    3917.70   3918.30   2252.00   1666.30    2.351     +0.76
  PMA/18    3883.60   3886.40   2240.40   1646.00    2.359     -0.73
  PMA/19    3930.90   3932.10   2265.80   1666.30    2.359     -0.67
  PMA/20    3976.50   3979.60   2294.70   1684.90    2.360     -0.85
  PMA/21    3919.20   3921.80   2257.40   1664.40    2.355     +0.11
  PMA/22    3767.40   3768.80   2167.50   1601.30    2.353     +0.47
  PMA/23    3899.40   3901.50   2244.10   1657.40    2.353     +0.47
  PMA/24    3874.50   3875.50   2233.30   1642.20    2.359     -0.72
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IDENTIFICATION OF THE PROJECT ********** THESIS HUSSAIN JUNE/89
CITY OF LETHBRIDGE AGGREGATE (MIX C) HUSKY PMA 2 (HIGH TEMP)

NUMBER OF SAMPLES = 24
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.355
THE STANDARD DEVIATION = 0.006
THE COEFFICIENT OF VARIATION (%) = 0.236

SAMPLE NAME	DRY WT. g.	SSDWT. g.	IM.WT. g.	VOL. cc.	SP.GR.	NO. OF ST.DEV. FROM MEAN
PMA/10	3930.40	3931.10	2268.30	1662.80	2.364	-1.50
PMA/14	3954.50	3955.70	2282.50	1673.20	2.363	-1.45
PMA/12	3901.70	3902.40	2249.90	1652.50	2.361	-1.03
PMA/20	3976.50	3979.60	2294.70	1684.90	2.360	-0.85
PMA/18	3883.60	3886.40	2240.40	1646.00	2.359	-0.73
PMA/24	3874.50	3875.50	2233.30	1642.20	2.359	-0.72
PMA/19	3930.90	3932.10	2265.80	1666.30	2.359	-0.67
PMA/13	3962.60	3963.50	2283.50	1680.00	2.359	-0.60
PMA/16	3993.40	3995.00	2301.90	1693.10	2.359	-0.59
PMA/7	3859.70	3860.70	2223.90	1636.80	2.358	-0.49
PMA/8	3847.80	3848.70	2215.60	1633.10	2.356	-0.14
PMA/21	3919.20	3921.80	2257.40	1664.40	2.355	+0.11
PMA/1	3804.60	3805.90	2189.50	1616.40	2.354	+0.29
PMA/9	3841.90	3842.60	2210.20	1632.40	2.354	+0.33
PMA/6	3893.40	3894.50	2240.20	1654.30	2.354	+0.33
PMA/11	3876.90	3877.50	2230.00	1647.50	2.353	+0.39
PMA/5	3846.00	3846.70	2212.30	1634.40	2.353	+0.39
PMA/2	3851.90	3853.30	2216.10	1637.20	2.353	+0.47
PMA/23	3899.40	3901.50	2244.10	1657.40	2.353	+0.47
PMA/22	3767.40	3768.80	2167.50	1601.30	2.353	+0.47
PMA/4	3868.70	3869.90	2225.00	1644.90	2.352	+0.61
PMA/15	3894.50	3895.80	2239.50	1656.30	2.351	+0.72
PMA/17	3917.70	3918.30	2252.00	1666.30	2.351	+0.76
PMA/3	3917.20	3918.40	2241.80	1676.60	2.336	+3.41

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THESE ARE THE POSSIBLE GROUPS

         SAMPLE     SP.GR.     MEAN         GROUP       COEFF. OF
          NAME                 SP.GR.       ST.DEV.     VARIATION (%)

         PMA/10      2.364
         PMA/3       2.336
         PMA/19      2.359
         PMA/2       2.353
         PMA/1       2.354
         PMA/14      2.363
                               2.355        +0.0102        0.432


         PMA/12      2.361
         PMA/17      2.351
         PMA/13      2.359
         PMA/5       2.353
         PMA/9       2.354
         PMA/21      2.355
                               2.355        +0.0038        0.159


         PMA/20      2.360
         PMA/15      2.351
         PMA/16      2.359
         PMA/11      2.353
         PMA/6       2.354
         PMA/8       2.356
                               2.355        +0.0034        0.144


         PMA/4       2.352
         PMA/7       2.358
         PMA/18      2.359
         PMA/22      2.353
         PMA/23      2.353
         PMA/24      2.359
                               2.356        +0.0036        0.153
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN AUGUST/89
SH 794 :02/:04 CONSOLIDATED 45N ESSO 150/200A AC (HIGH TEMP)

NUMBER OF SAMPLES =  18
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 0.000
THE STANDARD DEVIATION =   0.000
THE COEFFICIENT OF VARIATION (%) =   0.000

      SAMPLE     DRY WT.     SSDWT.     IM.WT.      VOL.      SP.GR.     NO. OF
       NAME        g.          g.         g.         cc.                 ST.DEV.
                                                                        FROM MEAN
      150A1     3849.50     3852.30    2203.90    2203.90     0.000      +0.00
      150A2     3898.40     3899.90    2232.90    2232.90     0.000      +0.00
      150A3     3856.90     3859.50    2206.20    2206.20     0.000      +0.00
      150A4     3899.90     3901.40    2233.70    2233.70     0.000      +0.00
      150A5     3822.70     3824.40    2186.10    2186.10     0.000      +0.00
      150A6     3864.10     3866.10    2209.80    2209.80     0.000      +0.00
      150A7     3845.70     3847.10    2199.00    2199.00     0.000      +0.00
      150A8     3860.70     3863.00    2212.90    2212.90     0.000      +0.00
      150A9     3822.90     3824.90    2191.80    2191.80     0.000      +0.00
      150A10    3863.90     3864.50    2208.00    2208.00     0.000      +0.00
      150A11    3868.10     3869.50    2220.00    2220.00     0.000      +0.00
      150A12    3867.00     3870.20    2214.80    2214.80     0.000      +0.00
      150A13    3848.90     3851.90    2205.00    2205.00     0.000      +0.00
      150A14    3895.20     3897.70    2230.00    2230.00     0.000      +0.00
      150A15    3892.40     3896.30    2232.20    2232.20     0.000      +0.00
      150A16    3872.50     3875.20    2223.80    2223.80     0.000      +0.00
      150A17    3928.70     3928.90    2257.20    2257.20     0.000      +0.00
      150A18    3841.90     3844.10    2198.60    2198.60     0.000      +0.00
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN AUGUST/89
SH 794 :02/:04 CONSOLIDATED 45N ESSO 150/200A AC (HIGH TEMP)

NUMBER OF SAMPLES =  18
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.338
THE STANDARD DEVIATION =   0.005
THE COEFFICIENT OF VARIATION (%) =   0.210

          SAMPLE    DRY WT.    SSDWT.    IM.WT.     VOL.      SP.GR.    NO. OF
           NAME       g.         g.        g.        cc.                ST.DEV.
                                                                       FROM MEAN
          150A1     3849.50    3852.30   2203.90   1648.40    2.335     +0.51
          150A2     3898.40    3899.90   2232.90   1667.00    2.339     -0.15
          150A3     3856.90    3859.50   2206.20   1653.30    2.333     +1.01
          150A4     3899.90    3901.40   2233.70   1667.70    2.338     -0.14
          150A5     3822.70    3824.40   2186.10   1638.30    2.333     +0.91
          150A6     3864.10    3866.10   2209.80   1656.30    2.333     +0.99
          150A7     3845.70    3847.10   2199.00   1648.10    2.333     +0.90
          150A8     3860.70    3863.00   2212.90   1650.10    2.340     -0.38
          150A9     3822.90    3824.90   2191.80   1633.10    2.341     -0.63
          150A10    3863.90    3864.50   2208.00   1656.50    2.333     +1.07
          150A11    3868.10    3869.50   2220.00   1649.50    2.345     -1.47
          150A12    3867.00    3870.20   2214.80   1655.40    2.336     +0.37
          150A13    3848.90    3851.90   2205.00   1646.90    2.337     +0.16
          150A14    3895.20    3897.70   2230.00   1667.70    2.336     +0.44
          150A15    3892.40    3896.30   2232.20   1664.10    2.339     -0.25
          150A16    3872.50    3875.20   2223.80   1651.40    2.345     -1.46
          150A17    3928.70    3928.90   2257.20   1671.70    2.350     -2.51
          150A18    3841.90    3844.10   2198.60   1645.50    2.335     +0.62
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN AUGUST/89
SH 794 :02/:04 CONSOLIDATED 45N ESSO 150/200A AC (HIGH TEMP)

NUMBER OF SAMPLES =  18
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.338
THE STANDARD DEVIATION =   0.005
THE COEFFICIENT OF VARIATION (%) =   0.210


     SAMPLE     DRY WT.      SSDWT.      IM.WT.       VOL.      SP.GR.    NO. OF
      NAME        g.           g.          g.          cc.                ST.DEV.
                                                                         FROM MEAN
     150A17     3928.70     3928.90     2257.20     1671.70     2.350      -2.51
     150A11     3868.10     3869.50     2220.00     1649.50     2.345      -1.47
     150A16     3872.50     3875.20     2223.80     1651.40     2.345      -1.46
     150A9      3822.90     3824.90     2191.80     1633.10     2.341      -0.63
     150A8      3860.70     3863.00     2212.90     1650.10     2.340      -0.38
     150A15     3892.40     3896.30     2232.20     1664.10     2.339      -0.25
     150A2      3898.40     3899.90     2232.90     1667.00     2.339      -0.15
     150A4      3899.90     3901.40     2233.70     1667.70     2.338      -0.14
     150A13     3848.90     3851.90     2205.00     1646.90     2.337      +0.16
     150A12     3867.00     3870.20     2214.80     1655.40     2.336      +0.37
     150A14     3895.20     3897.70     2230.00     1667.70     2.336      +0.44
     150A1      3849.50     3852.30     2203.90     1648.40     2.335      +0.51
     150A18     3841.90     3844.10     2198.60     1645.50     2.335      +0.62
     150A7      3845.70     3847.10     2199.00     1648.10     2.333      +0.90
     150A5      3822.70     3824.40     2186.10     1638.30     2.333      +0.91
     150A6      3864.10     3866.10     2209.80     1656.30     2.333      +0.99
     150A3      3856.90     3859.50     2206.20     1653.30     2.333      +1.01
     150A10     3863.90     3864.50     2208.00     1656.50     2.333      +1.07
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THESE ARE THE POSSIBLE GROUPS

         SAMPLE     SP.GR.     MEAN         GROUP       COEFF. OF
          NAME                 SP.GR.       ST.DEV.     VARIATION (%)

         150A17      2.350
         150A10      2.333
         150A2       2.339
         150A1       2.335
         150A18      2.335
         150A14      2.336
                               2.338        +0.0063        0.270


         150A11      2.345
         150A3       2.333
         150A4       2.338
         150A12      2.336
         150A7       2.333
         150A9       2.341
                               2.338        +0.0047        0.200


         150A5       2.333
         150A6       2.333
         150A8       2.340
         150A13      2.337
         150A15      2.339
         150A16      2.345
                               2.338        +0.0045        0.192
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN AUGUST/89
SH 794 :02/:04 CONSOLIDATED 45N ESSO PMA ASPHALT (HIGH TEMP)

NUMBER OF SAMPLES =  18
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 0.000
THE STANDARD DEVIATION =   0.000
THE COEFFICIENT OF VARIATION (%) =   0.000


        SAMPLE     DRY WT.     SSDWT.     IM.WT.      VOL.       SP.GR.     NO. OF
         NAME        g.          g.         g.          cc.                  ST.DEV.
                                                                            FROM MEAN
        IMH/1      3918.70     3922.60    2244.40    2244.40      0.000      +0.00
        IMH/2      3900.70     3902.50    2241.30    2241.30      0.000      +0.00
        IMH/3      3844.90     3847.30    2198.60    2198.60      0.000      +0.00
        IMH/4      3905.10     3906.80    2243.10    2243.10      0.000      +0.00
        IMH/5      3882.30     3883.30    2226.30    2226.30      0.000      +0.00
        IMH/6      3862.80     3863.80    2207.50    2207.50      0.000      +0.00
        IMH/7      3924.10     3925.10    2256.10    2256.10      0.000      +0.00
        IMH/8      3810.20     3811.10    2177.00    2177.00      0.000      +0.00
        IMH/9      3875.70     3877.30    2223.00    2223.00      0.000      +0.00
        IMH/10     3815.70     3817.20    2184.20    2184.20      0.000      +0.00
        IMH/11     3891.10     3891.90    2224.60    2224.60      0.000      +0.00
        IMH/12     3886.70     3889.90    2225.60    2225.60      0.000      +0.00
        IMH/13     3921.90     3924.40    2243.50    2243.50      0.000      +0.00
        IMH/14     3912.20     3913.20    2235.80    2235.80      0.000      +0.00
        IMH/15     3937.30     3938.70    2250.30    2250.30      0.000      +0.00
        IMH/16     3977.00     3979.90    2286.80    2286.80      0.000      +0.00
        IMH/17     3907.80     3909.90    2234.90    2234.90      0.000      +0.00
        IMH/18     3940.90     3942.90    2253.20    2253.20      0.000      +0.00
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN AUGUST/89
SH 794 :02/:04 CONSOLIDATED 45N ESSO PMA ASPHALT (HIGH TEMP)

NUMBER OF SAMPLES =  18
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.338
THE STANDARD DEVIATION =   0.007
THE COEFFICIENT OF VARIATION (%) =   0.297

        SAMPLE    DRY WT.    SSDWT.    IM.WT.     VOL.     SP.GR.   NO. OF
         NAME       g.         g.        g.        cc.               ST.DEV.
                                                                    FROM MEAN
        IMH/1     3918.70    3922.60   2244.40   1678.20    2.335    +0.40
        IMH/2     3900.70    3902.50   2241.30   1661.20    2.348    -1.48
        IMH/3     3844.90    3847.30   2198.60   1648.70    2.332    +0.83
        IMH/4     3905.10    3906.80   2243.10   1663.70    2.347    -1.35
        IMH/5     3882.30    3883.30   2226.30   1657.00    2.343    -0.74
        IMH/6     3862.80    3863.80   2207.50   1656.30    2.332    +0.81
        IMH/7     3924.10    3925.10   2256.10   1669.00    2.351    -1.92
        IMH/8     3810.20    3811.10   2177.00   1634.10    2.332    +0.88
        IMH/9     3875.70    3877.30   2223.00   1654.30    2.343    -0.72
        IMH/10    3815.70    3817.20   2184.20   1633.00    2.337    +0.17
        IMH/11    3891.10    3891.90   2224.60   1667.30    2.334    +0.58
        IMH/12    3886.70    3889.90   2225.60   1664.30    2.335    +0.36
        IMH/13    3921.90    3924.40   2243.50   1680.90    2.333    +0.66
        IMH/14    3912.20    3913.20   2235.80   1677.40    2.332    +0.79
        IMH/15    3937.30    3938.70   2250.30   1688.40    2.332    +0.84
        IMH/16    3977.00    3979.90   2286.80   1693.10    2.349    -1.60
        IMH/17    3907.80    3909.90   2234.90   1675.00    2.333    +0.69
        IMH/18    3940.90    3942.90   2253.20   1689.70    2.332    +0.79
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IDENTIFICATION OF THE PROJECT  **********  THESIS HUSSAIN AUGUST/89
SH 794 :02/:04 CONSOLIDATED 45N ESSO PMA ASPHALT (HIGH TEMP)

NUMBER OF SAMPLES =  18
THE MEAN SPECIFIC GRAVITY OF THE SAMPLES = 2.338
THE STANDARD DEVIATION =   0.007
THE COEFFICIENT OF VARIATION (%) =   0.297

          SAMPLE    DRY WT.     SSDWT.     IM.WT.      VOL.      SP.GR.   NO. OF
           NAME       g.          g.         g.         cc.               ST.DEV.
                                                                         FROM MEAN
          IMH/7     3924.10     3925.10    2256.10    1669.00     2.351     -1.92
          IMH/16    3977.00     3979.90    2286.80    1693.10     2.349     -1.60
          IMH/2     3900.70     3902.50    2241.30    1661.20     2.348     -1.48
          IMH/4     3905.10     3906.80    2243.10    1663.70     2.347     -1.35
          IMH/5     3882.30     3883.30    2226.30    1657.00     2.343     -0.74
          IMH/9     3875.70     3877.30    2223.00    1654.30     2.343     -0.72
          IMH/10    3815.70     3817.20    2184.20    1633.00     2.337     +0.17
          IMH/12    3886.70     3889.90    2225.60    1664.30     2.335     +0.36
          IMH/1     3918.70     3922.60    2244.40    1678.20     2.335     +0.40
          IMH/11    3891.10     3891.90    2224.60    1667.30     2.334     +0.58
          IMH/13    3921.90     3924.40    2243.50    1680.90     2.333     +0.66
          IMH/17    3907.80     3909.90    2234.90    1675.00     2.333     +0.69
          IMH/18    3940.90     3942.90    2253.20    1689.70     2.332     +0.79
          IMH/14    3912.20     3913.20    2235.80    1677.40     2.332     +0.79
          IMH/6     3862.80     3863.80    2207.50    1656.30     2.332     +0.81
          IMH/3     3844.90     3847.30    2198.60    1648.70     2.332     +0.83
          IMH/15    3937.30     3938.70    2250.30    1688.40     2.332     +0.84
          IMH/8     3810.20     3811.10    2177.00    1634.10     2.332     +0.88
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THESE ARE THE POSSIBLE GROUPS

          SAMPLE     SP.GR.     MEAN        GROUP       COEFF. OF
           NAME                 SP.GR.      ST.DEV.     VARIATION (%)

          IMH/7       2.351
          IMH/8       2.332
          IMH/10      2.337
          IMH/17      2.333
          IMH/18      2.332
          IMH/9       2.343
                                2.338       +0.0077        0.329


          IMH/16      2.349
          IMH/15      2.332
          IMH/12      2.335
          IMH/13      2.333
          IMH/14      2.332
          IMH/4       2.347
                                2.338       +0.0078        0.333


          IMH/1       2.335
          IMH/2       2.348
          IMH/3       2.332
          IMH/5       2.343
          IMH/6       2.332
          IMH/11      2.334
                                2.337       +0.0066        0.284
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