DEVELOPMENT AND EVALUATION OF PERMEABLE FRICTION COURSE MIX DESIGN FOR FLORIDA CONDITIONS

By

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This document is dedicated to my parents.

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A mix design procedure for 'Permeable Friction Course' that provides guidance on material properties, aggregate gradation, determination of optimum asphalt content, and mixture properties is needed for Florida conditions. This project involves 1) development of permeable friction course mix design procedure for Florida conditions, 2) evaluation of permeable friction course of I-295 project, 3) development of data extraction, analysis and database software for material properties, indirect tensile test results, and complex modulus test results, and 4) development of fracture test on sand asphalt for SEM analysis and tensile strength. In the course of study an extensive literature review was done on various mix design approach, material characteristics, and laboratory process guideline.

Sample preparation and testing are carried in the laboratory for granite and limestone aggregate permeable friction course for determination of optimum asphalt content, moisture conditioning and long-term oven aging. An indirect tensile test is done

on specimen with optimum asphalt content to evaluate performance of mixture. Film thickness, an important criterion for permeable friction course for ensuring resistance against stripping and asphalt hardening, is developed, based on the different absorption capacity of aggregate. This proposed mix design procedure was used to design PFC mixture for the I-295 project. Performance test database (PTD.exe) as data analysis and data storage software was developed using visual basic as the programming language. This software was used throughout the project for analyzing the test results and storing in database for future reference. Based on analysis of fracture test results of the I-295 PFC project, essentiality of fracture test on sand asphalt came up. A framework of fracture test on sand asphalt which can be conducted within SEM chamber is done. Observation of fracture test results of moisture conditioned sample of I-295 PFC mixture showed that coarse stone to stone contact is affected due to conditioning. Creep response of mixture remains approximately same after conditioning as compared with unconditioned sample.

Finally, specifications and mix design procedure for PFC mixture are recommended and recommendations for further development of sand-asphalt fracture test are provided. Fracture test results FC-5 granite and FC-5 limestone samples, both aged and unaged, are compared with mixture designed for GPEM development and I-295 PFC project.

CHAPTER 1
INTRODUCTION

1.1 Background

Porous Friction Course (PFC) improves the frictional resistance of pavements, along with the drainage of water, for reducing the potential of aquaplaning. In the 1990's the traditional FC-2 friction course developed by Florida was replaced by coarser open graded friction course (FC-5) which is ½-inch Nominal Maximum Aggregate Size (NMAS), placed approximately ¾-inch thick. Even though the FC-5 had coarser aggregate structure and additional water storage capacity as compared to the old FC-2, water ponding on pavement surfaces continued to be a problem. Many states in US developed porous friction courses to over come such problems.

The Georgia DOT developed their porous friction course design by utilizing a gap-grading aggregate and lowering the percentage of filler, following European PFC mixture designs. The combination of gap grading, low filler, and high asphalt content lead to the draining of asphalt binder from mixture during transportation and lay down procedure. Due to this problem, the Georgia DOT introduced mineral fibers in Georgia PEM mixtures.

This research project is focused to develop and evaluate the Georgia PEM (GPEM) mix design procedure for Florida conditions, and updating the GPEM mix design by introducing Superpave gyratory compaction. Also, in the course of this project two other important developments are accomplished. First, a Performance Test Database (PTD) was developed to facilitate data analysis and data storage of mixture design and performance test results. The second achievement is the preliminary design of a new fracture test for asphalt mastic.

1.2 Objectives

The primary objectives of the research are summarized below:

- Open Graded friction course because of their macro texture and air voids may not have enough water storage capacity for some applications, and may also be susceptible to stripping. The rate of susceptibility depends on climatic conditions. Therefore the development and evaluation of mix design procedure for Porous Friction Course (PFC) for Florida Climatic Condition is main objective of this research project.
- Mix design for a test strip on I-295, containing a Porous Friction Course (PFC) mixture design developed in this research project.
- Developing data analysis and database software, to store data from Fracture Test and Complex Modulus Test.
- Developing basics framework of fracture test for asphalt mastic.

1.3 Scope

Mix design for I-295 highway (PFC project) provides an excellent opportunity to use and implement mix design procedure developed for GPEM. Database developed for data analysis and data storage is an excellent tool for referring previous mixture properties and their performance, while selecting gradation and doing mix design .Fracture test done on various field and lab prepared mixes enlightens many factors affecting the fracture resistance of mixtures. These factors are discussed individually in this thesis. It is always assumed that coarse aggregate are mainly responsible for contribution towards fracture resistance. Steps taken to develop fracture test on sand asphalt provides view on the contribution of fines and binder towards fracture resistance.

1.4 Research Approach

A detailed literature review was performed previously by Varadhan (2004) to understand Georgia's mix design procedure. Figure 1-1 shows a flow chart of the approach adopted for this research. The Georgia DOT used Marshall's blow for mix design of PFC. This research introduced the Superpave Gyratory Compactor. Therefore, a primary objective was to determine number of gyration required to attain compaction level same as field compaction. Second step was to determine film thickness corresponding to this compaction level. Different methods of determining film thickness are carried out and then most optimize method is selected for mix design procedure. Superpave Indirect tensile test were carried out on Short Term Oven Aged (STOA) and Long Term Oven Aged (LTOA) mixtures for determination of facture resistance. Simultaneously, analysis and database software was developed in order to analyze and store data from this project. Once the mix design procedure was finalized a section of I-295 highway is designed based on this mix design method. Two trial gradations (JMF) were selected with in control points and mix design was carried on both of these gradations to determine optimum asphalt content. Final selection of gradation was done based strength and energy ratio criteria. Fracture testing was carried on all STOA and LTOA samples from US highways- 27 and I-295 PFC project. In the course of the project necessity of sand asphalt's fracture resistance lead to develop new fracture test.

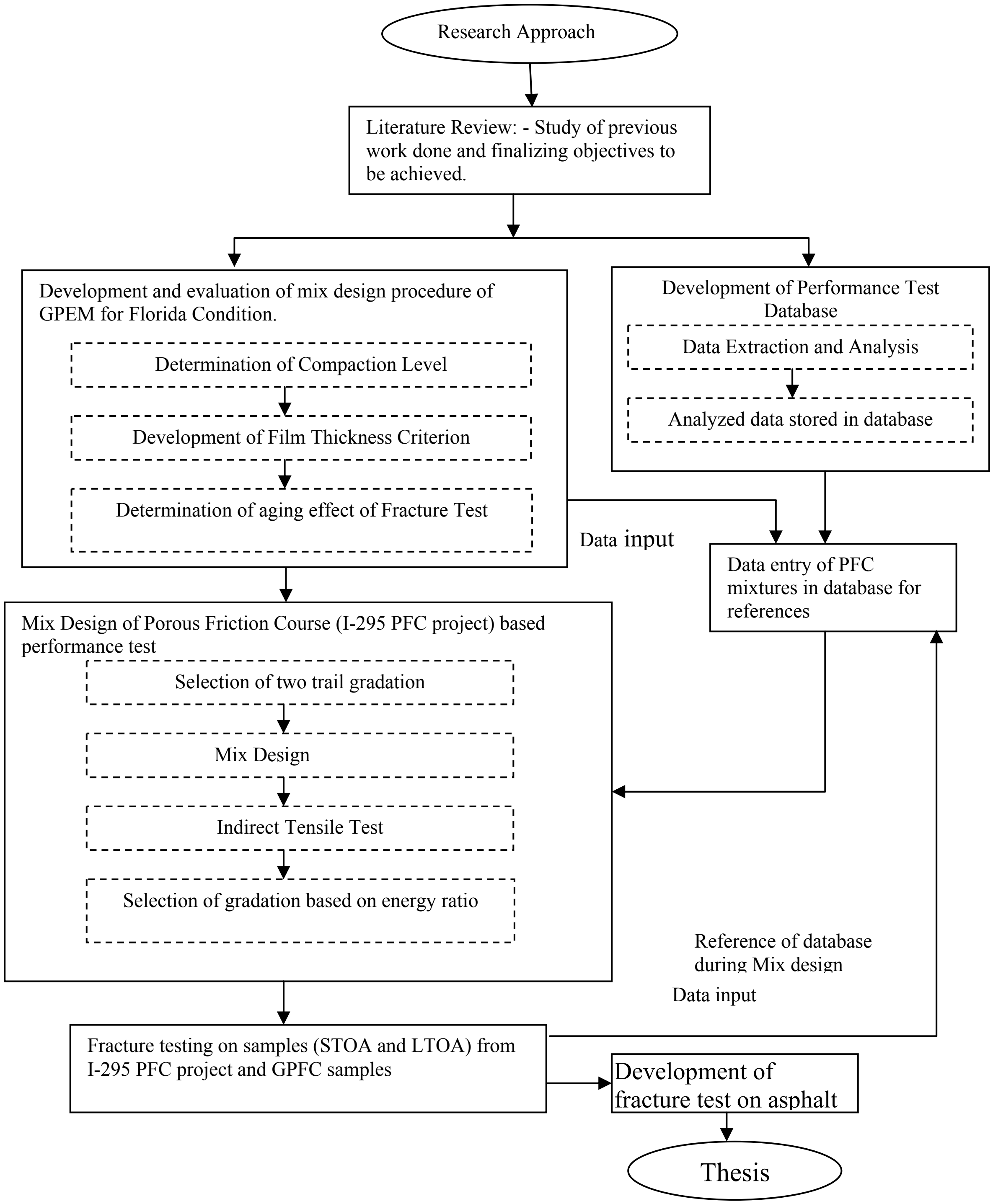


Figure 1-1. Flow chart showing Research Approach implemented

CHAPTER 2
DEVELOPMENT OF MIX DESIGN PROCEDURE FOR POROUS FRICTION COURSE

2.1 Initial Study and Objectives

The Georgia Department of Transportation started evaluation of Porous European Mix (PEM), a form of Porous Friction Course Mixture, in 1992 for development a mix design for Porous Friction Course (PFC), which is entitled for Georgia Permeable European Mixture. Georgia PEM mixtures proved to be more permeable than conventional OGFC, due to its gap-graded characteristics, with a predominant single size coarse aggregate fraction that contains high percentage of air voids as specified by Watson et al. (1998). The Georgia PEM mix design (GDT 114, 1996) was used as a starting point for the new Florida Permeable Friction Course (PFC) mixture design. In the following, the GPEM mixture design developed by the Georgia DOT will be reviewed briefly, followed by the development of a new Florida PFC mixture design, which is based on the GPEM mixture design.

Main objective of the 'Permeable Friction Course Design' is to design a highly permeable mixture with good durability characteristics, while also providing sufficient mixture stability through coarse stone to stone contact. In order to enhance durability, it is desirable to have a high asphalt content, while preventing the drain down of binder, thus providing sufficient binder film thickness. Once the coarse aggregate contact structure is chosen, the design asphalt content is obtained by selecting four (4) trial mixtures of varying asphalt contents, and choosing the asphalt content that results in a minimum

VMA. This is done to ensure reasonably high asphalt content. Importantly, it is necessary to use four trial asphalt contents, rather than three. Choosing only three asphalt contents will always result in one of the chosen asphalt contents to show a minimum, whereas choosing four asphalt contents will result in a true minimum that can be verified.

The objectives of this chapter is to develop a Porous Friction Course (PFC) mixture design for Florida conditions and materials using the Superpave gyratory compactor, and to evaluate the new PFC mixture design using two mixtures that contain aggregates and asphalt that are typical to Florida. The Georgia PEM mixture design is used as a starting point for the development of the Florida PFC mixture design.

2.2 Georgia PEM Mixture Design as per GDT 114 Test Method: B (1996)

In the following the Georgia DOT GPEM mixture design will be reviewed and used as a starting point for the Florida PFC mixture design approach. The first and foremost change was the introduction of the Superpave gyratory compaction into the mixture design in lieu of the Marshall compaction used by Georgia DOT. The main elements of the Georgia PEM mixture design are as follows:

- Georgia DOT GPEM mixture design method (GDT-114 Test Method: B, 1996) specifies the use of modified asphalt cement (PG 76-22) as specified in Section 820 (GDT 114,1996) and does not require the determination of surface capacity (KC) to determine initial trial asphalt contents.
- The Georgia DOT uses the Marshall Method of compaction during the design of the Georgia PEM mixtures.
- A stabilizing fiber is added to mixture for avoiding binder drain down, which meets the requirement of Section 819 (GDT 114, 1996).

In the following, the steps in the Georgia PEM mixture design (GDT-114 Test Method: B, 1996) are listed. Table 2-1 shows gradation limits as GDT 114 (1996).

A. SCOPE OF GPEM MIXTURE DESIGN

The Georgia DOT method of design for a modified open graded bituminous GPEM mixture consists of four steps. The first is to conduct a modified Marshall mix design (AASHTO T-245) to determine asphalt cement content. The second step is to determine optimum asphalt content. The third step is to perform a drain down test, according to GDT-127 (2005), or AASHTO T 305-97 (2001). The final step is to perform a boil test, according to GDT-56, or ASTM D 3625. Table 2-1 gives gradation limits and design requirement for Open Graded Friction Course (For 9.5 mm and 12.5 mm Gradation) and Permeable European Mixture (12.5 mm Gradation). Gradation limits specified for 12.5 GPEM are used as design limits for development of PFC mix design for Florida Design. There are no mixture design guidelines currently available for the determination of trial gradations within the specification limit. Rather, the mixture designer has to use his own judgment to determine a trial gradation within the limits provided.

Table 2-1. Gradation specifications according to GDT 114 (1996)

Mixture Control Tolerance	**Asphalt Concrete**	**12.5 mm PEM**
	Grading Requirements	
± 0.0	3/4 in (19 mm) sieve	100
± 6.1	1/2 in (12.5 mm) sieve	80-100
± 5.6	3/8 in (9.5 mm) sieve	35-60
±5.7	No. 4 (4.75 mm) sieve	10-25
±4.6	No.8 (2.36 mm) sieve	5 10
±2.0	No. 200 (75 μm) sieve	1-4
	Design Requirement	
±0.4	Range for % AC	5.5-7.0
	Class of stone (Section 800)	"A" only
	Coating retention (GDT-56)	95
	Drain-down, AASHTO T 305 (%)	<0.3

B. APPARATUS

The apparatus required shall consist of the following:

1. Drain-Down equipment as specified in GDT-127 (2005) or AASHTO T 305-97 (2001)
2. Marshall design equipment as specified in AASHTO T-245
3. Boil Test Equipment as specified in GDT-56 (2005) or ASTM D 3625
4. Balance, 5000 grams Capacity 0.1 grams accuracy.

<u>Step 2 – Modified Marshall Design and Optimum AC</u>

After determining a trial aggregate blend the following steps are required to determine the asphalt content:

1. Heat the coarse aggregate to 350ºF ± 3.5ºF (176ºC ± 2.5 º C), heat the mould to 300ºF ± 3.5 º F (148º C ± 2.5 º C) and heat the AC to 330 º F ± 3.5 º F (165º C ± 2.5 º C).

2. Mix aggregate with asphalt at three asphalt contents in 0.5 % interval nearest to the optimum asphalt content establishes in step 1. The three specimens should be compacted at the nearest 0.5% interval to the optimum and three specimens each at 0.5% above and below the mid interval.

3. After mixing, return to oven if necessary and when 320ºF ± 3.5ºF (160º C ± 2.5 º C) compact using 25 blows on each side

4. When compacted, cool to the room temperature before removing from the mold

5. Bulk Specific Gravity: Determine the density of a regular shaped specimen of compacted mix from its dry mass (in grams) and its volume in cubic centimeters obtained from its dimensions for height and radius. Convert the density to the bulk specific gravity by dividing by 0.99707 g/cc, the density of water at 25ºC

   Bulk Sp.Gr = W / (π r2h/ 0.99707)
   = Weight (gms) × 0.0048417/Height (in)
   W = Weight of specimen in grams
   R = radius in cm
   H = height in cm

6. Calculate percent air voids, VMA and voids filled with asphalt based on aggregate specific gravity

7. Plot VMA curve versus AC content

8. Select the optimum asphalt content at the lowest point on VMA curve

Step 3 - Drain-Down Test

Perform the drain test in accordance with the GDT – 127 (2005) (Method for determining Drain Down characteristics in Un-compacted Bituminous Mixtures) or AASHTO T 305-97 (2001). A mix with an optimum AC content as calculated above is placed in a wired basket having 6.4 mm (1/4 inch) mesh openings and heated 14ºC (25ºF) above the normal production temperature (typically around 350ºF) for one hour. The amount of cement, which drains from the basket, is measured. If the sample fails to meet the requirements of maximum drain down of 0.3%, increase the fiber content by 0.1% and repeat the test.

Step 4 - Boil Test

Perform the boil test according to GDT – 56 (2005) or ASTM D 3625 with complete batch of mix at optimum asphalt content as determined in step 2 above. If the sample treated with hydrated lime fails to maintain 95% coating, a sample shall be tested in which 0.5% liquid anti stripping additive has been used to treat the asphalt cement in addition to the treatment of aggregate with hydrated lime.

2.3 Overview of Evaluation of Preliminary OGFC/PFC Mix design Procedure Developed by Vardhan (2004)

Varadhan (2004) introduced the Superpave gyratory compaction into PFC mixture design in lieu of the Marshall compaction used by Georgia DOT. The study used to make the specified changes in preliminary mix design approach and the development of long-term aging procedure for compacted PFC mixture are discussed in the following.

2.3.1 Determination of Compaction level for PFC

The Georgia DOT prepares specimen using the Marshall Hammer with 25 blows on each side of the specimen. Due to the overall strong desire by both the FDOT and the

University of Florida researchers to use a compaction procedure that is more in line with current mix design compaction procedures in America, it was decided to use the Superpave gyratory compactor for compacting the specimens. Based on the work performed by Varadhan (2004) it was determined that an appropriate compaction level of 50 gyrations was sufficient to compact OGFC mixtures. This determination was based on a modified locking point concept (Vavrik & Carpenter, 1998). The approach by Vavrik (1998) was developed for dense graded mixtures. Varadhan (2004) found that the use of the locking point concept by Vavrik & Carpenter (1998) resulted in a severe over compaction of OGFC mixtures, leading to aggregate breakdown. Therefore, the locking point concept was modified for use in OGFC mixtures, as described by Varadhan (2004).

As determined by Vardhan (2004) the compaction curve for OGFC/PFC mixtures follows a logarithmic trend. To identify the locking point, the rate of change of slope of compaction curve was used. The stage, at which the rate of change of compaction was insignificant, is the point of maximum resistance to compaction. Thus, using the logarithmic regression of the compaction data, the rate of change of slope can be obtained as follows:

$y = m * \ln(x) + c$

Rate of compaction = $dy/dx = m/x$ (at any $x=N$)

Rate of change of slope of compaction curve = $d2y/dx2 = -m/ x2$ (at any $x =N$)

Based on the above idea the locking point was identified as the point at which two gyrations at same gradient of slope were preceded by two gyrations at same gradient of slope. The gradient was taken up to four decimal places, as shown in Table 2-2 for FC-5 Granite (Varadhan, 2004). The reason this was chosen as locking point was based on the fact the change in air voids was insignificant at this stage and that this trend was consistently observed in all the mixtures. In addition, the compaction level as identified from visual observation was around 50-60. Thus, based on the above study, the locking points for theses mixtures were identified as shown in Table 2-3

Table 2-2. Locking Point Based on Gradient of Slope (Varadhan, 2004)

FC-5 Granite	
# of Gyrations	Gradient of slope
39	0.0018
40	0.0017
41	0.0016
42	0.0015
43	0.0014
44	0.0014
45	0.0013
46 (LP)	0.0013
47	0.0012
48	0.0012
49	0.0011
50	0.0011

Table 2-3. Locking Points of all Mixtures based on Gradient of Slope (Varadhan, 2004)

Mixtures	Locking Point
FC-5 Limestone	56
FC-5 Granite	46
NOVACHIP	50

Thus based on above concept the locking points for FC-5 with Limestone, FC-5 with Granite and NOVACHIP were 56, 46 and 50 respectively. The specimens were compacted again to these gyrations and extraction of asphalt was performed to observe the gradations after compaction.

For FC-5 Lime even when the gyrations were reduced to 56 from 125, the same amount of breakdown was observed. This clearly indicated that in case of limestone, the breakdown occurred in the initial stages itself i.e. at very low gyrations. Hence, even if the gyrations were to be further reduced, the breakdown was still going to persist. For FC-5 with granite and NOVACHIP, the gradation looks nearly the same as that of the original gradation. In addition, the air voids for FC-5 Granite and NOVACHIP were around 21 % and 15 % respectively, which is typical for these open graded mixtures.

Thus, from the above the study it is clear that, though the locking point of each of these mixtures differed slightly from each other, it was around 50 gyrations. This was further corroborated by the study done by NCAT on the compaction levels of friction courses. NCAT suggests 50 gyrations as compaction level for all friction courses.

Thus based on this study from visual observation and rate of change of compaction, NCAT study for friction course, Varadhan (2004) stated that 50 gyrations should be the compaction level for friction course mixes.

2.3.2 OGFC/PFC Mixture Design Procedure Proposed By Varadhan (2004)

Use of modified asphalt cement does not require determination of surface capacity (Kc) as per GDT 114 Test method: B (1996). Boil test is not included in proposed mix design of PFC as a modified asphalt cement PG76-22 with 0.5% anti strip agent is used. The gradation band used by Varadhan (2004) with in GDT 114 (1996) specified gradation limits (Ref. Table 2-1) is shown in Figure 2-1.

Following is the method developed and proposed:

Modified GDT 114 test method: B by Varadhan (2004)

1. Heat the coarse aggregate, the mould to 350 º F ± 3.5 º F (176 º C ± 2.5 º C) and the AC to 330 º F ± 3.5 º F (165º C ± 2.5 º C)

2. Mix aggregate with asphalt at three asphalt contents, viz., 5.5%, 6% and 6.5%. Just before mixing, add the required amount of mineral fibers to the aggregate. Prepare three samples at each of the asphalt content

3. After mixing, return to oven for two hours for STOA at 320 º F ± 3.5 º F (160º C ± 2.5 º C). Then compact using the Superpave Gyratory Compactor 50 gyrations

4. When compacted, cool to the room temperature before removing from the mold. It typically takes 1 hour 45 min to cool down.

5. Bulk Specific Gravity: Determine the density of a regular shaped specimen of compacted mix from its dry mass (in grams) and its volume in cubic centimeters obtained from its dimensions for height and radius. Convert the density to the bulk specific gravity by dividing by 0.99707 g/cc, the density of water at 25 ºC

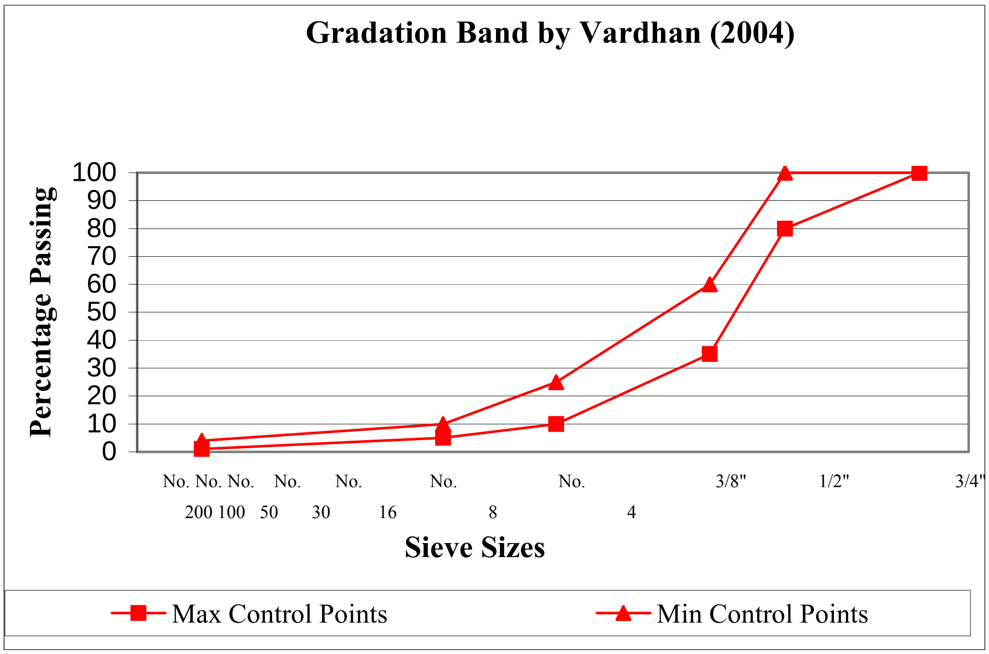


Figure 2-1. Gradation Band with in GDT 114 (1996) specified gradation limits used by Varadhan (2004)

6. Bulk Sp.Gr = W / (π r2h/ 0.99707) = Weight (gms) × 0.0048417/Height (in)

7. W = Weight of specimen in grams

8. R = radius in cm

9. H= height in cm

10. Calculate percent air voids, VMA and voids filled with asphalt based on aggregate specific gravity

11. Plot VMA curve versus AC content

12. Select the optimum asphalt content at the lowest point on VMA curve

Drain-Down Test

Perform the drain test in accordance with the GDT – 127 (2005) or AASHTO T 305-97 (2001). A mix with an optimum AC content as calculated above is placed in a wired basket having 6.4 mm (1/4 inch) mesh openings and heated 14 ºC (25 ºF) above the normal production temperature (typically around 350ºF) for one hour. The amount of cement, which drains from the basket, is measured. If the sample fails to meet the requirements of maximum drain down of 0.3 %, increase the fiber content by 0.1 % and repeat the test.

It is recommended by GDOT that the asphalt content should not be below 6% because of coating issues. The film thickness requirement for granite mixture as per Georgia DOT is 27 microns.

Moisture Damage Test

Perform the moisture damage test in accordance with AASHTO T-283 (2003) on compacted specimen. The specimens are rolled in 1/8" wire mesh which are kept in position using two clamps on either edges of pills for avoiding fall down at high temperature of 60ºC (140ºF).

2.3.3 Long-Term Oven Aging Procedure Proposed for PFC Mixture by Varadhan (2004)

In order to evaluate the mixture susceptibility to aging, it was necessary to develop a modified long-term aging procedure that was based on AASHTO PP2 (1994). Since these mixtures are very course and open, there is a possibility of these mixes falling apart during aging. Hence, a procedure was developed to contain the compacted pills from falling apart during aging.

- A 1/8" opening wire mesh is should be rolled around pills, with two clamps tightened at 1-inch distance from each end of the pill. The mesh size is chosen in order to ensure that there is good circulation of air within the sample for oxidation and at the same time, to prevent the smaller aggregate particles from falling off through the mesh.

- Specimens are kept in ovens with porous plate at bottom for 185º F ± 5.4º F (85º C ± 3º C) for 120 ± 0.5 hours.
- After that time period, turn off the oven and open the door. Allow the oven and specimen to cool to room temperature for about 16 hours.

2.4 Verification of Florida Permeable Friction Course Mixture Design

2.4.1 Materials

Aggregate and gradation selection

An existing Georgia PEM gradation obtained from the Georgia DOT was used as a starting point in the mixture design. Figure 2-2 shows the gradation for the Georgia PEM. Interestingly, the Georgia DOT mixture design follows the middle of the specified gradation band on the coarse side, transitioning to the maximum allowable fines content on the fine side. This selection of gradation will likely result in a good coarse aggregate to aggregate contact structure, as well as ensuring the highest possible amount of asphalt binder in the mixture, without significant drain down. Two types of aggregate are used for this development i.e. Granite and Limestone. Nova Scotia granite and oolitic limestone from South Florida (White Rock) were used for preparing the mixtures. The same JMF is used for both granite and limestone mixture composed of aggregates from different stockpiles. The Job mix formula for the granite was composed of aggregates from stockpiles #7, #789 and Granite Screens. The job mix formula for the limestone was composed of aggregates from stockpiles S1A, S1B and limestone screens. Hydrated lime (1% by weight of aggregate) was used as anti-stripping agent for the granite aggregates. All aggregates were heated to 350ºF ± 3.5ºF (176º C ± 2.5 º C) as specified in GDT 114

Test Method: B Section C (1996). Table 2-4 and Table 2-5 shows composing of GPEM-limestone and GPEM-garanite job mix formula.

Table 2-4. Composition of GPEM-Limestone gradation JMF

Type		**S1A**	**S1B**	**Scrns**	**JMF**	**Control Points**	
% Amount		**55.56**	**37.37**	**7.07**	**100**	**Max**	**Min**
Sieve Size	Size^0.45						
37.5	5.11	100	100	100	100		
25	4.26	100	100	100	100		
19	3.76	100	100	100	100	100	100
12.5	3.12	82	100	100	90	100	80
9.5	2.75	28	99	100	60	60	35
4.75	2.02	3	39	99	23	25	10
2.36	1.47	2	8	70	9	10	5
1.18	1.08	2	3	54	6		
0.6	0.79	1	1	40	4		
0.3	0.58	1	1	30	3		
0.15	0.43	1	1	13	2		
0.075	0.31	1	1	2	1	4	1

Table 2-5. Composition of GPEM-Granite gradation JMF

Type		**#7**	**#789 Granite**	**Granite Screens**	**Lime**	**JMF**	**Control Points**	
% Amount		**55**	**37**	**7**	**1**	**100**	**Max**	**Min**
Sieve Size	Size^0.45							
37.5	5.11	100	100	100	100	100		
25	4.26	100	100	100	100	100		
19	3.76	100	100	100	100	100	100	100
12.5	3.12	82	100	100	100	90	100	80
9.5	2.75	28	99	100	100	60	60	35
4.75	2.02	2	39	99	100	23	25	10
2.36	1.47	2	6	69	100	9	10	5
1.18	1.08	2	2	46	100	6		
0.6	0.79	1	1	30	100	4		
0.3	0.58	1	1	17	100	3		
0.15	0.43	0	1	7	100	2		
0.075	0.31	0	0	1	100	1	4	1

Binder and mineral fiber

SBS modified PG 76-22 asphalt, with 0.5% anti strip agent was used in the mixture design. Mineral fiber (Fiberand Road Fibers) supplied by "SLOSS Industries, Alabama", 0.4% by weight of total mix, was added to mix in order to avoid binder drain drown. Chemical composition of the mineral fiber is Vitreous Calcium Magnesium Aluminum Silicates. Mineral fibers were shredded into fine fragments before adding to the mixture.

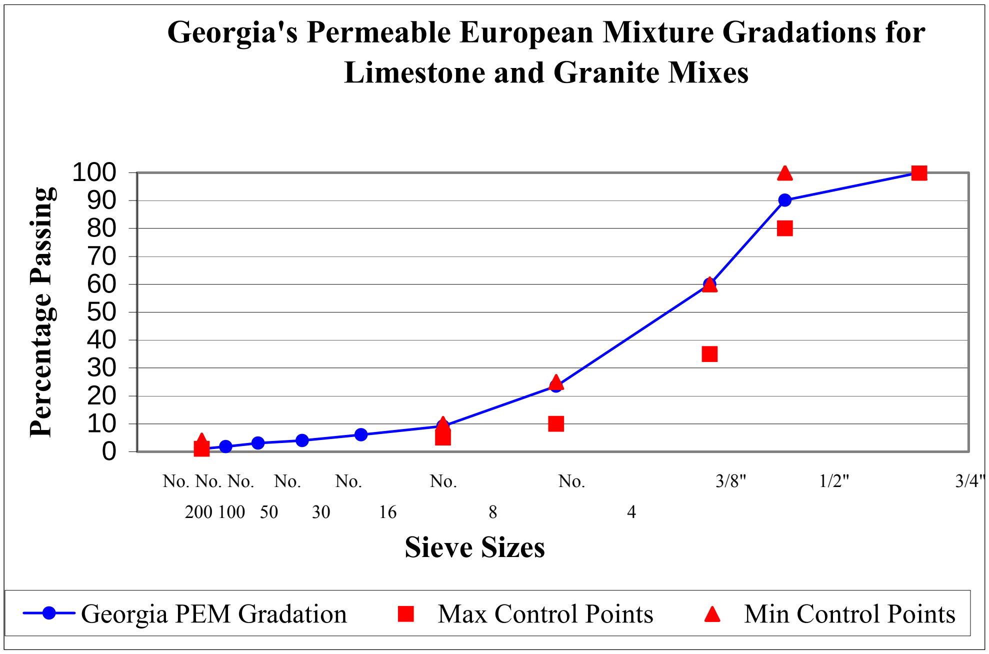


Figure 2-2. Georgia's Permeable European Mixture gradation band

<u>2.4.2 Sample Preparation for Determination of Optimum Asphalt Content</u>

Based on experience, the Georgia DOT procedure almost always results in design asphalt content of 6 percent, when Georgia granite aggregates are used. However, following the GDOT GDT-114 (1996) procedure, three trial mixtures were prepared at different asphalt contents. The trial asphalt content of 5.5%, 6% and 6.5% were selected for the Nova Scotia granite blend for choosing the asphalt content that results in a minimum VMA. As per GDT 114 (1996), the specified range of percent asphalt content is 5.5%-7.0%.

As a note, based on the early experience with the use of only three trial asphalt contents to obtain an optimal asphalt content, it was observed that it is necessary to use four trial asphalt contents for determining the optimum asphalt content. Choosing only three asphalt contents will always result in one of the chosen asphalt contents to show a minimum, whereas choosing four asphalt contents will result in a true minimum that can be verified. Figure 2-3 shows example of determination of higher asphalt content as optimum asphalt content due selection of (3) trial asphalt contents.

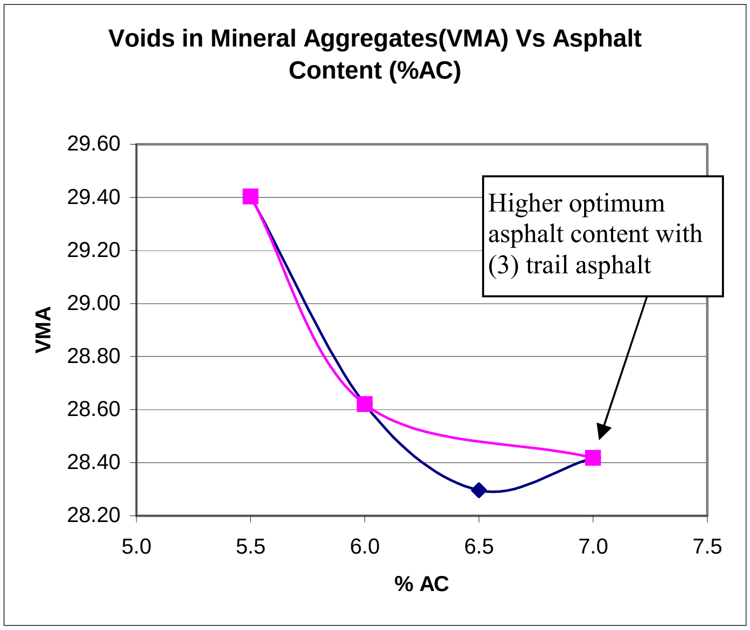


Figure 2-3. Example of determination of inconsistent optimum asphalt content

Because of this reason, a broader range of trial asphalt contents was used for the limestone mixture, namely 5.5%, 6.0%, 6.5% and 7%. For each trail asphalt content three pills were prepared.

2.4.4 Mixing and Compaction of Samples for Determination of Bulk Specific Gravity

Sieved aggregates from each stockpile are batched by weight of 4400 grams for each pile. Three pills are prepared for each trial percentage. Hydrated lime 44 grams (1.0% of aggregate weight) is added to batched samples. Table 2-2 shows the amount of material used for mixing. Aggregates, tools, mixing drum, shredded fibers and the asphalt binder are heated to 330º F ± 3.5 º F (165º C ± 2.5 º C) for at least 3 hours. Aggregates are mixed with asphalt at all trial asphalt contents. Just before mixing, add the required amount of mineral fibers to the aggregate. Table 2-2 shows amount of aggregates and asphalt used for each trial blend. Once the sample is mixed it is placed in a clean metal tray. Due to the presence of the SBS in the asphalt binder, these mixtures tend to be "sticky" making the mixing somewhat challenging. In particular, it is important to ensure that there is no loss of fines while retrieving the mix from the mixing drum. The AASHTO RM 30 specification for loss of fines was used, requiring that a maximum 0.1 percent loss of fines. After mixing, mixtures are aged for short term of two hours at 320º F ± 3.5 º F (160ºC ± 2.5 º C) as per AASHTO PP2 (1994).

The specimens are compacted to 50 gyrations using the Superpave Gyratory Compactor. Molds should be lubricated. The angle of gyration during compaction is 1.25 degrees. From prior experience, compacted samples should not be retrieved from molds immediately. They should be allowed to cool for 1hr 45 min before extracting the specimens from the molds. Once the specimen is ejected from the mold, it is allowed to cool for another 5 minutes at ambient room temperature before handling. It was found that if sufficient cooling of the specimen after extraction of the specimen from the mold were not followed (especially for granite mixtures), small aggregate particles would tend to dislodge and stick to gloves due to the high specimen air voids. Finally, it was found that it was necessary to allow the pills to cool at ambient room temperatures for another 24 hours before processing them any further.

Table 2-6. Material quantities

Bulk Specific Gravity			
Aggregate Weight = 4400 grams			
AC Content	AC Weight (Grams)	Fiber Weight (Grams)	Total Weight
5.5	256.1	18.6	4674.7
6	280.9	18.7	4699.6
6.5	305.9	18.8	4724.7
7	331.2	18.9	4750.1
5.5	58.2	4.2	1062.4
6.0	63.8	4.3	1068.1
6.5	69.5	4.3	1073.8
7.0	75.3	4.3	1079.6

2.4.4 Determination of Optimum Asphalt Content

The determination of bulk specific gravity test in accordance with AASHTO T166 (2000) cannot be conducted on the PFC mixtures because of their high air voids. The determination of Saturated Surface Dry (SSD) weight of the pills is not reliable for mixtures at these high air void contents as per Cooley et al (2002). Therefore, bulk specific gravity (Gmb) of pills was determined by Dimensional analysis, as described in GDOT-114 (1996). The determination of Theoretical Maximum Specific Gravity (Gmm) was made via the use of the Rice test procedure as per AASHTO T209 (2004). For preparation of samples for determination of Theoretical Maximum Specific Gravity as per AASHTO T-209-99 (2004), aggregates are batched by weight of 1100 grams. Two mixes for each trial asphalt percentage are prepared.

Once all trial asphalt content pills had been prepared, the VMA was determined from the Theoretical Maximum Specific Gravity (Gmm) and the Bulk Specific Gravity (Gmb) determined from Dimensional analysis. The design asphalt content is selected at the point of minimum VMA. The main purpose of using minimum VMA criterion is to ensure reasonably high asphalt content of the mixture. Secondly, VMA is calculated on a volume basis and is therefore not affected significantly by the specific gravity of aggregate.

Refer Appendix A for detail calculations and Laboratory work sheets of volumetric properties of PFC mixtures.

Figure 2-4and Figure 2-5 show a summary of the volumetrics for the limestone and granite mixtures. Optimum asphalt contents of PFC mixtures were found to be 6.5% and 6.0% for the limestone and granite mixtures, respectively. The porous nature of limestone resulted in a higher optimum asphalt content.

Effective Sp Grav. of Agg.	% AC[6]	Gmm[1]	Gmb[2]	VMA[3] (%)	VTM[4] (%)	VFA[5] (%)
2.513	5.5	2.323	1.877	29.40	19.21	34.67
	6.0	2.314	1.908	28.62	17.54	38.71
	6.5	2.298	1.927	28.30	16.16	42.89
	7.0	2.286	1.934	28.42	15.39	45.84

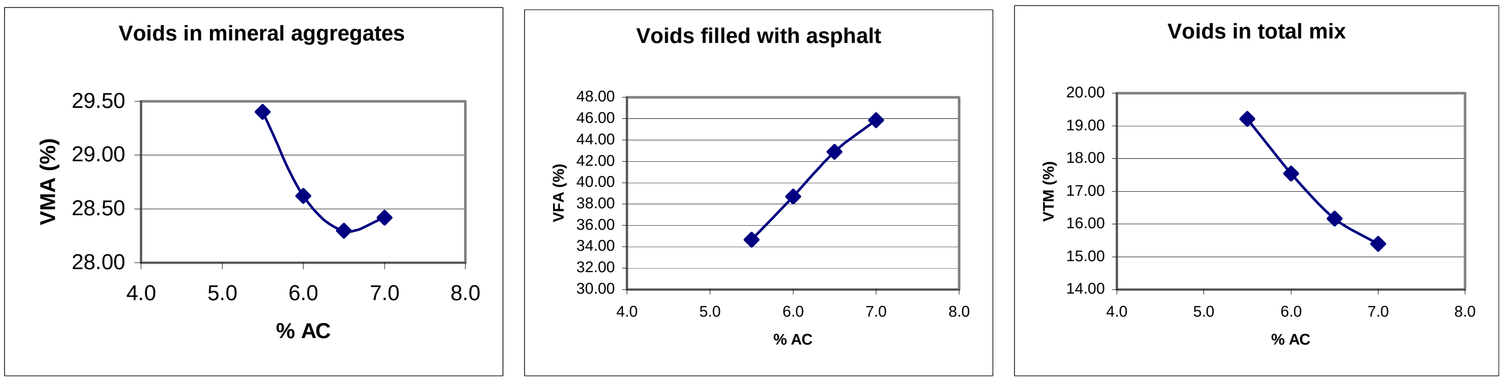


Figure 2-4. Mix Design of OGFC with aggregate type: - Limestone

Optimum Asphalt Content: - 6.5%
VMA at Optimum Asphalt Content:- 28.30%
Mineral Fiber: - 0.4% of Total Mix
Aggregate Type: - Limestone

Gmm[1] = Maximum specific gravity of mixture, Gmb[2] = Bulk specific gravity of mixture, VMA[3] = Voids in Mineral Aggregates, VTM[4] = Voids in Total Mix, VFA[5] = Voids filled with Asphalt, AC[6] = Asphalt Content

Effective Sp Grav. of Agg.	% AC[6]	Gmm[1]	Gmb[2]	VMA[3] (%)	VTM[4] (%)	VFA[5] (%)
2.641	5.5	2.442	1.936	30.74	20.72	32.60
	6	2.414	1.961	30.23	18.78	37.86
	6.5	2.389	1.967	30.38	17.68	41.82

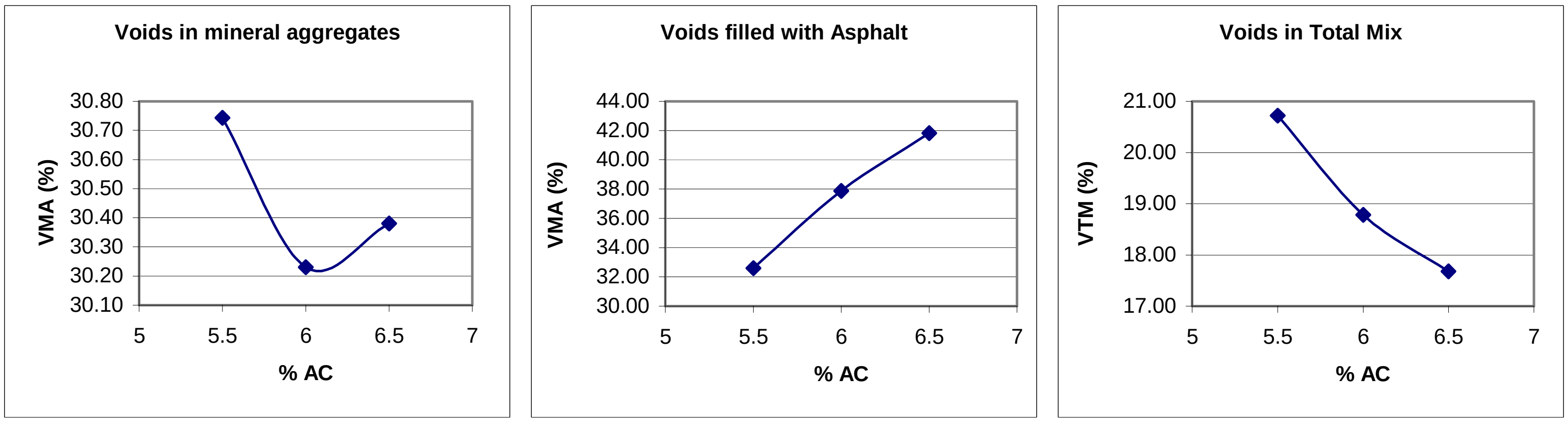


Figure 2-5. Mix Design of OGFC with aggregate type: - Granite

Optimum Asphalt Content: - 6.0% VMA at Optimum Asphalt Content:- 30.23%
Mineral Fiber: - 0.4% of Total Mix Aggregate Type: - Limestone
Gmm[1] = Maximum specific gravity of mixture, Gmb[2] = Bulk specific gravity of mixture, VMA[3] = Voids in Mineral Aggregates, VTM[4] = Voids in Total Mix, VFA[5] = Voids filled with Asphalt, AC[6] = Asphalt Content

2.5 Evaluation of Film Thickness Criterion in PFC Design

The Georgia DOT uses a required minimum calculated asphalt film thickness criterion for ensuring that the mixture has enough asphalt for adequate durability._Since durability of mixtures is a surface phenomenon, where the binder is damaged from the surface inward, a mixture with a low film thickness is expected to damage more than a mixture with a thicker film, irrespective of surface area. Therefore, it is important to clearly establish a link between the calculated film thickness and the physics of the mixture in question. The appropriate film thickness calculation is affected by the aggregate structure of the mix. The first attempts to calculate minimum asphalt film thicknesses were made by Goode and Lufsey (1965). Their method was based on empirical considerations, leading to the development of the theoretical film thickness (Hveem, NCAT 1991), which assumes that all aggregates are rounded spheres, with predefined surface areas, which are coated with an even thickness of asphalt film.

Recognizing that these “theoretical film thickness” calculations were developed primarily for fine-graded mixtures with very different aggregate structures from that found in coarse-graded mixtures, let alone OGFC and PFC mixtures, Nukunya et al. (2001) developed an effective film thickness concept based on a physical model of coarse-graded mixtures. Nukunya, et al. (2001) observed that the aggregate structure for fine- and coarse-graded mixtures is fundamentally different, as shown in Figure 2-6 Fine-graded mixtures tend to have more continuous grading such that the fine-aggregates are an integral part of the stone matrix. Coarse mixtures, on the other hand, tend to have aggregate structures that are dominated by the coarse aggregate portion (i.e., stone-to-stone contact).

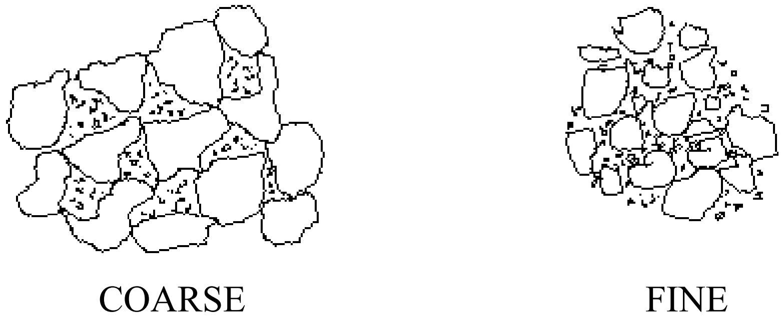


Figure 2-6. Aggregate Structure for Coarse and Fine Mixtures (Nukunya et al. [2001])

Therefore, coarse-graded PFC mixtures are effectively composed of two components: the first one is the interconnected coarse aggregate, and the second component is the fine mixture embedded in between the coarse aggregate particles. The mixture made up of asphalt and fine aggregates coats the coarse aggregate particles, and the fine aggregates within that matrix have access to all the asphalt within the mixture. This results in film thicknes that is much greater than that calculated using conventional theoretical film thickness calculation procedures that assume that the asphalt is uniformly distributed over all aggregate particles. To account for the different nature of the aggregate structure in coarse-graded mixtures, a modified film thickness calculation, entitled the "effective film thickness," was developed by Nukunya, et al. (2001), in which the asphalt binder is distributed onto the portion of the aggregate structure that is within the mastic.

Also recognizing that the Theoretical Film Thickness (Hveem, NCAT 1991) may not adequately represent the physics of PFC mixtures, the Georgia DOT introduced a modified film thickness calculation. However, the Georgia DOT modified film thickness calculation method is based on empirical considerations and yields similar results to the theoretical film thickness calculations.

More recently, work at the University of Florida under the direction of Drs. Roque and Birgisson has led to the establishment of a tentative gradation selection framework for the optimization of the fracture and rutting resistance of dense graded mixtures. Key concepts in this new proposed framework include the observation that enhanced cracking and rutting resistance can be obtained by ensuring that the aggregates in the course portion of the mixture gradation interact sufficiently amongst each other to allow for the effective transfer of forces through the course-aggregate portion of the mixture. This interaction of the course aggregate component should not reach down to the finer materials, so as to control mixture sensitivity. For optimizing the fracture resistance of mixtures, the material within the interstitial volume of the course aggregate portion also needs to be proportioned and designed so that an adequate Dissipated Creep Strain Energy (DCSE) limit is maintained, as well as providing enough flow and ductility to enhance the fracture resistance of the mixture. Too little interstitial material, or interstitial material with a low creep strain rate, will result in a brittle mixture. It is anticipated that these gradation concepts will be transferable to OGFC and PFC mixtures, thus allowing for the development of guidelines for the selection of gradations that optimize the resistance to cracking and rutting. Using these concepts it is also possible to define a modified film thickness that is calculated strictly based on the interstitial volume component of the mixture.

In the following the Georgia DOT modified film thickness criterion will be compared to the effective film thickness criterion developed by Nukunya, et al. (9), as well as the new film thickness criterion based on interstitial volume considerations. For completeness the "Theoretical Film Thickness proposed by (Hveem, NCAT 1991) is also calculated and included in the comparison, even though it is recognized that it may not adequately represent the structure of PFC mixtures. However, first the methods for calculating these asphalt film thicknesses are reviewed.

2.5.1 Review of Asphalt Film Thickness Calculation Methods

Goode and Lufsey's method

Even though this method is not used in this research, it is important to note the contributions of Goode and Lufsey (1965), who related empirically asphalt hardening to voids, permeability and film thickness. They recognized that the hardening of the asphalt binder in a mix was a function of air voids, film thickness, temperature, and time.

Goode and Lufsey (1965) introduced the concept of the ratio of the air voids to bitumen index, as a measure of the aging susceptibility of a mix (developed for dense graded mixture with 4% air voids). Goode and Lufsey (1965) had proposed a maximum value of 4.0 for this ratio, which they believed, would prevent pavement distress by reducing the aging of the asphalt film coating the aggregate. Mathematically, what they stated was:

$$\frac{AirVoids(\%)}{BitumenIndex \times 10^3} = 4 \text{ (Maximum)} \quad (2.1)$$

Where:

Film thickness (microns) = Bitumen index x 4870

Equation 2-1 with the air voids content of the mixture is reduced to a minimum film thickness requirement based on air voids to bitumen index ratio analysis. The film thickness then varies with the percent air voids as follows (Goode and Lufsey, 1965):

$$FilmThickness = \frac{AirVoids(\%) \times 4870}{4 \times 10^3} \text{(Minimum)} \quad (2.2)$$

The total air voids in the compacted PFC limestone mixtures at 50 gyrations is 16.16%. Goode and Lufsey's minimum film thickness requirement for 16.16% is 19.67 microns.

Theoretical film thickness method

This technique for calculating film thickness is based on the surface area calculated as per Hveem (1991). The surface area factors suggested by Hveem (1991) is shown in Table 2-7. The Film thickness of asphalt aggregates is a function of the diameter of particles and the effective asphalt content. The film thickness is directly proportional to volume of the effective asphalt content and inversely proportional to diameter of particle:

$$T_{film} = \frac{V_{eff} \times 1000}{SA \times W_{agg}} \quad (2.3)$$

T_{film} = Film Thickness

SA = Surface Area

W_{agg} = Weight of aggregate

Table 2-7. Surface Area Factor Hveem (1991)

Sieve Size	Surface Area Factor
Percentage Passing Maximum Sieve Size	2
Percent Passing No. 4	2
Percent Passing No. 8	4
Percent Passing No. 16	8
Percent Passing No. 30	14
Percent Passing No. 50	30
Percent Passing No. 100	60
Percent Passing No. 200	160

Effective film thickness method (Nukunya et al, 2001)

According to this method only aggregates passing the No. 8 Sieve are taken into account in the calculation of the surface area by using factors suggested by Hveem (1991) Then Equation 2-3 is used for calculating Film Thickness.

Table 2-8. Surface area Factor suggested by Nukunya (2001) for coarse aggregate structure

Sieve Size	**Surface Area Factor**
Percent Passing No. 8	4
Percent Passing No. 16	8
Percent Passing No. 30	14
Percent Passing No. 50	30
Percent Passing No. 100	60
Percent Passing No. 200	160

Modified film thickness method used by gdot

Georgia developed this method primarily for PEM mix with granite aggregate. The basic assumption was that the absorption of asphalt is very low or no absorption by surface pores of granite aggregate. The method is empirical and assumes that fixed aggregate unit weight per pound of aggregate, based on Georgia aggregates. Hence, the effective film thickness (T_{eff}) is given as:

$$T_{eff} = \frac{[\,453.6 \text{ g per Pounds divided by \% Aggregate}\,] - [\,453.6 \text{ g per Pounds}\,]}{\text{Surface area in square ft / lb} * 0.09290 \text{Sq. m per sq. ft.} * \text{Sp. gr. of AC}} \qquad (2.4)$$

Where,

T_{eff} = Effective Film Thickness

Film thickness based on interstitial volume concept

The aggregate interaction curve is plotted to determine the portion of the gradation curve with interacting aggregate sizes. Following is equation used for calculating points of interaction

:

$$\%\text{Retained\_Particle\_Interaction\_Point} = \frac{(\%\text{Retained\_at\_Sieve\_Size})*100}{(\%\text{Retained\_at\_Succesive\_Sieve\_Size} + (\%\text{Retained\_at\_Sieve\_Size})} \quad (2.5)$$

The aggregates are considered to be interacting, if the percent-retained particle interaction is between 30% and 70%. Any point that falls outside these limits is considered to be non-interacting. Therefore, aggregate sizes below this break point are not interacting towards contribution of strength. These aggregate sizes are filling the cavities between the coarse aggregate structure defined by aggregate sizes above the break point. The aggregate sizes below the break point along with asphalt are contributing to Interstitial Volume. Mastic, comprising aggregate sizes below the break point, asphalt, and air voids, form the interstitial volume of the compacted mixture. Hence, the interstitial volume is the ratio of mastic in specimen to the total volume of the compacted mixture, as shown in Equation 2-6:

$$Interstitial\_Volume = \frac{(Volume\_of\_Mastic)}{Total\_Volume\_of\_Compacted\_Mixture} \quad (2.6)$$

In order to calculate the film thickness of the particles in the interstitial volume, the surface area of the particles in the interstitial volume needs to be determined. As per the hypothesis discussed above, aggregates below the break point are within the interstitial volume. Hence, the surface area (SA) of aggregates below break point can be obtained from the surface area factors given in Table 2-9. As the absorption in granite is negligible, the as the effective asphalt content (V_{eff}) is taken to be the total asphalt content of the compacted mixture. Weight of aggregates (W_{agg}) in air is taken into account for calculating film thickness. Equation 2-7 denotes calculation of film thickness with in interstitial volume:

$$T_{film} = \frac{V_{eff} \times 1000}{SA \times W_{agg}} \tag{2.7}$$

Recognizing that these film thickness calculations all use effective asphalt content to determine the available amount of asphalt binder for the coating of particles, it is important to establish clear guidelines for determining the effective asphalt content of PFC mixtures.

Table 2-9. Surface area factors for Interstitial Volume

Sieve Size	Surface Area Factor
Percentage Passing Maximum Sieve Size	2
Percent Passing No. 4	2
Percent Passing No. 8	4
Percent Passing No. 16	8
Percent Passing No. 30	14
Percent Passing No. 50	30
Percent Passing No. 100	60
Percent Passing No. 200	160

Aggregate with in interstitial volume

Aggregate with in interstitial volume

The Georgia DOT method of film thickness calculations assumes that there is no absorption of asphalt into the aggregate surfaces. Their method of film thickness calculation is an empirical approach. This assumption may be a reasonable approximation for low absorption granite aggregates. However, for high absorption limestone aggregates it is necessary to account for absorption. In this research, asphalt absorption was estimated using two approaches:

1) Asphalt absorption obtained from basic volumetric equations is used to calculate effective asphalt content. This is the true asphalt contributing towards in film thickness: -

13. Effective Specific gravity (Gsb): - The effective specific gravity is calculated from the maximum specific gravity (Gmm) of mixture and Asphalt content (Pb).

$$G_{se} = \frac{1 - \frac{Pb}{100}}{\frac{1}{Gmm} - \frac{\frac{Pb}{100}}{Gb}} \tag{2.8}$$

14. Asphalt Absorption (P_{asb}): - The absorbed asphalt content is differences of bulk volume of aggregate and the effective volume.

$$P_{asb} = 100 \times \left(\frac{Gse - Gsb}{Gse \times Gsb} \right) \times Gb \tag{2.9}$$

15. Effective Volume of Asphalt (V_{eff}): - The effective volume of asphalt is amount of asphalt available for coating aggregates, which is obtained by subtracting absorbed asphalt from Total Asphalt Content (P_{Total}).

$$V_{eff} = P_{Total} - P_{asb} \tag{2.9}$$

2) Determination of effective asphalt content based on bulk specific gravity determined through from the CoreLok test procedure as per CoreLok manual (2003). The main justification for using the CoreLok procedure is that open graded mixes readily absorb water and drain quickly when removed from the water tank, during the determination of Saturated Surface Dry (SSD). Weight conditions in traditional laboratory-based procedures for determining. The lack of control over the penetration and drainage of water in and out of asphalt specimens creates a problem with the water displacement measurement using the current principles for determination of specific gravity as per Cooley et all (2002). The CoreLok system makes the determination of SSD conditions unnecessary.

Perform calculation as per directions given in Data Collection Table: 2.10

Table 2-10. CoreLok calculation Sheet

Sample ID	A	B	C	D	E	F	G	H	I	J
	Bag Weight (g)	Dry Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Dry Sample Weight After Water Submersion (g)	Ratio B/A	Bag Volume Correction From Table	Total Volume (A + D) - C	Volume of Sample A/F	Volume of Sample (G-H)	Bulk Specific Gravity B/I
I										
II										

After determination of Bulk Specific gravity (Gmb) following steps in calculation are involved for estimating the effective asphalt content. Air Voids in compacted mix (VTM) and Voids in Mineral Aggregates (VMA) are calculated using Equation 2-10 and Equation 2-12 based on bulk specific gravity determine by CoreLok method.

$$VTM = \left(1 - \frac{Gmb}{Gmm}\right) \times 100 \qquad (2.10)$$

$$VMA = 100 - \frac{\left(\frac{W_{agg}}{Gsb}\right)}{\left(\frac{W_T}{Gmb}\right)} \times 100 \qquad (2.11)$$

$$Veff = \frac{VTM.V_T}{100} - Vagg + V_T \qquad (2.12)$$

Where,

V_T = Total volume of compacted specimen

$Vagg$ = Volume of aggregate

Gmm = Maximum theoretical specific gravity.

Gsb = Aggregate bulk specific gravity

VTM = Voids in total mix

VMA = Voids in Mineral aggregate.

W_T = Weight of Total specimen

W_{agg} = Weight of aggregate

2.5.2 Comparison of Results Obtained from Each Film Thickness Calculation Method

Limestone has higher absorption capacity than granite aggregate. Figure 2-7 shows the absorption of asphalt into the surface cavities of limestone aggregate, therefore reducing the effective asphalt content and resulting in a lower film thickness when compared to granite mixtures.

(a) (b)

Figure 2-7. (a) Granite with high film (Required against stripping) (b) Limestone with low film thickness as compared with granite due to absorption

The four different asphalt film thickness calculations methods discussed previously were used to calculate the film thickness of asphalt with in compacted granite and limestone PFC mixtures.

The surface area calculated by the Nukunya et al (2001) Method and the Interstitial Volume method is exactly same for the two mixtures evaluated, due to the fact that the break point defining the interstitial volume is at the No. 8 Sieve Size.

Table 2-11. Comparison of Film Thickness method for Limestone mixture

Method	Film Thickness (microns) Asphalt absorption	Film Thickness (microns) Corelok Method
Theoretical Film Thickness (Hveem 1991)	34.20	31.22
Nukunya's Effective Film thickness	50.71	46.29
GDOT	34.80	31.58
Interstitial Volume	50.71	46.29

Table 2-11 shows the comparison of true film thickness to film thickness calculated from CoreLok bulk specific gravity.

CoreLok is determining comparative film thickness. Nukunya's method and Interstitial volume method are predicting higher film due consideration of coarse aggregate structure.

Table 2-12. Comparison of Film Thickness method for Granite mixture

Method	**Film Thickness (microns) Asphalt Absorption**
Theoretical Film Thickness (Hveem 1991)	37.25
Nukunya's Effective Film thickness	55.23
GDOT	38.10
Interstitial Volume	55.23

As shown in Table 2-12, Comparison of Film Thickness method for Granite mixture, GDOT method is over predicting film thickness. Hence, in summary, either the CoreLok or the equivalent water absorption methods can be used. However, the Corelok method is still under review and development, nationally. Therefore, until the method has been thoroughly verified on the national level, it is recommended that the equivalent water absorption method be used as a lower limit on asphalt absorption. Similarly, the asphalt film thickness of the aggregates within the interstitial volume is the most theoretically correct method.

However, it is still under development and evaluation. Therefore, it is recommended that the Effective Film Thickness calculation proposed by Nukunya, et al. (2001) be used to determine the film thickness of PFC mixtures.

2.5.3 Relative Minimum Film Thickness Requirement

For establishing minimum film thickness requirement based on Effective Film Thickness Nukunya et all (9), Georgia Department of Transportation minimum film thickness criterion is used as standard. According to GDOT minimum film thickness required for granite PFC mixture against stripping is 27 microns for surface area calculated based on GDOT factors. This requirement is not specified in their specification but they use it as tentative film thickness criterion.

Georgia DOT typically uses granite aggregate for their GPEM mixtures. Georgia DOT, ignore asphalt absorption while calculating film thickness as per Eason (2004). But limestone due to its porous surface texture has high asphalt absorption capacity. This property of limestone does not allow attainment of high film thickness. Aggregates with different asphalt absorption will lead different minimum film thickness. Therefore, the relative minimum film thickness requirement is calculated for set of range of asphalt absorption, i.e. 0-0.5%, 0.5-1 %, 1 % or more. While calculating minimum film thickness requirement for each of these ranges, upper limit of range is considered.

For calculating the relative minimum film thickness requirement, 27 micron is used to back calculate the effective asphalt content $(Veff_{GDOT})$.

As Georgia DOT ignores asphalt absorption this effective asphalt content is total asphalt content of the mixture. Subtracting upper limit of range of asphalt absorption ($Asphalt_{absorption}$) from this the total asphalt content gives actual effective asphalt content ($Veff_{Nukunya}$). This value of effective asphalt content is substituted in standard film thickness Equation 2-3 using surface area as per Nukunya et al (2001) as shown in Step V for calculating relative minimum film thickness ($T_{\mathrm{Re}lative\_Minimum}$).

Optimum gradation band for surface area calculation

A gradation band, which is representative of all gradations with in specified control limits, is required for calculating surface area for relative minimum film thickness requirement. Average of maximum control points and minimum control points of specified gradation limits as per GDT-114 (1996) to obtain optimum gradation, which represents gradation between those gradation limits.

Figure 2-8 shows optimum gradation band used for calculating surface area. Job mix formula of this optimum gradation showed in Table 2-13 is used to calculate surface area as per Georgia DOT method ($SurfaceArea_{GDOT}$) and Nukunya et al. (2001) ($SurfaceArea_{Nukunya(2001)}$). It is assumed that this optimum gradation represents the different gradation band with in this specified limit. Therefore the film thickness calculated for this optimum gradation band represents al set of gradation band with in this gradation limit.

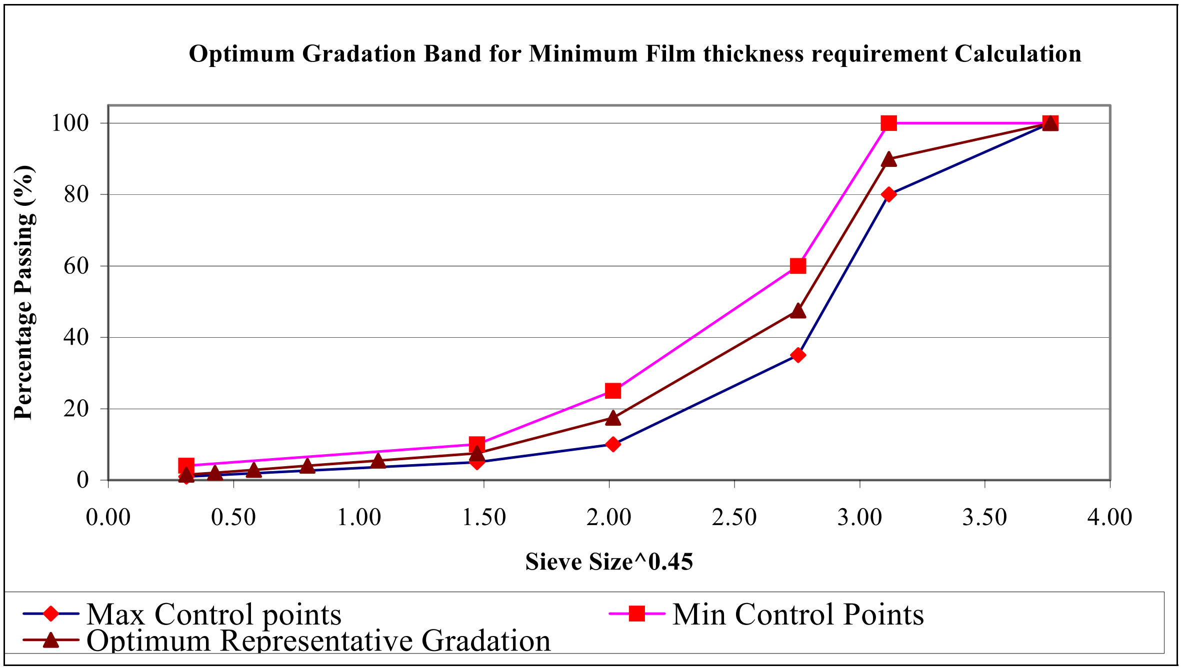


Figure 2-8. Optimum Gradation Band for Calculating Minimum film thickness requirement

Table 2-13. JMF of Optimum gradation for Gradation limits as per GDT 114 (1996)

Type		**Optimum Gradation Band**
% Amount		
Sieve Size	**Size^0.45**	
37.5	5.11	100
25	4.26	100
19	3.76	100
12.5	3.12	90
9.5	2.75	48
4.75	2.02	18
2.36	1.47	8
1.18	1.08	5
0.6	0.79	4
0.3	0.58	3
0.15	0.43	2
0.075	0.31	2

Following steps are used for calculating relative film thickness requirement: -

Step I: $T_{\min imumGDOT} = 27 microns$

Step II: $Veff_{GDOT} = \dfrac{T_{\min imumGDOT} \times SurfaceArea_{GDOT} \times W_{aggregate}}{1000}$

Step III: $Total_{asphalt} = Veff_{GDOT}$

Step IV: $Veff_{Nukunya} = Total_{asphalt} - Asphalt_{absorption}$

Step V: $T_{\mathrm{Re}lative\_Minimum} = \dfrac{Veff_{Nukunya} \times 1000}{SurfaceArea_{Nukunya(2001)} \times W_{aggregate}}$

Based on above steps minimum film thickness requirement is calculated for different set of asphalt absorption. The relative minimum film thickness for Nukunya et al (2001) based on this concept is tabulated in Table 2-14.

Table 2-14. Minimum film thickness requirements for different set of Asphalt absorption

Asphalt absorption Range	**Total asphalt content (ml)**	**Maximum asphalt absorption (%)**	**Effective asphalt content (ml)**	**Minimum film thickness requirement (microns)**
0 % to 0.5%	213.84	0.5%	191.84	32
0.5% + to 1 %	213.84	1%	169.84	28
1%+ to 1.5%	213.84	1.50%	147.84	24
1.5% or more	214.84	Greater than 1.5 %	125.84	13

2.6 Recommended Specification for PFC Mixture Design

SCOPE

The method of design for a modified open graded bituminous mixture consists of four steps. The first step is the selection of a trial aggregate blend and asphalt binder. The second step involves the determination of optimum asphalt content and checking for adequate asphalt film thickness to ensure durability. The third step involves the performance of AASHTO T 305-97 (2001) (i.e. a asphalt drain down test), and the fourth step involves the performance of AASTHO T-283 (2001). The details of each step are discussed below.

APPARATUS

The apparatus required shall consist of the following:

1. Drain-Down equipment as specified in AASHTO T 305-97 (2001).
2. Superpave gyratory compactor.
3. Equipment to perform AASHTO T-84 and T-85.
4. Balance, 5000 gr. Capacity, 0.1 gr. Accuracy.
5. 10 metal pie pans
6. Oven capable of maintaining 330 º F ± 3.5 º F (165º C ± 2.5 º C)
7. Oven capable of maintaining 350 º F ± 3.5 º F (176º C ± 2.5 º C
8. Timer.

STEP 1: Determination of Trial Blend and Asphalt Binder

The aggregate trial blend should be selected to fit within the gradation limits listed in Table 2-15 and shown in Figure 2-9. The asphalt binder should be SBS modified PG 76-22 asphalt. Either the addition of 0.5% liquid anti-strip agent or 1 percent hydrated lime is required. The use of hydrated lime requires pretreatment of the aggregates with the hydrated lime. 0.4 % mineral fiber by weight of total mix should be added to avoid binder drain down.

Table 2-15. Proposed Gradation and Design specifications for Florida Permeable

Mixture Control Tolerance	**Asphalt Concrete**	**12.5 mm PFC**
	Gradation Requirement	
± 0.0	3/4 in (19 mm) sieve	100
± 6.1	1/2 in (12.5 mm) sieve	80-100
± 5.6	3/8 in (9.5 mm) sieve	35-60
±5.7	No. 4 (4.75 mm) sieve	10-25
±4.6	No.8 (2.36 mm) sieve	5 10
±2.0	No. 200 (75 μm) sieve	1-4
	Design Requirements	
±0.4	Range for % AC	5.5-7.0
	AASHTO T-283 (TSR)	80
	Drain-down, AASHTO T 305 (%)	<0.3

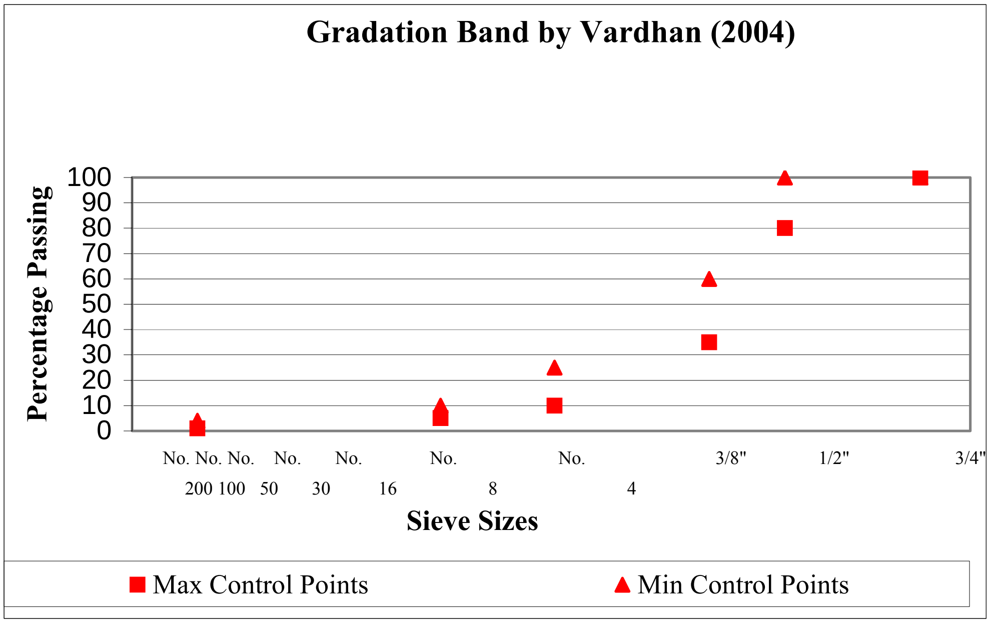


Figure 2-9. Proposed Gradation limits for Florida Permeable Friction Course Mixtures

STEP 2: Determination of Optimum Asphalt Content and Asphalt Film Thickness

- Heat the coarse aggregate, the mould to 350ºF ± 3.5ºF (176ºC ± 2.5 º C) and the AC to 330º F ± 3.5º F (165º C ± 2.5 º C)

- Mix aggregate with asphalt to obtain at least four trial asphalt contents, viz., 5.5%, 6%, 6.5% and 7%. Just before mixing, add the required amount of mineral fibers to the aggregate. Prepare three samples at each of the asphalt contents

- After mixing, return the mix to oven for two hours for STOA at 320º F ± 3.5 º F (160 ºC ± 2.5 º C). Then compact to 50 gyrations using the Superpave Gyratory Compactor

- When compacted, cool down at room temperature for 1 hour 45 minutes before removing the specimens from the compaction mold.

- Determine Bulk Specific Gravity: Determine the density of a regular shaped specimen of compacted mix from its dry mass (in grams) and its volume in cubic centimeters obtained from its dimensions for height and radius. Convert the density to the bulk specific gravity by dividing by 0.99707 g/cc, the density of water at 25 ºC

$$\text{Bulk Sp.Gr} = W / (\pi \, r2h / 0.99707)$$

$$= \text{Weight (gms)} \times 0.0048417/\text{Height (in)}$$

W = Weight of specimen in grams

R = radius in cm

H = height in cm

- Determine Theoretical Maximum Specific Gravity according to AASHTO T-209-99 (2004).
- Calculate percent air voids, VMA and voids filled with asphalt based on aggregate specific gravity
- Plot VMA curve versus AC content and determine point of minimum VMA, select corresponding AC as Optimum asphalt content.
- Prepare a mixture at the optimal asphalt content.
- Determination of film thickness: -

Step (I) Determination of Effective Specific gravity (P_{asb}): -

$$G_{se} = \frac{1 - \frac{Pb}{100}}{\frac{1}{Gmm} - \frac{\frac{Pb}{100}}{Gb}} \tag{2.13}$$

Step (II) Determination of Asphalt absorption (P_{asb}): -

$$P_{asb} = 100 \times \left(\frac{Gse - Gsb}{Gse \times Gsb} \right) \times Gb \tag{2.14}$$

$Water_{abs}$ Determined is in percentage of weight of aggregate. Convert into volume of water in ml, by using following equation:-

$$P_{abs\,abs\_ml} = \frac{P_{abs} * Weight\_of\_aggregate(grams)}{100 * 1.03} \tag{2.15}$$

Step (III) Determination of Effective Volume of Asphalt (V_{eff}): -

$$V_{eff} = P_{Total} - P_{abs\,abs\_ml} \tag{2.16}$$

(Where P_{Total} = Total asphalt content in ml)

- Calculate the Effective Film thickness using following procedure as per Nukunya et al (2001):

a) Determine Surface area (SA) from Table 2 below:

Table 2-16. Surface area factor as per Nukunya et al (2001)

Sieve Size	**Surface Area Factor**
Percent Passing No. 8	4
Percent Passing No. 16	8
Percent Passing No. 30	14
Percent Passing No. 50	30
Percent Passing No. 100	60
Percent Passing No. 200	160

b) Film thickness of asphalt (in microns):

$$T_{film} = \frac{V_{eff} \times 1000}{SA \times W_{agg}} \qquad (2.17)$$

where,

W_{agg} = Weight of aggregate
SA = Surface area

The minimum acceptable effective film thickness is determined as a function of the measured percent asphalt absorption per weight of aggregate as follows:

Table 2-17. Minimum Effective Film Thickness Requirements

Percent Asphalt Absorption	**Minimum Required Film Thickness (micron)**
0.5 % or less	32
0.5+ to 1 %	28
1.0+ to 1.5 %	24
Greater than 1.5 %	13

E Step 3: Performance of Drain-Down Test

Perform the drain test in accordance with the AASHTO T 305-97 (2001). A mix with an optimum AC content as calculated above is placed in a wired basket having 6.4 mm (1/4 inch) mesh openings and heated 14 ºC (25 ºF) above the normal production temperature (typically around 350ºF) for one hour. The amount of cement, which drains from the basket, is measured. If the sample fails to meet the requirements of maximum drain down of 0.3 %, increase the fiber content by 0.1 % and repeat the test.

Step 4: Performance of Moisture Damage Test

Perform the moisture damage test in accordance with AASHTO T-283 (2003) on compacted specimen. The specimens are rolled in 1/8" wire mesh which are kept in position using two clamps on either edge of the pill for avoiding mixture damage or breakdown at the conditioning temperature of 60ºC (140ºF). Minimum requirements should include TSR of 0.8 or greater.

2.7 Conclusion of Verification of PFC mixture Design Procedure

The research presented in this chapter led to the following conclusions:

- It is recommended that at least (4) trial asphalt content should be used for predicting fairly accurate optimum asphalt content.

- Only PG 76-22 SBS modified binder containing 0.5% liquid anti stripping agent should be used.

- Minimum amount of batched sample for sample should not be less than 1000 grams for all purposes of testing.

- Air voids levels in the PFC limestone mixture were around 16% at 50 gyrations. Gradation analysis by Varadhan (2004) on extracted aggregate after compaction showed that the limestone undergoes crushing early in the compaction process. Therefore, the specified gradation limits may have to be adjusted for limestone to obtain air voids in the desired 18-22 percent range.

- In order to ensure adequate durability, the effective film thickness method developed by Nukunya, et al. (2004) should be used. In order to determine the effective asphalt content, the aggregate asphalt absorption should be used.

CHAPTER 3
EVALUATION OF I-295 PFC MIX DESIGN

PFC pavements are subjected to high temperature variance, hydroplaning and are in direct contact with rolling loads. In order to check field performance of PFC in Florida, construction of a test section was proposed at I-295, Jacksonville, FL. The Mix design of for this section follows the procedure discussed in Chapter 2.

3.1 Objective

The objective of this study is to evaluate mix design procedure of PFC mixture at I-295 test section. The I-295 test section will be monitored for its long-term performance.

Gradation selections for optimizing fracture resistance. Determination of optimum asphalt content for attaining minimum voids in the mineral aggregate (VMA) for ensuring high binder coating without drain down. Obtain a mixture for I-295 with highest Energy Ratio among selected gradation to ensure best performance.

3.2 Scope of Project

Separate mix design was carried on gradation proposed by DOT contractor (Gradation (1)) and designed gradation (Gradation (2) to determine optimum asphalt content. Following is the complete plan of project:-

For each of the gradations, 4-trial asphalt percentages are used to obtain a VMA curve. The reason for selecting 4-trial percentages is to obtain polynomial curve for determining point of minimum VMA. Sieving, batching, mixing and compaction, as discussed in section 3.3.1 of this chapter, of mixes is done as specified in previous development in laboratory. Asphalt used is SBS modified PG76-22, which contains 0.5%

anti strip agent in addition to 1% of hydrated lime added to aggregates to resist against stripping. Dosage rate of mineral fiber is 0.4% by total weight of mix. Superpave Indirect tensile test is run on compacted mixes for both gradations, in order to obtain fracture test parameters including energy ratio. Process of testing and criteria considered are discussed in section 3.4 of this chapter. Selection of gradation based on higher energy ratio for I-295 test section. Effect of moisture conditioning and long-term oven aging on selected gradation.

3.3 Materials used for I-295 PFC project

3.3.1 Aggregate and Hydrated Lime

The final aggregate blend for Gradation (1) and Gradation (2) is composed of #67 Granite stone from Pit No TM-579/NS-315, #78 Granite Stone from Pit No GA-383 and Granite Screens from Pit No. TM-579/NS-315. The FDOT codes for these source stone stockpiles, #67 Granite is '54', #78 Granite is '54', and for Granite Screens is '23' respectively. The producer of these aggregates is 'Martin Marietta Aggregate'. Figure 3-1 shows the gradation band used for I-295 PFC project and control points as per FDOT specification SECTION 337. Table 3-1 and Table 3-2 gives details of composing of job mix formula of Gradation (1) and Gradation (2) respectively. One percent by weight of aggregate hydrated lime is added to the mixture as an antistrip agent. 'Global Stone Corporation' provided hydrated lime.

3.3.2 Binder and Mineral Fiber

An SBS polymer modified asphalt cement PG 76-22 with 0.5% antistrip agent was used in this project. Mineral fiber used was regular FIBERAND ROAD FIBERS. 'Atlantic Coast Asphalt Co.' supplied asphalt and mineral fiber. The dosage rate of mineral fiber was 0.4% by weight of total mix.

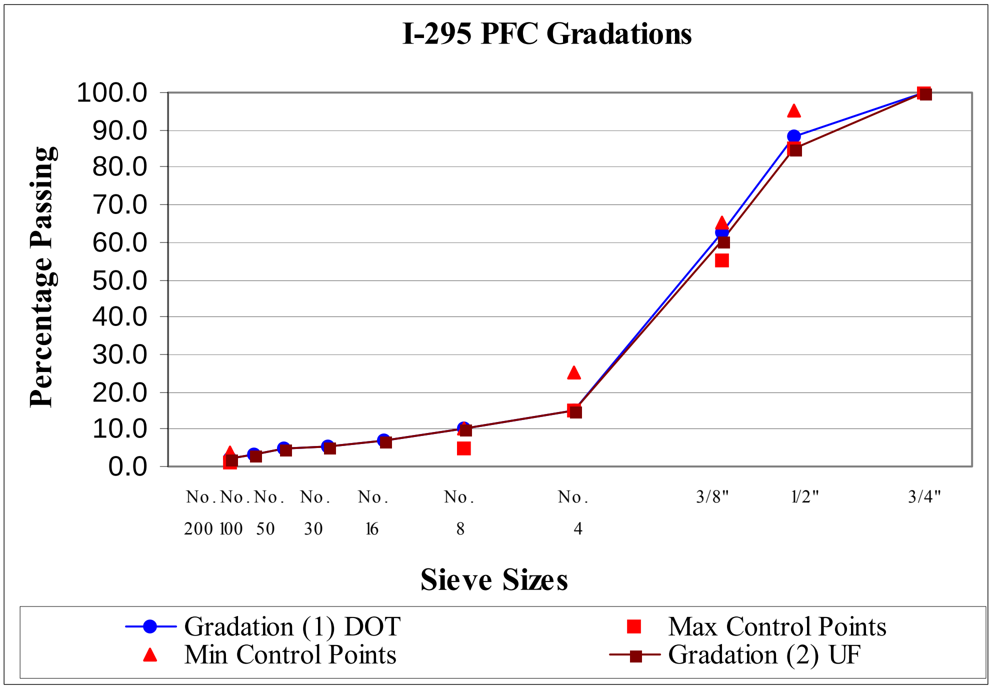


Figure 3-1. Gradation of I-295 PFC mixtures

Table 3-1. JMF composition of Gradation (1)

Type		**#67 Granite**	**#78 Granite**	**Granite Screens**	**Lime**	**JMF**	**Control Points**	
% Amount		**20**	**70**	**9**	**1**	**100**	**Max**	**Min**
Sieve Size	Size^0.45							
37.5	5.11	100	100	100	100	100		
25	4.26	100	100	100	100	100		
19	3.76	100	100	100	100	100	100	100
12.5	3.12	60	95	100	100	89	95	85
9.5	2.75	45	62	100	100	62	65	55
4.75	2.02	8	6	91	100	15	25	15
2.36	1.47	4	4	61	100	10	10	5
1.18	1.08	3	3	38	100	7		
0.6	0.79	2	3	22	100	5		
0.3	0.58	2	3	15	100	5		
0.15	0.43	2	2	7	100	3		
0.075	0.31	1	1	3.5	100	2	4	1

Table 3-2. JMF composition of Gradation (2)

Type		**#67 Granite**	**#78 Granite**	**Granite Screens**	**Lime**	**JMF**	**Control Points**	
% Amount		**30.0**	**60.3**	**8.8**	**1**	**100**	**Max**	**Min**
Sieve Size	Size^0.45							
37.5	5.11	100	100	100	100	100		
25	4.26	100	100	100	100	100		

Table 3-2. Continued

Type	#67 Granite	#78 Granite	Granite Screens	Lime	JMF	Control Points		
% Amount	**30.0**	**60.3**	**8.8**	**1**	**100**	**Max**	**Min**	
19	3.76	100	100	100	100	100	100	100
12.5	3.12	60	95	100	100	85	95	85
9.5	2.75	45	62	100	100	61	65	55
4.75	2.02	8	6	91	100	15	25	15
2.36	1.47	4	4	61	100	10	10	5
1.18	1.08	3	3	38	100	7		
0.6	0.79	2	3	22	100	5		
0.3	0.58	2	3	15	100	5		
0.15	0.43	2	2	7	100	3		
0.075	0.31	1	1	3.5	100	2	4	1

3.4 Location of Project

Figure 3-2 shows the project location, which is on I-295 between Lem Turner Road and Duval Road in Jacksonville, Florida. The test section starts at MP 31.910 (Station 1684+88.86 on I-295) and ends at MP 32.839 (Station 1733+91.61 on I-295), outside lane at northbound and south bound.

Figure 3-2. Project Location

3.5 Specification and Hypothesis Used

As per FDOT specification SECTION 337-4, developed based on previous work done described in Chapter 2, and the design of the PFC mixtures is based on the final procedure developed in Chapter 3. The basic steps in the mixture design may be summarized as follows:

1. The design number of gyration should be 50.
2. Final JMF should be within the gradation limit specified in Table 337-2 of FDOT specification SECTION 337-3.3.2. This specified gradation limit is shown in Table 3-3
3. The PFC mix design should use a SBS modified PG 76-22 asphalt binder.
4. The optimum asphalt content should be selected at the minimum voids in the mineral aggregate (VMA) content.
5. The air void content should be between 18 and 22 percent.
6. Hydrated Lime dosage rate of 1.0% by weight of the total dry aggregate.
7. Mineral fiber dosage rate of 0.4% by weight of the total mix.

Table 3-3. PFC Gradation Design Range from FDOT specification SECTION 337

Sive Size (mm)	**Control Points**	
	Max	**Min**
	% Amount Passing	
37.5		
25		
19	100	100
12.5	95	85
9.5	65	55
4.75	25	15
2.36	10	5
1.18		
0.6		
0.3		
0.15		
0.075	4	1

The FDOT contractor proposed a JMF (Gradation (1)) for the given source gradations of stockpiles. As the source gradation was gap graded and gradation limits according to SECTION 337 are tight, it was difficult to adjust this gradation to obtain another candidate gradation. Therefore, only one other trial gradation was used in addition to the contractor's gradation. The second gradation, denoted as Gradation (2) was based on increasing the amount of coarser stone in the mix. This objective was accomplished by increasing the percentage of # 67 granite from 20 % to 30 %.

Even though, the material type used in Georgia PEM mix design development is different than in the I-295 PFC project, its characteristics are used as base for the evaluation of fracture results. Table 3-1 and Table 3-2 shows source gradation and final JMF of Gradation (1), Gradation (2) and Georgia PEM gradation. The hump in gradation at No. 4 sieve might create some effect fracture resistance because of uneven aggregate arrangement in mix.

3.6 Determination of Optimum Asphalt Content

Based on number of experiments, the Georgia DOT suggested that if the gradation is within the specific limits, the initial estimate comes out to be 6% using granites that are native to Georgia. Hence, the probable optimum asphalt content with in this gradation band is 6% if the aggregate is Georgia granite. Depending on surface texture and angularity of aggregates, or a change in the JMF might cause changes in optimum asphalt content. Therefore, four trial percentages (5.5%, 5.8%, 6.2% and 6.5%) for each gradation, and two piles for each trial percentage are produced in this project.

3.6.1 Mixing and Compaction

Sieved and batched aggregates, asphalt and mineral fiber are preheated for 3 hours in an oven before mixing. Due to the SBS modified viscous asphalt and addition of mineral fiber; the mixing temperature was selected as 330 º F (165º C), to maintain enough flow during mixing. All tools and mixing drum were also preheated to 350º F (176º C).

While mixing, asphalt is added to mix of aggregate and mineral fiber. These SBS mixes are very sticky, making mixing and handling challenging. Therefore, it is important to ensure that while retrieving material from mixing drum there is no loss of fines. Mixing procedure was the same for both Rice testing specimens as well as the Superpave gyratory compacted specimens. It is also important to avoid over heating of binder during mixing, as it causes aging of binder.

Before compaction, the mixes are subjected to Short Term Oven Aging (STOA) for two hours, which includes stirring after one hour. Compaction temperature is reduced to 320 º F, for avoiding draindown of binder during compaction. As already stated, 50 gyrations were used to attain compaction level similar to field after traffic consolidation. The angle of gyration kept during compaction was 1.25. Essentially, because of sticky nature of these mixture oil is sprayed in molds.

From prior experience, compacted samples are not retrieved from the molds immediately. They are allowed to cool from 1hr 45 min before retrieving from molds. Once the specimen is ejected from the mold let it cool for 5 min before holding specimen. Especially in granite mixtures if cooling after ejection is not allowed small aggregates due to high air voids stick to gloves and comes out causing discontinuity in specimen.

Allow piles to cool for 24 hr before any further processing or activity related to the compacted specimens.

Determination of Rice specific gravity (Gmm) on loose PFC mixes was done in accordance with AASHTO T209 (See Appendix B). Calculations of all volumetric properties are shown in Appendix B. The determination of optimum asphalt content was as per recommended specification, as specified in Chapter 3, by selecting AC at the lowest point of the VMA curve.

Gradation (2) is coarser than Gradation (1), which results in more surface area in Gradation (1) as compared to Gradation (2). Refer to Figure 3-3 and Figure 3-4 for mix design details for Gradation (1) and Gradation (2), respectively. A decrease in effective specific gravity of Mixture 2 with respect to Mixture 1 shows the increase in volume of water permeable pores not absorbing asphalt. These facts support reduction in optimum asphalt content of Gradation (2). Essentially, the VMA at optimum asphalt content is not changing significantly for both gradations. Basically, Gradation (2) is giving air voids (21.93 %) similar to Gradation (1) (21.2%) and all other volumetric properties are comparable and within the restricted specification ranges. Therefore, the final selection of gradation depends on fracture test results.

Effective Sp Grav of Agg	% AC[6]	Gmm[1]	Gmb[2]	VMA[3] (%)	VTM[4] (%)	VFA[5] (%)
2.732	5.5	2.513	1.944	32.777	22.655	30.883
	5.8	2.501	1.955	32.603	21.820	33.073
	6.2	2.473	1.964	32.600	20.578	36.877
	6.5	2.470	1.966	32.721	20.379	37.718

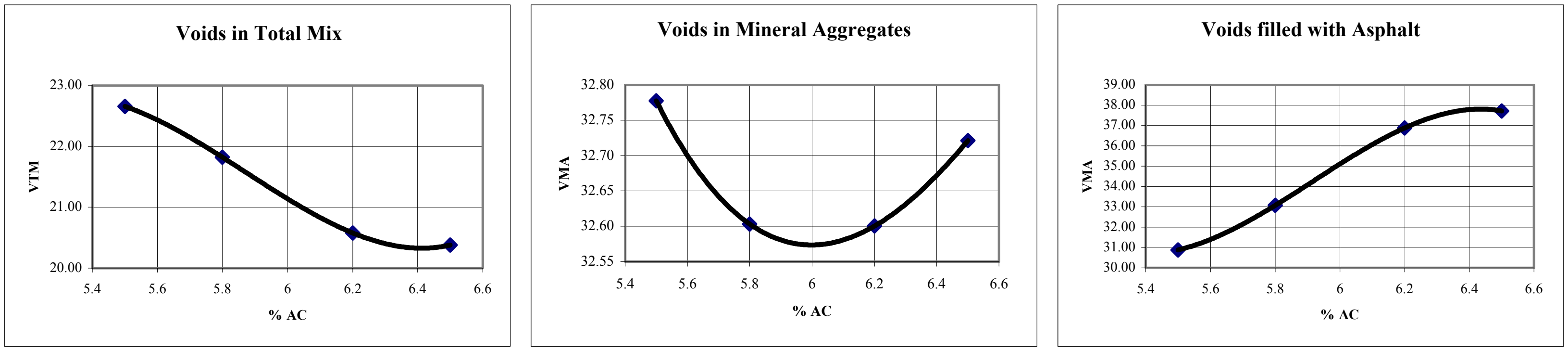


Figure 3-3. Mix Design of PFC Gradation (1) with aggregate type: - Granite

Optimum Asphalt Content: - 6.0%

Gmm at Optimum Asphalt Content:- 2.485

Mineral Fiber: - 0.4% of Total Mix

VMA at Optimum Asphalt Content: - 32.69%

Gmm[1] = Maximum specific gravity of mixture, Gmb[2] = Bulk specific gravity of mixture, VMA[3] = Voids in Mineral Aggregates, VTM[4] = Voids in Total Mix, VFA[5] = Voids filled with Asphalt, AC[6] = Asphalt Content

Effective Sp Grav. of Agg.	% AC[6]	Gmm[1]	Gmb[2]	VMA[3] (%)	VTM[4] (%)	VFA[5] (%)
2.722	5.5	2.497	1.935	32.819	22.501	31.440
	5.8	2.494	1.946	32.648	21.963	32.727
	6.2	2.479	1.953	32.713	21.245	35.057
	6.5	2.452	1.957	32.788	20.212	38.357

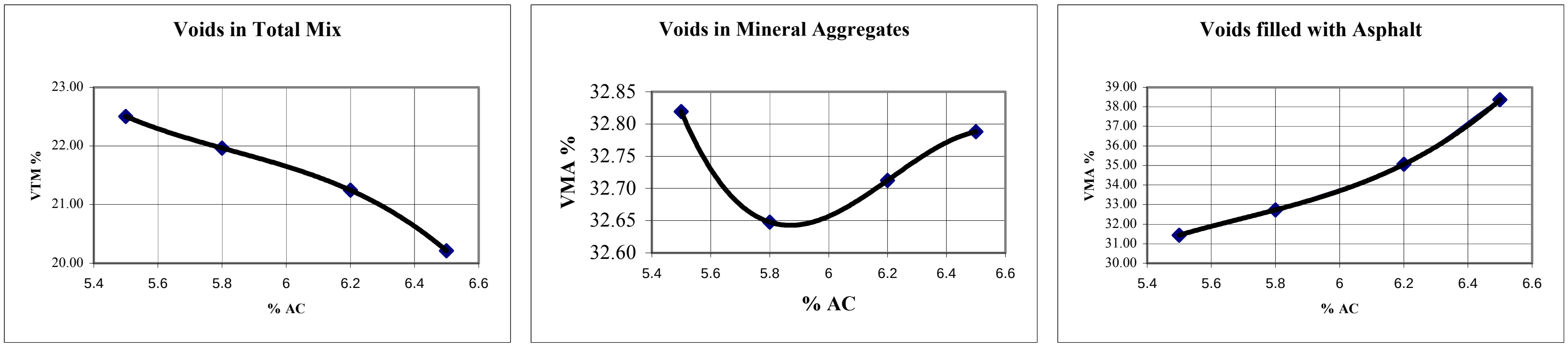


Figure 3-4. Mix Design of PFC Gradation (2) with aggregate type: - Granite

Optimum Asphalt Content: - 5.9% Gmm at Optimum Asphalt Content:- 2.491

Mineral Fiber: - 0.4% of Total Mix VMA at Optimum Asphalt Content: - 32.76%

Gmm[1] = Maximum specific gravity of mixture, Gmb[2] = Bulk specific gravity of mixture, VMA[3] = Voids in Mineral Aggregates,

VTM[4] = Voids in Total Mix, VFA[5] = Voids filled with Asphalt, AC[6] = Asphalt Content

3.6.2 Asphalt Film Thickness

As granite has fine texture, the surface absorption is negligible, meaning that water absorption ($Water_{abs}$=0) can be assumed to be negligible. The surface areas calculated for Gradation (1) and Gradation (2) are based on the method proposed by Nukunya et al (2001 and discussed in Chapter 3. The resulting surface areas for Mixture 1 and Mixture 2 are 1.8 m^2/Kg and 1.78 m^2/Kg, respectively. Taking the total asphalt content for both gradation as the effective asphalt content the film thickness is calculated by following equation mentioned in recommended specification (Chapter 2):

$$T_{film} = \frac{V_{eff} \times 1000}{SA \times W_{agg}} \qquad (2.3)$$

Where,

16. W_{agg} = Weight of aggregate

SA = Surface area

Gradation (1) has film thickness of 33.12microns where as Gradation (2) has of 31.65 microns. These film thicknesses for Gradation (1) and Gradation (2) are calculated assuming zero asphalt absorption. Both film thicknesses are above the specified minimum film thickness requirement, i.e. 32 microns, for 0% to 0.5% asphalt absorption. The minimum film thickness requirement is to ensure resistance against stripping and asphalt hardening.

3.7 Superpave IDT Performance Test Results

In the following, the results from the Superpave IDT fracture testing results are presented. The basics of the Superpave IDT test equipment and data acquisition system have been specified by Buttlar and Roque (1994), Roque et al., (1997), and AASHTO

TP-9. Additional information on the specific testing system used in this study is as follows:

- An environmental chamber was used to control specimen temperature. The chamber is capable of maintaining temperatures between -30° C and 30° C with an accuracy of ±0.1° C.
- Loads were controlled using a MTS Model 418.91 MicroProfiler.
- Vertical and horizontal deformation measurements were obtained using extensometers designed by MTS specifically for use with the Superpave IDT. A gage length of 1.5 inches was used for all specimens.

Since the friction course mixtures are very porous, it was decided that the sample thickness be around 1.5 –2 inches in order to avoid end effects. A cutting device, which has a cutting saw and a special attachment to hold the pills, was used to slice the pill into specimens of desired thickness. Two two-inch samples were obtained from each specimen. Because the saw uses water to keep the blade wet, the specimens were dried for one day at room temperature to achieve the natural moisture content. Before testing, the specimens were placed in the humidity chamber for at least two days to negate moisture effects in testing.

Gage points were attached to the samples using a steel template and vacuum pump setup and a strong adhesive. Four gage points were placed on each side of the specimens at distance of 19 mm (0.75 in.) from the center, along the vertical and horizontal axes. A steel plate that fits over the attached gage points was used to mark the loading axis with a marker. This helped placing the sample in the testing chamber assuring proper loading of the specimen.

Standard Superpave IDT tests were performed on all mixtures to determine resilient modulus, creep compliance, m-value, D_1, tensile strength, failure strain, fracture energy, and dissipated creep strain energy to failure. The tests were performed at 10°C. First, resilient modulus test was conducted on specimen. Thereafter, specimen was allowed to rest for 45 min, before creep test was conducted, in order to regain delayed elasticity. The indirect tensile strength test was performed after the creep test.

3.7.1 Superpave Indirect Test Results and Analysis

Superpave fracture testing was conducted on both mixes prepared for Gradation (1) and Gradation (2). Mixes were subjected to short-term oven aging. Even though, these porous mixtures with air voids around 21% does not hold moisture, the specimens were kept in dehumidifier for 48 hours before testing. The applied stress used for calculation of Energy ratio is 88.23 psi. Georgia PEM fracture test results were used as a reference to understand the mechanism of aggregate structure. Table 3-4 provides a summary of fracture test results of Georgia PEM and I-295 PFC project mixtures.

Figure 3-5 (a) through (i), show comparison of the Superpave IDT test results. The parameters presented include: Energy Ratio, Fracture Energy, Dissipated Creep Strain Energy, Failure Strain, Creep Compliance, Resilient Modulus, Strain Rate, Creep Rate and Tensile Strength between Georgia PEM and PFC mixtures. Although, Gradation (1) shows higher tensile strength, the Energy Ratio for Gradation (1) and Gradation (2) are 1.66 and 1.20 for Gradation (1) and Gradation (2) respectively. Because of reduction in surface area and increase in volume of water permeable pores not absorbing asphalt there should be increase in film thickness in Gradation (2) over Gradation (1). But, the reduction in optimum asphalt content counteracted this effect. Hence the creep response, which is a measure of the visco-elastic nature of asphalt, was about the same for both gradations. The creep compliance of Gradation (1) is 17.53 (1/Gpa), which is comparable with the creep compliance of Gradation (2) i.e. 18.07 (1/Gpa).

Table 3-4. Summary of Indirect Tensile Test performed on I-295 PFC mixtures

Sample	Property									Stress=	88.23 psi	
	Resilient Modulus (Gpa)	Creep compliance at 1000 seconds (1/Gpa)	Tensile Strength (Mpa)	Fracture Energy (kJ/m^3)	Failure Strain (10-6)	m-value	D_1	DCSE (kJ/m^3)	$e_0(10^{-6})$	Elastic E. (kJ/m^3)	Energy Ratio	Strain Rate per Unit stress
Georgia PEM	4.97	19.933	1.24	4.2	4383.2	0.74	8.35E-07	4.05	4133.73	0.154	1.95	1.1E-07
Gradation (1)	4.41	17.531	1.15	3.6	3940.1	0.66	1.2E-06	3.45	3679.32	0.150	1.67	7.9E-08
Gradation (2)	5.01	18.078	1.12	2.4	2742.3	0.71	8.9E-07	2.27	2518.79	0.125	1.21	8.6E-08

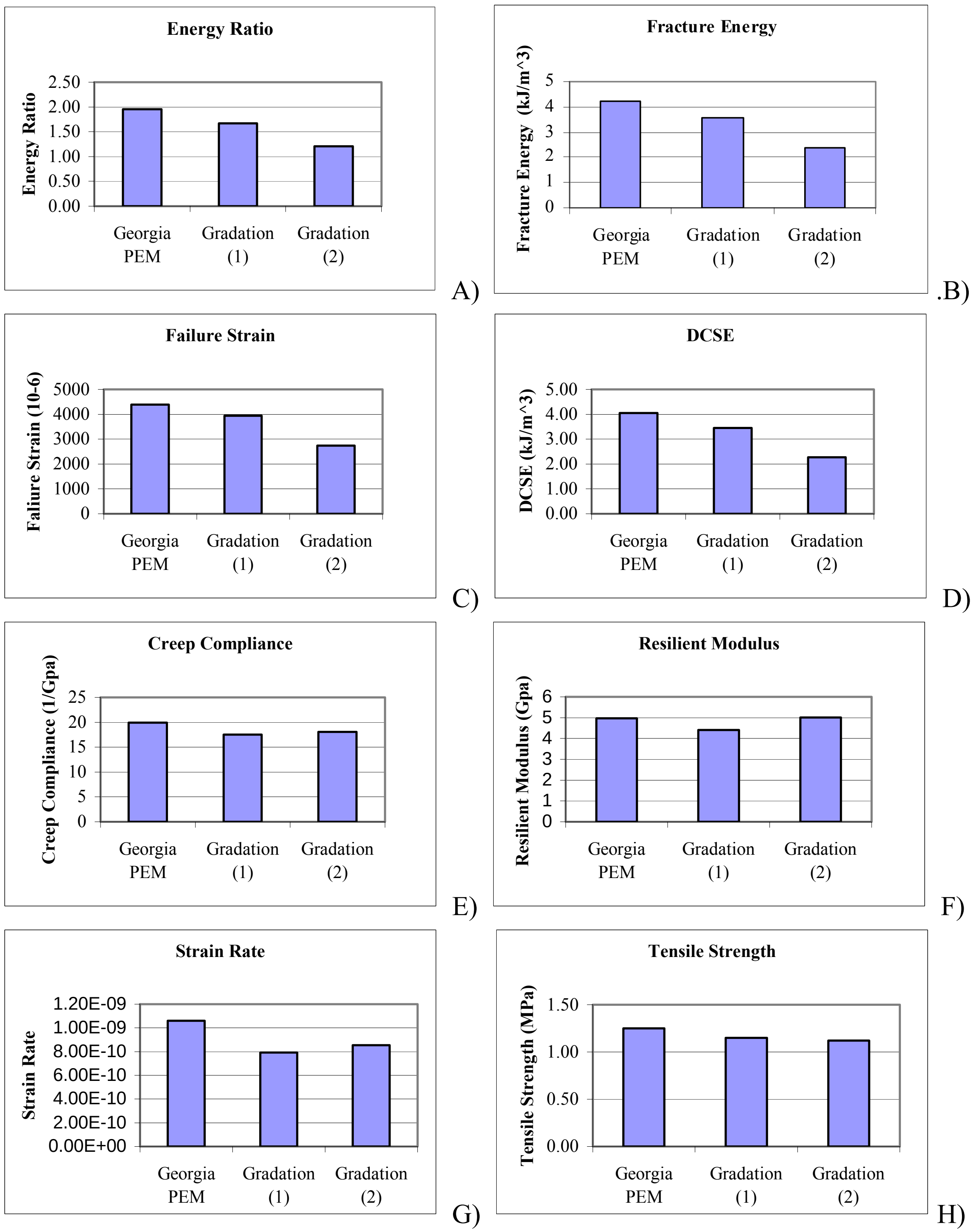
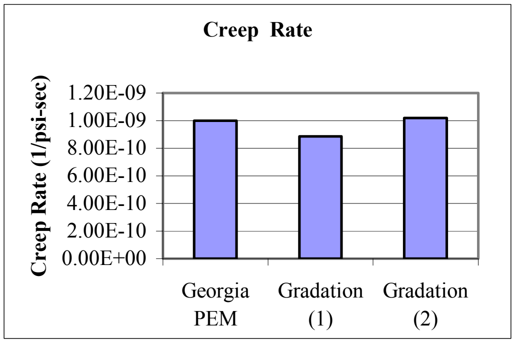


Figure 3-5. A)Energy Ratio, B) Failure Energy, C) Failure Strain , D) DCSE, E) Creep Compliance, F) Resilient Modulus, G) Strain Rate, H) Tensile Strength , I) Creep Rate



I)

Figure 3-5. Continued

Essentially, due to this reason, the resilient modulus of Gradation (1) and Gradation (2) are 4.41 Gpa and 5.01 Gpa, respectively, which are comparable magnitudes for the resilient modulus. The Georgia PEM had a creep compliance of 19.933 1/Gpa and a creep rate of 1x10^-7 1/psi-sec, which implies that the arrangement of aggregate structure is such that it is giving more room for mastic between coarse aggregate. This indicates the aggregate arrangement and interaction of coarse and fine aggregate in mixes plays an important role thus affecting the strength of Gradation (2) relative to Gradation (1).

3.8 Analysis of Fracture Result Based on Interstitial Volume and Aggregate Interaction

Ongoing work at the University of Florida has led to the establishment of a tentative gradation selection framework for the optimization of the fracture resistance of dense graded mixtures. Key concepts in this new proposed framework include the observation that enhanced cracking resistance can be obtained by ensuring that the aggregates in the course portion of the mixture gradation interact sufficiently amongst each other to allow for the effective transfer of forces through the course-aggregate portion of the mixture. This interaction of the course aggregate component should not reach down to the finer materials, so as to control mixture sensitivity. The material within the interstitial volume of the course aggregate portion also needs to be proportioned and designed so that an adequate Dissipated Creep Strain Energy (DCSE) limit is maintained, as well as providing enough flow and ductility to enhance the fracture resistance of the mixture. Too little interstitial material, or interstitial material with a low creep strain rate, will result in a brittle mixture. It is anticipated that these gradation concepts will be transferable to Georgia-PEM mixtures, thus allowing for the development of guidelines for the selection of gradations that optimize the resistance to cracking.

3.8.1 Determination of Porosity and Interstitial Volume

In the following, the portion of the coarse aggregate for each of the three mixtures will be evaluated, followed by a characterization of the interstitial volume component. First, the aggregate interaction curve needs to be defined:

The Aggregate Interaction Curve: Aggregate interaction curve is plot of points of interaction of aggregate size with its successive aggregate size. Following is equation used for calculating points of interaction: -

$$\%Retained\_Particle\_Interaction\_Point = \frac{(\%Retained\_at\_Sieve\_Size)*100}{(\%Retained\_at\_Succesive\_Sieve\_Size + (\%Retained\_at\_Sieve\_Size)} \quad (3.1)$$

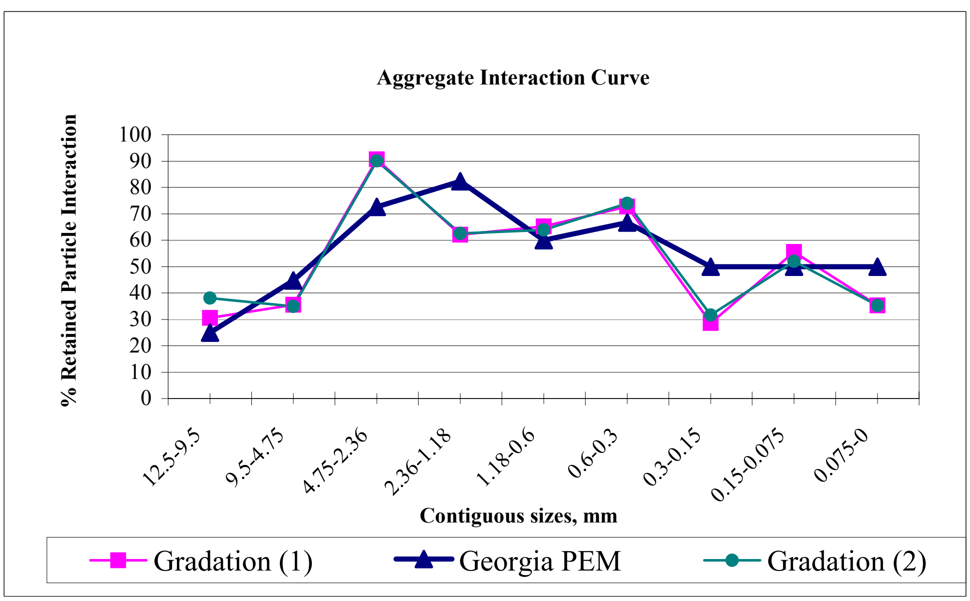


Figure 3-6. Curve showing interaction between contiguous aggregate sizes

Figure 3-6 shows the aggregate interaction curves for Georgia PEM and I-295 PFC projects. If the percent Retained Particle Interaction falls outside the range between 30% and 70% the aggregates in that size range are not interacting. Therefore, aggregate sizes below this break point are not interacting towards contribution of strength. These aggregate sizes are filling the cavities between coarse aggregate above the break points. The aggregate sizes below the break point along with asphalt are contributing to the Interstitial Volume. The range of aggregate sizes above this break point between 30%-70% is called the "Dominant Aggregate Size Range" (DASR).

Porosity: - Porosity for this DASR represents the actual porosity for the total mix. It is the ratio of summation of volume of air voids and effective asphalt in compacted mix, to volume of DASR and below.

$$Porosity = \frac{(Volume\_of\_Air\_Voids) + (Volume\_of\_Effective\_Asphalt)}{Volume\_of\_Aggregates\_within\_DASR\_and\_below\_DASR)} \quad (3.2)$$

Interstitial Volume: - Mastic, comprising aggregate sizes below break point, asphalt and air voids, forms the interstitial volume of compacted mixture. The interstitial volume is the ratio of mastic in specimen to the total volume of compacted mixture.

$$Interstitial\_Volume = \frac{(Volume\_of\_Mastic)}{Total\_Volume\_of\_Compacted\_Mixture} \quad (3.3)$$

The film thickness based on Interstitial Volume (T_{film}): Calculation of surface area is main issue of this method. As per the hypothesis discussed above, aggregates below the break point (i.e. aggregates within the interstitial volume) contain all of the effective asphalt volume, thus covering the coarse aggregate. The surface area (SA) of aggregates below the break point is calculated using surface area factors tabulated in Table 3-7 are calculated. As the absorption in granite is negligible, the total asphalt content is taken as effective asphalt content (V_{eff}) of the compacted mixture. Weight of aggregates (W_{agg}) in air is taken into account for calculating film thickness. Equation 3-1 denotes calculation of film thickness with in interstitial volume:

$$T_{film} = \frac{V_{eff} \times 1000}{SA \times W_{agg}} \quad (3.4)$$

Table 3-5. Surface area factors

Sieve Size	Percent Passing	Surface Area Factor		Surface Area	
		ft.2/lb.	m2/Kg	ft2/lb.	m2/Kg
11/2 in.(37.5mm)	100				
1 in. (25.0mm)	100				
3/4 in. (19.0mm)	100				
1/2 in. (12.5mm)	89				
3/8 in .(9.5mm)	62			2.0	0.41
No. 4 (4.75mm)	15	2	0.41	0.3	0.06
No. 8 (2.36mm)	10	4	0.82	0.4	0.08
No.16 (1.18mm)	7	8	1.64	0.6	0.12
No.30 (600um)	5	14	2.87	0.8	0.16
No.50 (300um)	5	30	6.14	1.5	0.30
No.100 (150um)	3	60	12.29	2.1	0.42
No.200 (75um)	2	160	32.77	3.5	0.73

Aggregate with in interstitial volume

Aggregate with in interstitial volume

3.8.2 Analysis and Conclusion

The DASR of Gradation (1) and the Georgia PEM is 9.5-4.75 mm, resulting in porosity of 46.29% and 49.51% respectively. Table 3-6 shows the porosity and interstitial volume of all the three JMFs. Due to the interaction of 12.5 mm aggregate size with successive aggregate size, the DASR of Gradation (2) is 12.5-4.75, resulting in a porosity of 42.71%. As porosity is below 50% the mixes should perform well in strength. Similarly, due to the relatively high interaction resulting in percent retained particle interaction of 44.77 percen (see Figure 3-6) in the critical 9.5-4.75 range, the Georgia PEM mixture is expected have a higher energy ratio than Gradation (1) and Gradation

(2), which had percent retained particle interaction of 35.55% and 34.85% respectively, as shown in Figure 3-6.

Table 3-7 shows the interstitial volume for the three mixtures studied. The interstitial volume of Gradation (1) and Gradation (2) is comparatively the same. Therefore due to the same amount of interstitial volume component, for both gradations, it is not surprising that both gradations result in a similar creep response.

Table 3-6. Porosity for all the dominant aggregate size ranges (DASR)

	9.5mm	4.75mm		2.36 mm		
Range	12.5-9.5	9.5-4.75	12.5-4.75	4.75-2.36	9.5-2.36	12.5-2.36
Gradation (1)	74.65	46.29	42.70	52.77	42.71	39.39
Georgia PEM	71.97	49.51	46.04	50.34	38.96	36.23
Gradation (2)	73.44	47.51	42.71	53.56	43.76	39.34

The Similarly, Georgia PEM results in a higher creep compliance and strain rate due to the higher interstitial volume. Due to this reason, the DCSE threshold for Gradation (1) and Gradation (1) is reduced to 2.27 KJ/m^3 and 3.45 KJ/m^3, respectively from 4.05 Kj/m^3 for the Georgia-PEM granite.

Table 3-7. Interstitial Volume for different JMFs

JMF	Interstitial Volume (%)	Film Thickness with in Interstitial Volume (Microns)
Gradation (1)	42.70	33.12
Georgia PEM	46.04	54.58
Gradation (2)	42.71	31.65

In summary, it is not possible to differentiate between the fracture performance of Gradation (1) and (2) at the low Superpave IDT test temperature of 10 C. Therefore, it was recommended that Gradation (1) be selected since the FDOT contractor had already obtained all necessary materials to run that mixture. The difference in fracture performance between Gradations (1) and (2) did not justify the selection of Gradation (2) over Gradation (1).

3.9 Verification of Locking Point of Selected Gradation for I-295 PFC Project

According to Vardhan (2004) the compaction curve follows a logarithmic trend. To identify the locking point, the rate of change of slope of compaction curve was used. The stage, at which the rate of change of compaction was insignificant, was essentially the point of maximum resistance to compaction. The locking point, i.e. 49, was identified as the point at which two gyrations at same gradient of slope were preceded by two gyrations at same gradient of slope. The gradient was taken up to four decimal places (as shown in Table 3-8 for PFC-Granite mixture, Gradation (1)).

Table 3-8. Locking Point Based on Gradient of Slope

Number of Gyration	Gradient of Slope
39	0.0022
40	0.0020
41	0.0020
42	0.0019
43	0.0018
44	0.0017
45	0.0016
46	0.0015
47	0.0015
48	0.0014
49 (LP)	0.0014
50	0.0013

3.10 Summary and Conclusion

The optimum asphalt content for Gradation (1) and Gradation (2) were determined at 6% and 5.9% respectively. The difference in fracture test parameters for both gradations is not significant. As shown in Table 3-7, the coarser portion in Gradation (2) was increased by 10% over that of Gradation (1), but the interstitial volume of both mixtures was unchanged at 42.70%. Therefore, the creep response of both mixtures is approximately the same. This implies that interaction between coarser and finer part of gradation and aggregate arrangement plays important role in optimizing fracture resistance.

Gradation (1) is recommended for construction of test section at I-295 even though both gradations are performing well, as the Gradation (1) is giving higher Energy Ratio, and there was simply no justification for selecting Gradation (2) over Gradation (1).

CHAPTER 4
A PROPOSED NEW FRACTURE TEST FOR ASPHALT MASTIC

4.1 Purpose and Need

Analysis of I-295 project mixture's fracture test results shows importance of interstitial volume in the fracture performance of mixtures. Mastic within the interstitial volume, which is comprised of asphalt and aggregates below the break point of the 'Aggregate Interaction Curve' likely has an impact on the creep and fracture response of mixtures. Therefore, it is important to be able to study the tensile strength and the fracture energy of the mastic component under direct tension loading conditions. This chapter presents the preliminary design of a new mastic fracture test.

4.2 Background

A device for studying fracture initiation and crack growth in mortar was developed by Mindess & Diamond (1980). This device was modified version of work developed by Subramanian et al (1978) for study of crack growth in ceramics. The specimen configuration used by Mindesss & Diamond (1980) was similar to the compact tension described in ASTM E399 (1978): Plain-Strain fracture toughness of Metallic Material. This device functions is such a way that cracking is induced under carefully controlled conditions, so that the details of slow crack growth may be observed at high magnification in the SEM at all stages in the cracking process. This device was constructed to permit the testing of wedge-loaded compact tension. Using this device, the process of cracking was observed in mortar specimens. It was found that the process of crack extension in mortars is very complicated: the crack is tortuous, there is some branch cracking, discontinuities in the cracks are observed, and there is some tearing away of small bits of material in some areas of cracking. The results suggest that the simple fracture mechanics models oversimplify the geometric features of the crack extension process.

4.3 Specimen and Test Device Design

The basic idea for this test is that tension can be induced by penetrating a wedge between two rollers that lie on steel rods that penetrate through the specimen. . Figure 4-1 shows specimen with bearings mounted on steel rods and wedge in loading direction

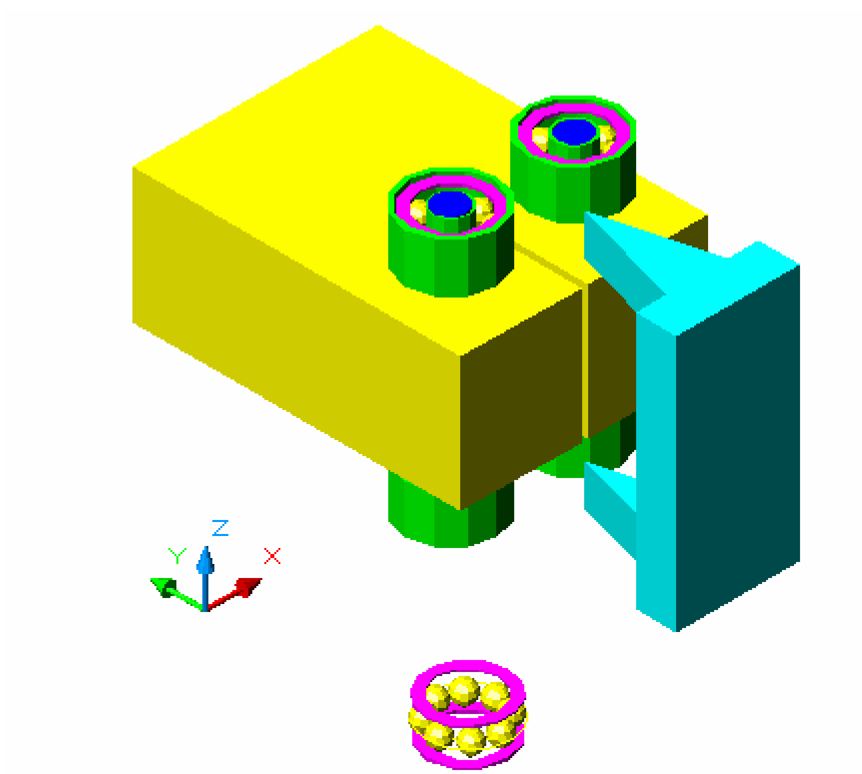


Figure 4-1. Model showing Specimen along with bearings fitted on steel rods and wedge in loading direction.

The specimen is 32 mm long, 24 mm wide and 13 mm thick with a 13 mm long and 0.6 mm wide notch at loading side of specimen.

Two 3.10 mm diameter steel rods on either side of notch were cast into specimen for applying load. Figure 4-2 and 4.3 show the geometry of the specimen. Steel rods are placed at 6 mm distance from outer edge of specimen. Steel bearings were fitted on steel rods to make friction less application of load on specimen through rods.

A notch is provided in the specimen to create a stress concentration and pre-define the path of cracking. Also, without the notch, there is a slight possibility that cracks initiate at the contact area between the steel rods and the mastic, rather than in the desired center portion of the test specimen. The steel rods are extended for 6.5 mm over the specimen surface at both the top and the bottom sides of the specimen in order to avoid contact of bearing roller and the driving wedge with the specimen

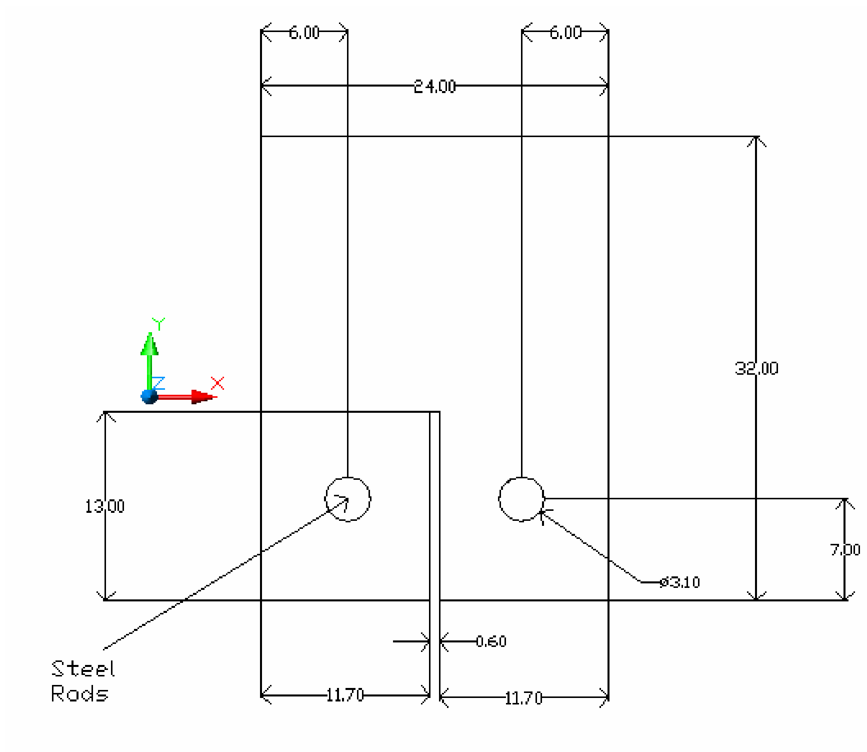


Figure 4-2. Plan view showing geometry of specimen

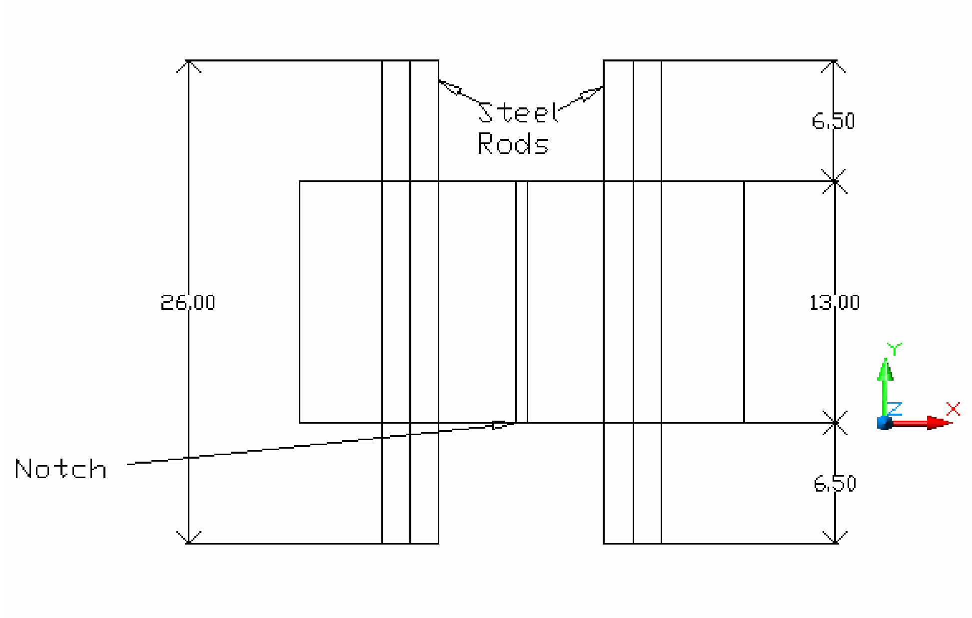


Figure 4-3. Front view showing geometry of specimen

The rate of loading is directly proportional to angle of wedge. As the wedge moves in forward direction, the distance between the bearings is increasing gradually, causing an increase in tension at the tip of the notch stress concentrator. Due to the roller bearings, there is no friction associated with the load transfer from the wedge to the steel rods. A mechanical system is required to propel the wedge in a forward direction. Mindess & Diamond (1980) developed a device, which uses a screw system for the driving of the wedge. Their test device is shown in Figure 4-4. It consists of a frame to support the specimen and the loading wedge; the turning of a screw advances the wedge, such that one complete rotation of the screw advances the wedge 0.64 mm. The screw feed is activated through a pulley system driven by a small electric motor and a gearbox with a reduction of 360:1. The motor is rated at 12 volts; by varying the voltage using a variable power supply, different rates of motion of the wedge can be achieved. The overall dimensions of the device are 82.6 mm long, 41.0 mm wide and 54.0 mm high.

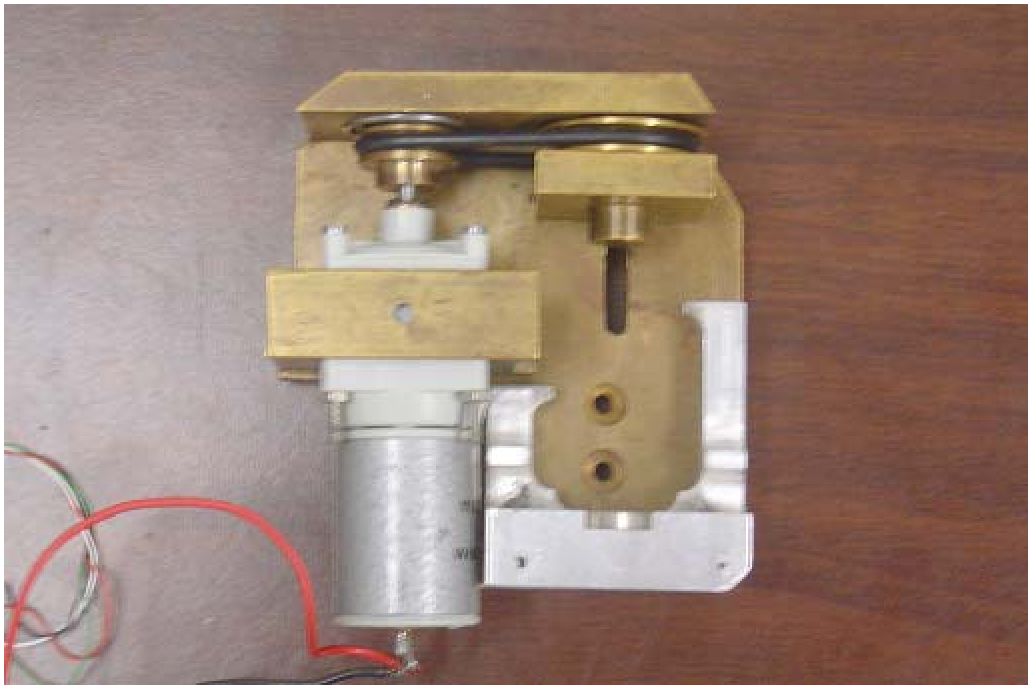


Figure 4-4. Testing Device used by Mindess & Diamond (1980) for SEM testing on cement mortar

4.4 Formulation of Tensile Force Transfer from Wedge to Specimen

The rotary action of an electrical motor moves a screw through pulley action with the help of a rubber belt. One complete rotation of this screw moves the wedge for 0.64 mm in direction towards notch. The load applied on the wedge can be measured by placing a load cell at the back of the specimen. As it can be assumed that the complete system is acting as a rigid body for the determination of the balance of external forces. The load (P) on the specimen applied by wedge, is measured by a load cell located at the end of the specimen.

In the following, the static analysis is presented for calculating horizontal thrust on the steel rod due to wedge loading:

Taking Moment at point B, shown in Figure 4-5, results in:

$$-(P \times \frac{x}{2}) + V_a \times x = 0 \tag{4.1}$$

Solving for V_a: -

$$V_a \times x = (P \times \frac{x}{2})$$

$$V_a = \frac{P}{2} \tag{4.2}$$

Where,

P = Applied load on wedge

V_a = Vertical component of resultant 'Ra'

x = Horizontal distance between bearings

As the wedge moves in the y-direction, there is a change of distance 'x'. In the above equation there is no affect of 'x'. The force components Va and Ha, shown in Figure 4-5 denote the the vertical and horizontal component of the reaction Ra. The angle θ in Equation 4-3 is the half angle of the wedge used to apply the load. Resolving forces in the horizontal direction for equilibrium at point A results in:

$$H_a = \cos\theta \times R_a \tag{4.3}$$

and $$V_a = \sin\theta \times R_a \tag{4.4}$$

Substituting Equation 4-2 into Equation 4-4, results in:

$$\sin\theta \times R_a = \frac{P}{2}$$

Hence, solving for Ra results in:

$$R_a = \frac{P}{2} \times \frac{1}{\sin\theta} \tag{4.5}$$

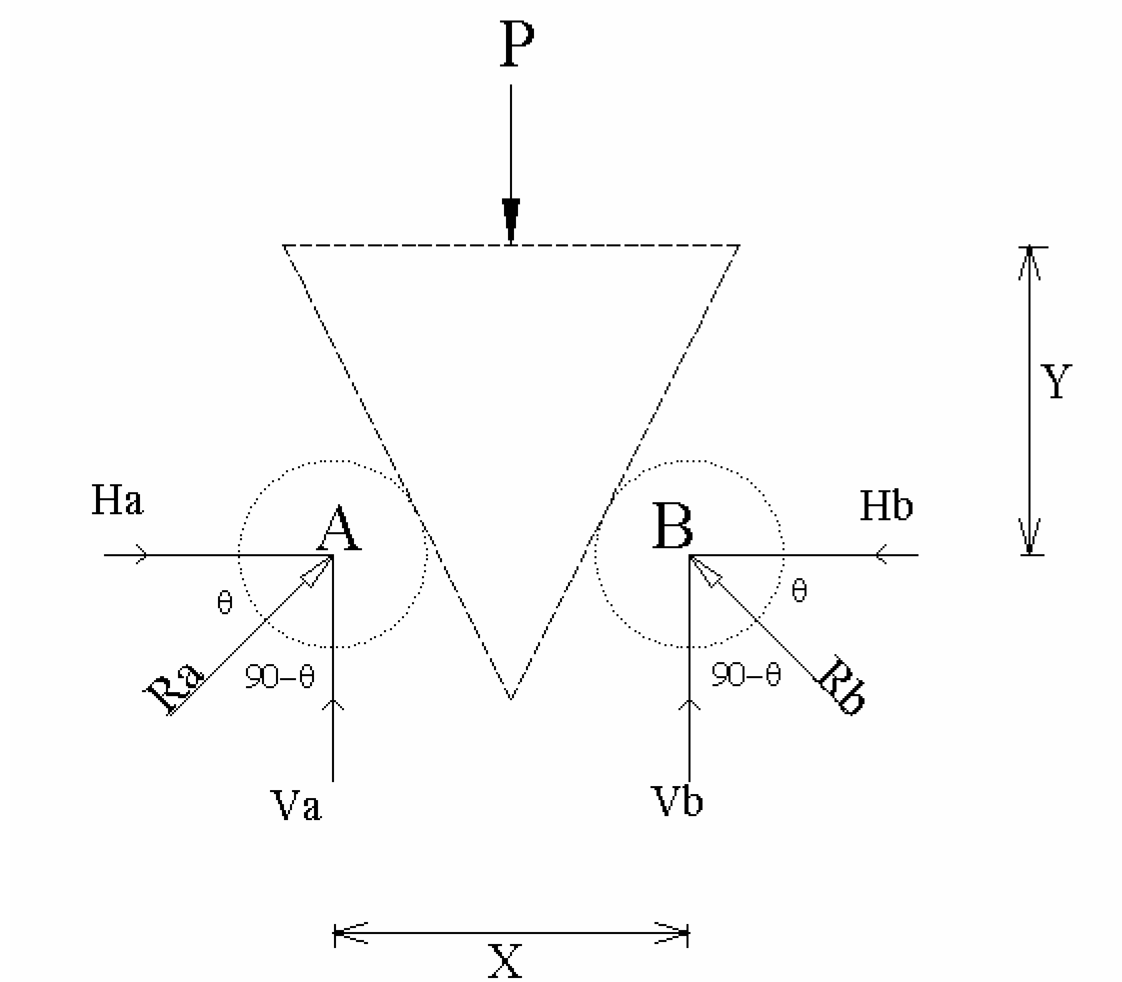


Figure 4-5. Static analysis of force transfer from Wedge to Steel rods (Wedge angle = 2xθ)

Finally, solving for H_a by substituting value of Ra from Equation 4-5 to 4.3 results in:

$$H_a = \cos\theta \times \frac{P}{2} \times \frac{1}{\sin\theta} \tag{4.6}$$

This means that the wedge angle (θ x 2) is inversely proportional to horizontal thrust H_a. Therefore, a small wedge angle will result in a high horizontal thrust, hence minimizing the effect of the vertical component of the vertical force 'P'. However, a small wedge angle requires a longer wedge to cause the same magnitude of horizontal force (tensile force) than a large angle wedge. As this specimen is designed for compact fracture testing on mastic, it may be desirable to keep the testing device as small as possible. Therefore, it is recommended to make the wedge angle at least 4-5 degrees. The final wedge designed for this study has has a wedge angle of 4.5º, resulting in:

$$H_a = 12.72 \times P \quad \text{(For } \theta = 2.25^{\circ}\text{)} \tag{4.7}$$

Hence horizontal thrust is approximately 12 times P.

4.5 Verification of Stress States within Loaded Specimen

In order to verify the stress concentration at the notch and to ensure that the sizing of the steel rods did not cause excessive bearing forces in the specimen, a finite element analysis using ADINA was performed.

Considering the line of symmetry along the centerline of the notch, the specimen is divided into two half, with only one half being analyzed with ADINA. Plain stress analysis is done on 2-D model of specimen in ADINA by dividing the total surface in to 15 sub surfaces, shown in Figure 4-6. The isotropic linear elastic material finite element analysis in ADINA is done on specimen. The critical section line is divided into 170 elements with last element to first element ratio 0.25. Figure 4-7 shows meshing of sub surfaces divided. The modulus of steel adopted is 19GPa with Poisson ratio of 0.3 for the finite element analysis. The modulus of asphalt mastic at temperature 10º C is taken 4 Gpa and poisons ratio was 0.18. Essentially, while executing plain stress finite element analyses in ADINA the stress obtain at any section are irrespective to modulus.

In order to keep the problem general, all results below are presented in terms of normalized loads. A horizontal thrust of 12.72 x P is applied at steel pin's center. In ADINA, the load P is taken as P = 1, for simplicity. Therefore the Ha = 12.72 and Va =

0.5 from Equation 4-4 and Equation 4-7. Figure 4-8 shows the exaggerated deformation of the 2-D model due to the effects of Ha and Va.

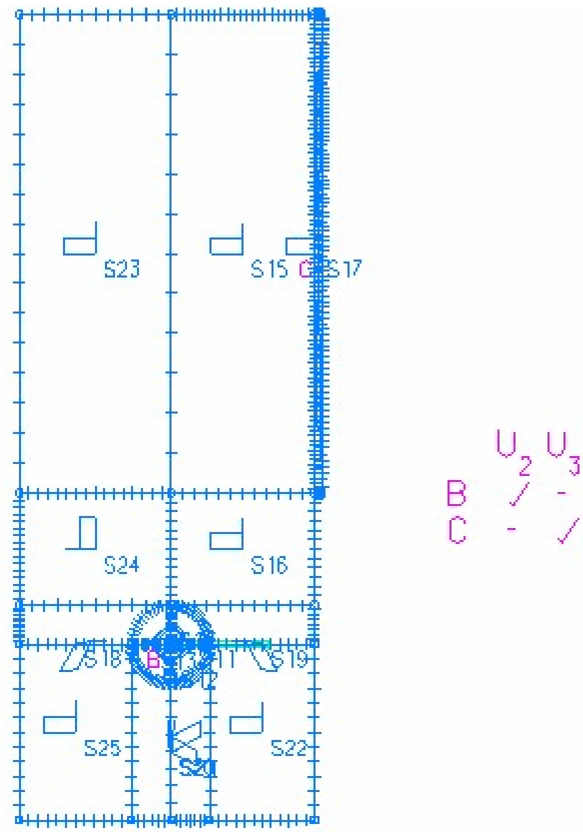


Figure 4-6. Specimen 2-D Model subdivided in to 15 surfaces

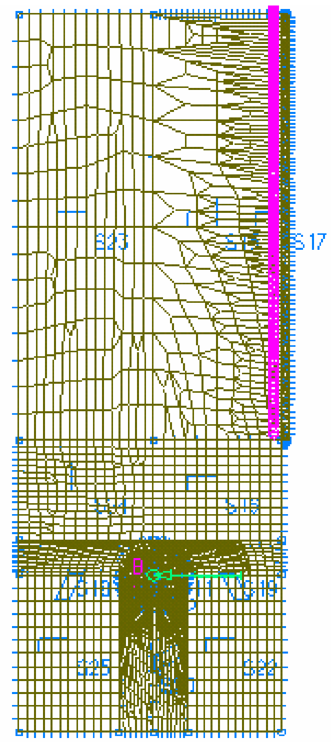


Figure 4-7. Meshing of 15 sub surface with critical model line divided into 175 elements.

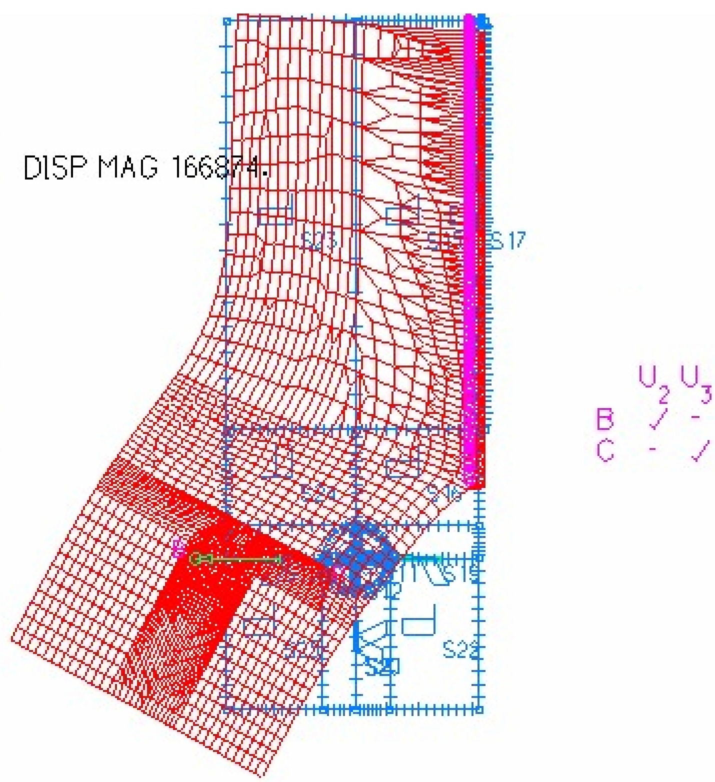


Figure 4-8. Deflection of Specimen’s 2-D Model subdivided.

The predicted stress (σyy) distribution along the centerline of the specimen is shown in Figure 4-9. As expected, the maximum stress is found at the tip of notch (σyy = 273 x P/ mm2), which confirms the stress concentration effects of the notch.

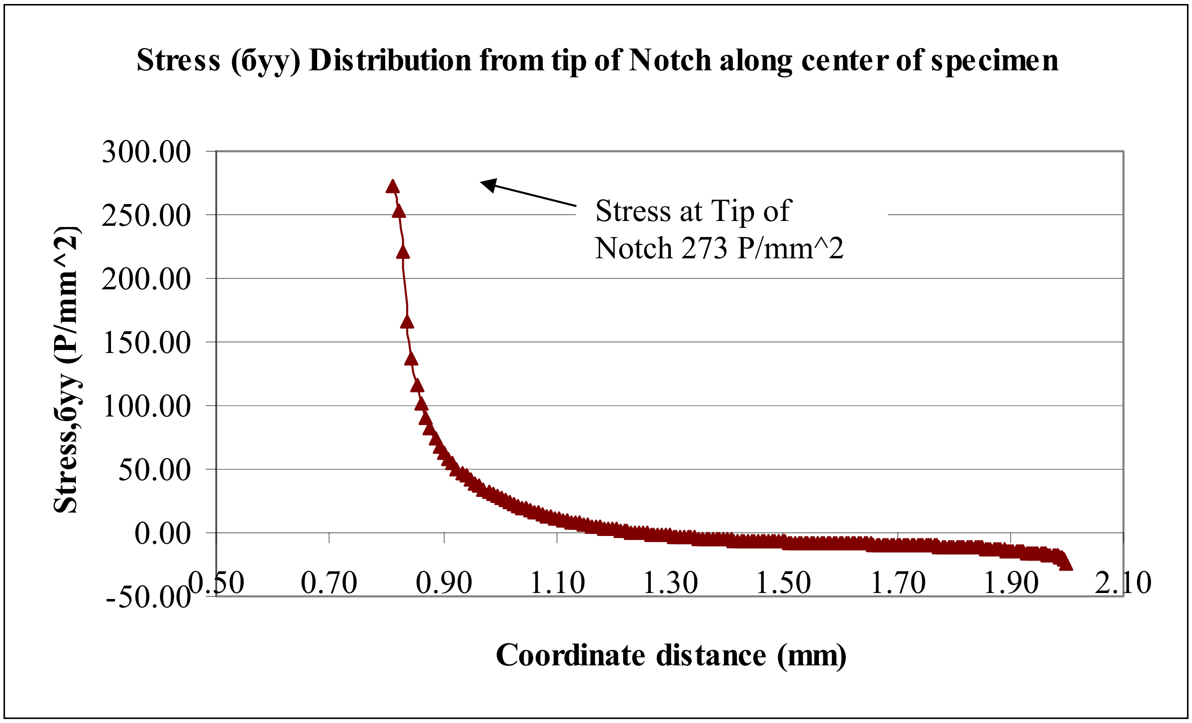


Figure 4-9. Stress distributions along centerline of specimen – Tensile stress is shown as positive.

Figure 4-10 shows the distribution of stresses (σyy) along the circumference of the steel pins at contact with the mastic. The normalized stress distribution is a function of the load “P” which is applied to the wedge. Part of this contact surface facing loading is in compression. As the steel pin is loaded, the surface behind the loading area develops tension. Due to the observed stresses at the tip of notch being substantially higher than stresses at the contact surface between the mastic and the steel pins, the initiation of crack is much more likely to be at the tip of the notch.

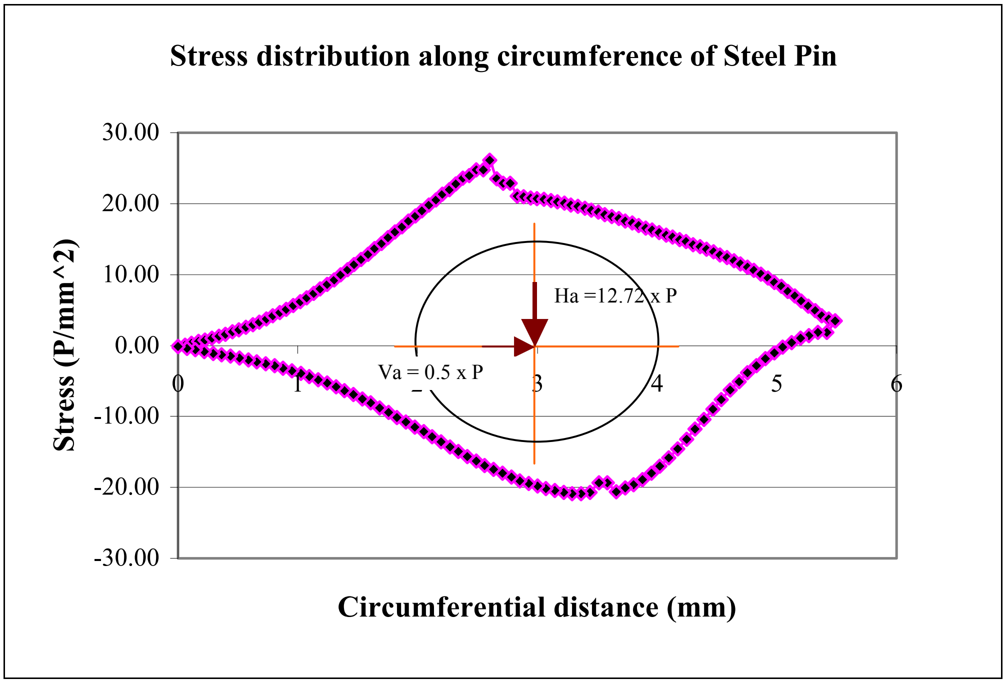


Figure 4-10. Stress distribution along circumference of steel pin

4.6 Sample Preparation Guidelines

Aggregates contributing to the interstitial volume below the break point in the aggregate interaction curve, dicussed previously in section 5.5.1, are mixed with total asphalt content of the I-295 PFC mixture for preparing the mastic.

Table 4-1 shows the proportion of the aggregate gradation below the breakpoint for the I-295 PFC mixture that is mixed with the 6 percent asphalt by weight of the total mixture (see Chapter 5 for mixture design details).

Table 4-1. Part of fine aggregates to be mixed with total asphalt content (6%) of I-295 PFC project

Sieve Size
11/2 in. (37.5mm)
1 in. (25.0mm)
3/4 in. (19.0mm)
1/2 in. (12.5mm)
3/8 in .(9.5mm)
No. 4 (4.75mm)
No. 8 (2.36mm)
No.16 (1.18mm)
No.30 (600um)
No.50 (300um)
No.100 (150um)
No.200 (75um)

Aggregate within interstitial volume

Aggregate within interstitial volume

The aggregates and asphalt binder are heated to 330º F ± 3.5 º F (165º C ± 3.5ºF) for 2 hours before mixing. The aggregates are mixed with the asphalt binder using equipment as specified in AASHTO T-209-99 (2004) for mixing. The prepared mastic is molded into the desired shape, using a mold shown in Figure 4-11. Figure 4-12 shows geometry of main base plate to which side plates are attached. As the asphalt tends to bulge inside after cooling at the surface in contact with air, it is recommended that the mastic should be filled to a level slightly above the mold surface. The mold in Figure 4-10 is designed to provide a flat surface for trimming the excess mastic. First fit the steel pins and then assemble the mold into the groves of the bottom base plate and notch plate. Then, the top base plate is fitted on top and all bolts are screwed into position for a tight mold.

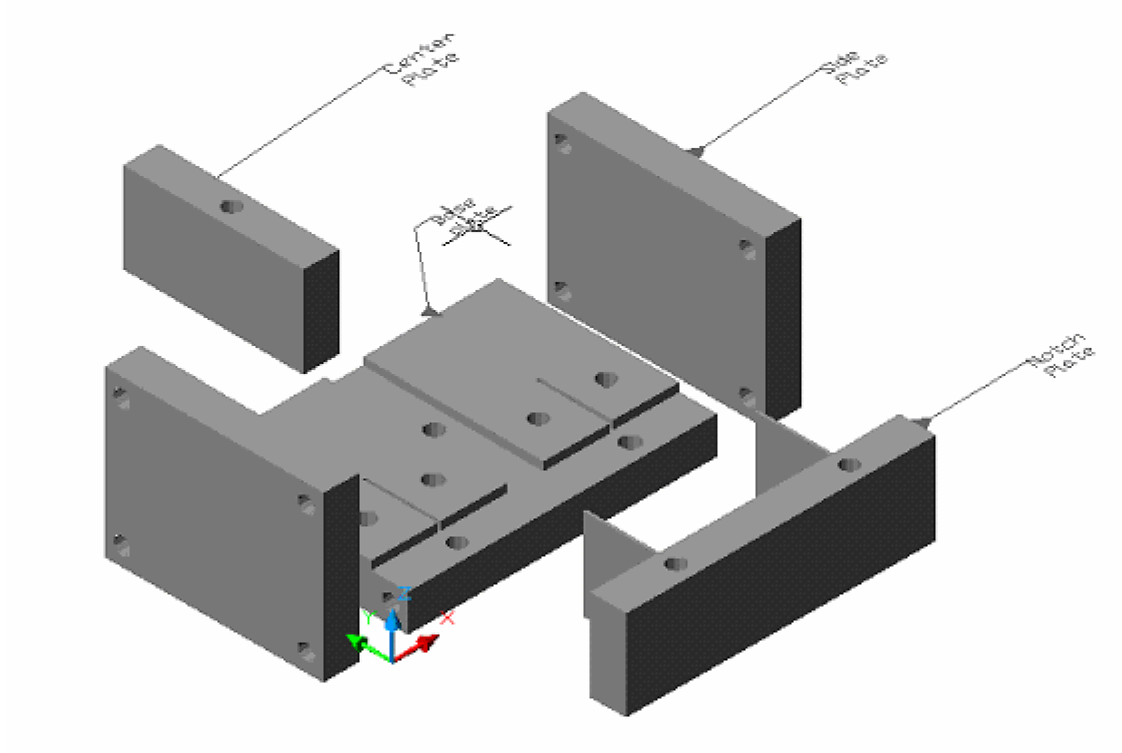


Figure 4-11. Mold for preparing specimen for Fracture and SEM testing

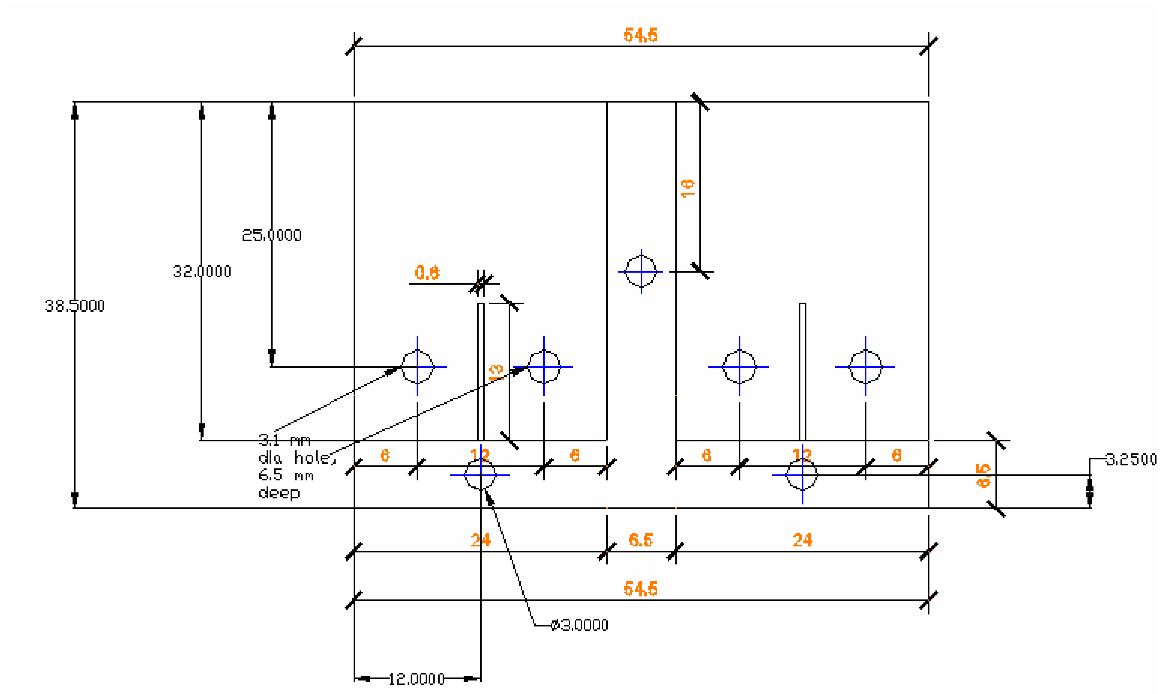


Figure 4-12. Geometry of main base plate to which side plates are attached

4.7 Recommendation for Further Development

Further work needs to be done for developing a test device and deformation measurement system. The following recommendations should be considered in further development:

- A trial test specimen needs to be molded using the mold shown in Figure 4-11 to check workability.
- A wedge angle within the range of 4% to 5% to obtain maximum horizontal thrust with optimum wedge length, is recommended.

CHAPTER 5
PERFORMANCE TEST DATABASE (PTD)

5.1 Preface

This program was developed to store and analyze data from performance testing of mixtures (Performance Test Database: PTD). The program is entirely interactive. It is set up for easy navigation from one part of the program to another. The functionalities included are: 1) data input, 2) data extraction, 3) data export to database, 4) data analysis, and 5) report generation. All the instructions for using the tutorial are available in the help menu and user's manual in order to work with the program's interface.

Program details in this manual are provided for system administrators or programmers that want to understand its architecture and design, to extend or modify the PTD.

5.1.1 Package Information

This package for the PTD contains the following:

a) The User's Manual.

b) One set of CDs labeled PTD

The User's Manual contains information on how to operate the program and how to execute the commands. It also describes terminology behind programming and provides details of algorithms developed for specific task.

5.1.2 System Requirements

The minimum requirements for successfully executing the PTD program are:

a) Windows2000/Me/Xp or later.

b) 64 MB RAM.

c) Hard disk with 2.5 MB of free space.

The PTD program may be installed either onto a hard-disk system or onto a network computer system, and can also be easily uninstalled by using the provided installation software.

5.1.3 Supported Output Format Requirement

The P.T.D. supports multiple report output formats. All reports are generated in a native Access format which is transformed into other output formats by Visual Basic commands. The following formats are supported :

Print

This output format requires a computer system connected to a printer. This format uses default printer settings. The report is printed directly using this option.

Rich text format

This format creates word file with a rich text format extension (.rtf) at a user specified directory. Image characters of the report are not retained in this output format.

Email

This output format provides the means to export a report to other systems through email. An automated function is used to send a report as an attachment to an email. This option requires that the Microsoft Outlook Sendmail™ be activated. There is an option to choose the format of the report from the Rich text format, Snapshot format, Microsoft Excel Format, HTML, and MS-Dos text format.

The rich text , Snapshot and HTML formats are preferred as orignal alignment is maintained in the extracted data.

5.2 Program Overview

The Superpave Indirect Tensile Test at Low Temperatures (ITLT) computer program can be used to analyze test data obtained from the Superpave Indirect Tensile Test. The ITLT program generates five text files, which have the following extensions: - .MRO, .FAM, .OUT, .IN an .STR files. For input into the PTD database, the Data from these text files need to be extracted, analyzed and stored for a future reference. This database is designed with an aim to not only store performance test data, but also to keep track of the findings and analysis of different mix design and performance test on various materials. Extracted data from text files is reformatted in order to make storage easier in the database. The included search engine makes allows the user to customize desired queries of data and analysis results. The data and analysis results categorized according to the search criteria are then reported through report generation.

Visual basic for Excel Applications was used to automate the process of data extraction and formatting in a tabular form. The flowchart in Figure 5-1 provides a complete overview on the flow of data from raw data files to storage, analysis, and final report generation.

All the test readings from text files are inputted into an Excel file. There is interface, which is developed in visual basic that has categorized option for each set of test data for extracting data from text file.

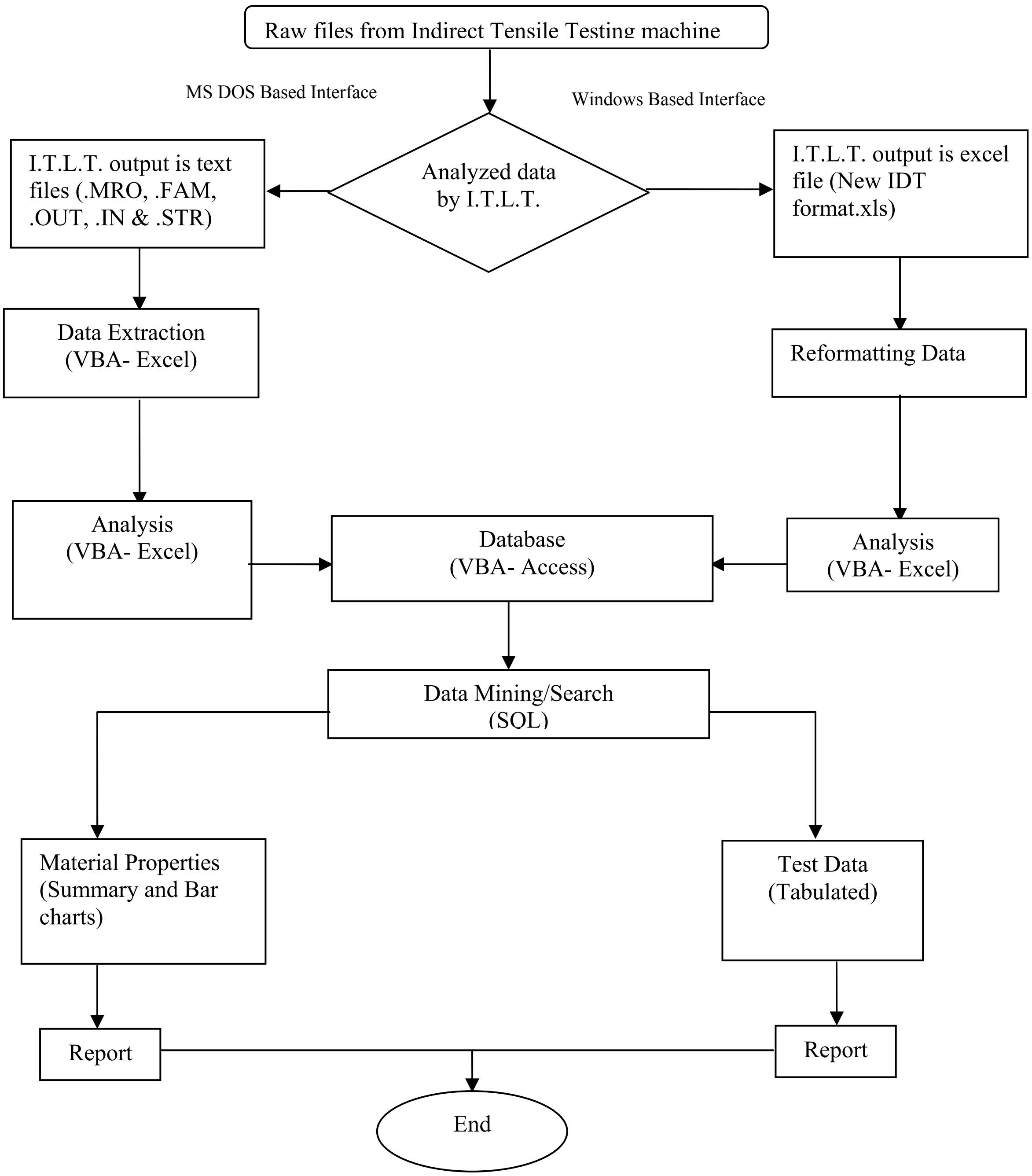


Figure 5-1. Flow chart showing extraction and input sequence of Indirect Tensile Test Data

For analysis of this data there is a customized button with caption 'Analyze'. Once this data is extracted visual basic pop-up form comes up asking for applied stress to be used for calculating energy ratio, after which the calculation of DCSE, Elastic Energy,

Energy ratio and Strain rate are performed. These raw and analyzed data are exported into the database developed in Microsoft Access. The Structural Query Language (SQL) is used to develop search criteria. Search results can be retained in desired output format through a “built-in” visual basic environment.

5.2.1 Database Storage Outline

Data stored in the database are organized for ease of retrieval. Following is the list of data and mixture properties that the database stores:-

1. Gradation
2. Volumetrics (Maximum specific gravtiy, Bulk specific gravity, Air voids, Absorbed asphalt, effective asphalt content, Voids in meneral aggregates, Voids filled with asphalt, N-design, Bulk specific gravity of aggregates)
3. Mixture properties:- Mixture type (Open graded Friction Course, Dense graded fine, or dense graded coarse) Aggregate Type, Mixture Source, Binder Type, Binder content and Miscelleanous
4. Superpave Indirect Tensile test data
    a. Resilient Modulus test data
    b. Creep Test data
    c. Strength test data
5. Superpave Indirect Test Analyzed data :- Resilient modulus, Creep compliance, Tensile strain, Fracture energy, Faliure strain, D1, m-value, Dessipated creep strain energy, Elastic energy, Energy ratio.
6. Compex Modulus test and analyzed data: Stress amplitude, Strain amplitude, Dynamic modulus, Elastic modulus, Phase angle. The flow chart

in Figure 5-2 depicts a brief sketch of the data flow in the program up to the report generation.

7. APA Ruth depth

5.2.2 Software Coding Architecture and Program Flow

The software broadly covers to basic types of data extraction, analysis and storage first is from Indirect Tensile Test and second is Complex Modulus Test Data. Appendix C gives complete coding written to generate:

Input template

Macros written in Excel for specific functions are called in Main Macro of the module to attain main task. Visual Basic Form components are assigned with a command to execute these modules. The data is analyzed based on extracted data values and external input of applied stress is required to complete variables values in equations with in Macros.

A common macro, which is programmed to change the 'Visual Basic Form Components' features on completion of specific tasks, is assigned to all modules. If any changes or extension is required to the main code, this macro does not need any changes. These macrocodes are specified in Appendix C.

Database

Data transfer is automated using Microsoft Clipboard Unicode text format. Each line ends with a carriage return/linefeed (CR-LF) combination. A null character signals the end of the data. Data entered on screen template is automatically transferred to tables that are contented/related with other table containing their identity properties. An Access-VBA code collects all fragmented query parameters and then returns a unified SQL (Structural Query Language) statement, which generates the master query. This master query is the source for the main search result template.

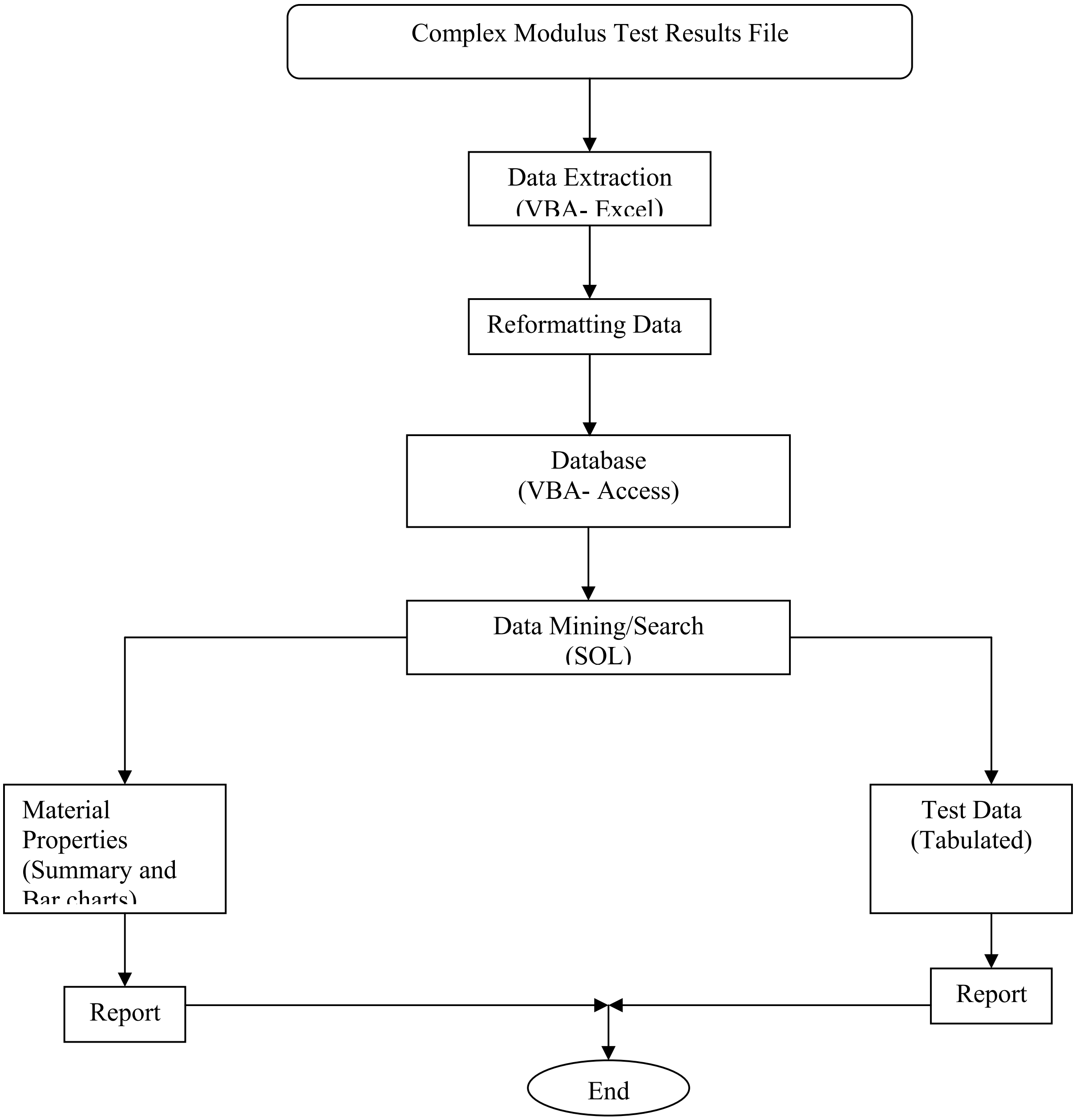


Figure 5-2. Flow chart showing data input of Complex Modulus test

5.3 Installation

The installation program copies the "Performance Test Database" software and other database supporting files into a directory. The default directory is c:\Program

Files\Database. The target drive or directory name can be changed during the installation as desired. The installation also creates a Windows Program Group called "PTD.exe"

Installation procedure:

1) Insert the CD into the CD drive.
2) Double click setup file 'setup.msi'.
3) On the installation screen, modify the drive or directory name if desired, and then click NEXT. Figure 5-3 shows the installation screen.
4) Once installation is completed, click CLOSE for closing installation program.
5) Same setup file can be used for uninstalling or repairing the program.

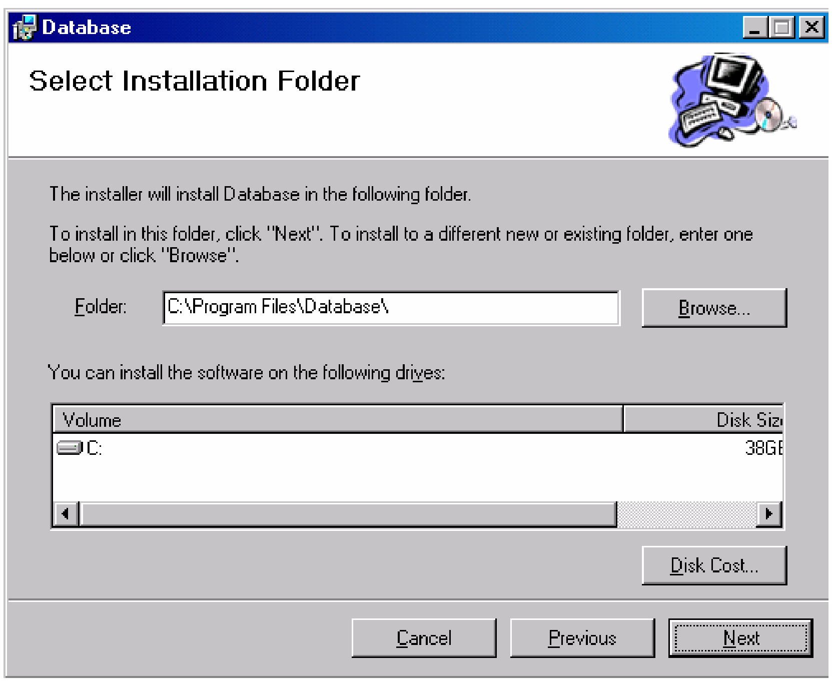
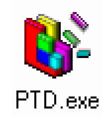


Figure 5-3. Installation Screen

5.4 User's Manual

5.4.1 Interaction to All Interfaces of Database

The user interface for the P.T.D. is browser based. Double click PTD icon on desktop or in start menu to run program.



As shown in Figure 5-1, on screen a Main Interaction form pop up. This form is means to direct user towards different part of PTD. Select the type of activity need to be carried out.

Step 1: - For data entry, select first option 'Open Input Template for data entry in database' and then press OPEN button.

Step 2: -Similarly for data search and report generation in different format, select second option 'Data Search and Report generation' and then press OPEN button.

Step 3: - To end program press QUIT button. Browser

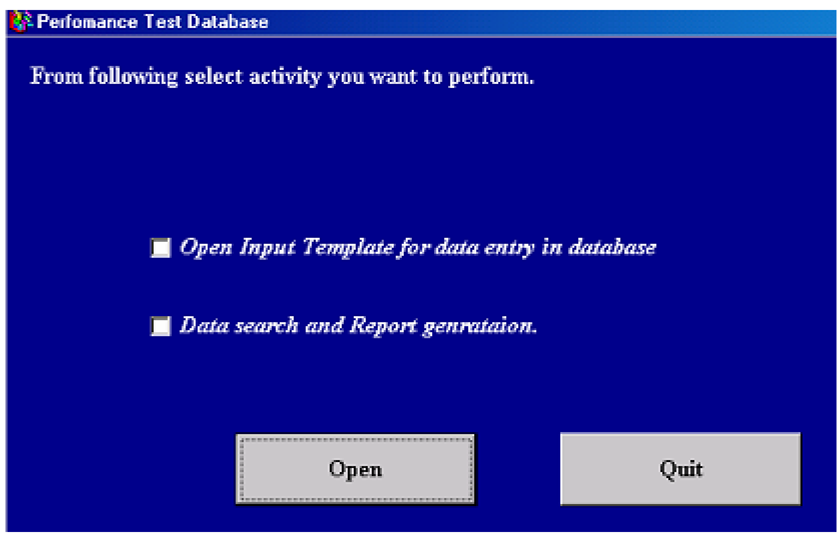


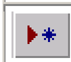
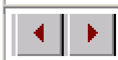
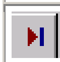
Figure 5-4. Main Interaction Template

5.4.2 Button Function

The most current functions corresponding to buttons is described as follows: -

Table 5-1 shows common button and there corresponding functions. All the menus, buttons, etc. conform as much as possible to the standards of Microsoft Windows Common User Access (CUA).

Table 5-1. Buttons and there corresponding function

Button	Function
Open	To open an activity, define by an option selected.
Quit	To quit program.
Input	To extract data from text file as indicated and populate table.
Copy	To copy data from table to the clipboard as indicated.
Reset	Erase the data from table and reset all control properties.
Main Menu	To close that template and switch to main menu template.
Help	To access user's manual.
	To add set of data record to database.
	To delete set of data record from database
	To navigate previous or next record.
	To navigate last record.
	End application.
Search	To search data records for selected query.
Print Report	To export search result in desired output format.

5.4.3 Data Entry

Output files from I.T.L.T software are text files or Excel files. Extraction and analysis of data from the both this formats is similar. Following are the steps for inputting data from MS DOS base interface or Windows Base Interface:

Step 1: - Once you choose data entry option two templates are opened. First is 'Performance Test Database Main Menu' (refer Fig) and 'Input Template options' (refer Figure 5-5). Select the type of format of your specimen test file, whether it is MS-DOS base text files or excel file. Desired option continues to template design for specified kind of format. Both template works in same manner except the input interfaces are designed to incorporate the different files from I.T.L.T software.

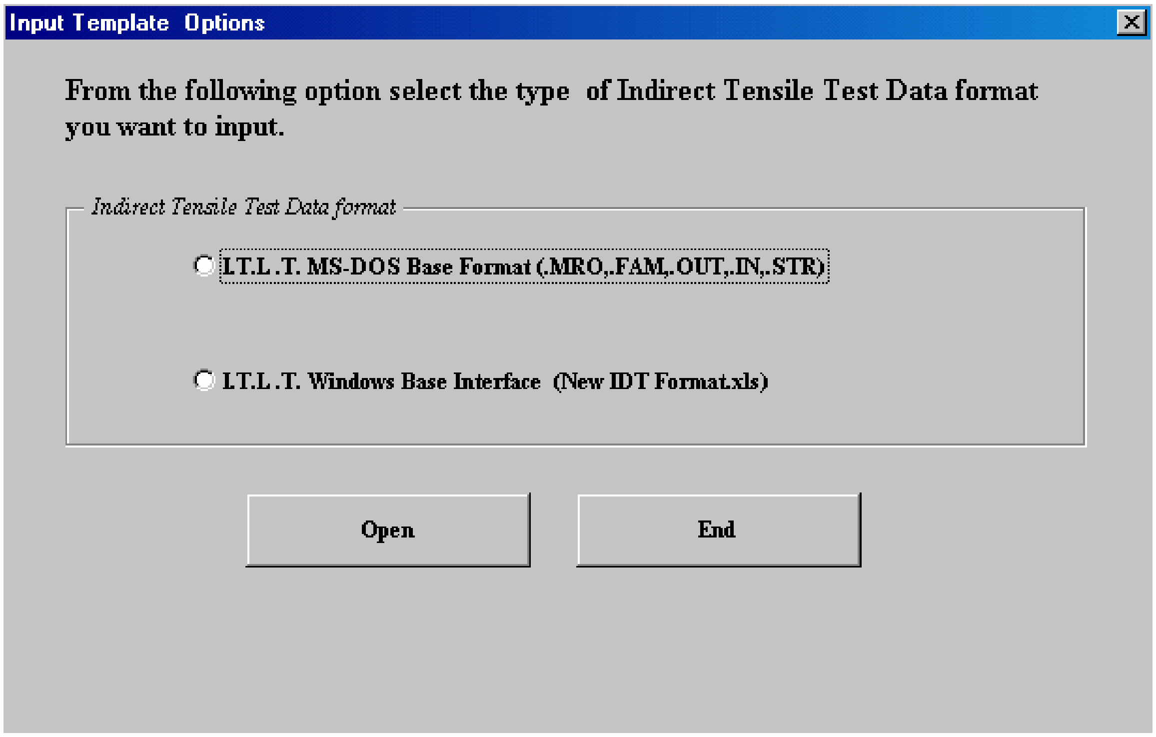


Figure 5-5. Input template options

Step 2: - As shown in Figure 5-6, page tab are provided for navigating different parts of program. Frame tags define the type of text file name and sub frame tags denote the test reading whose input is assigned to underneath button. You can access this user manual while using the program by clicking help button.

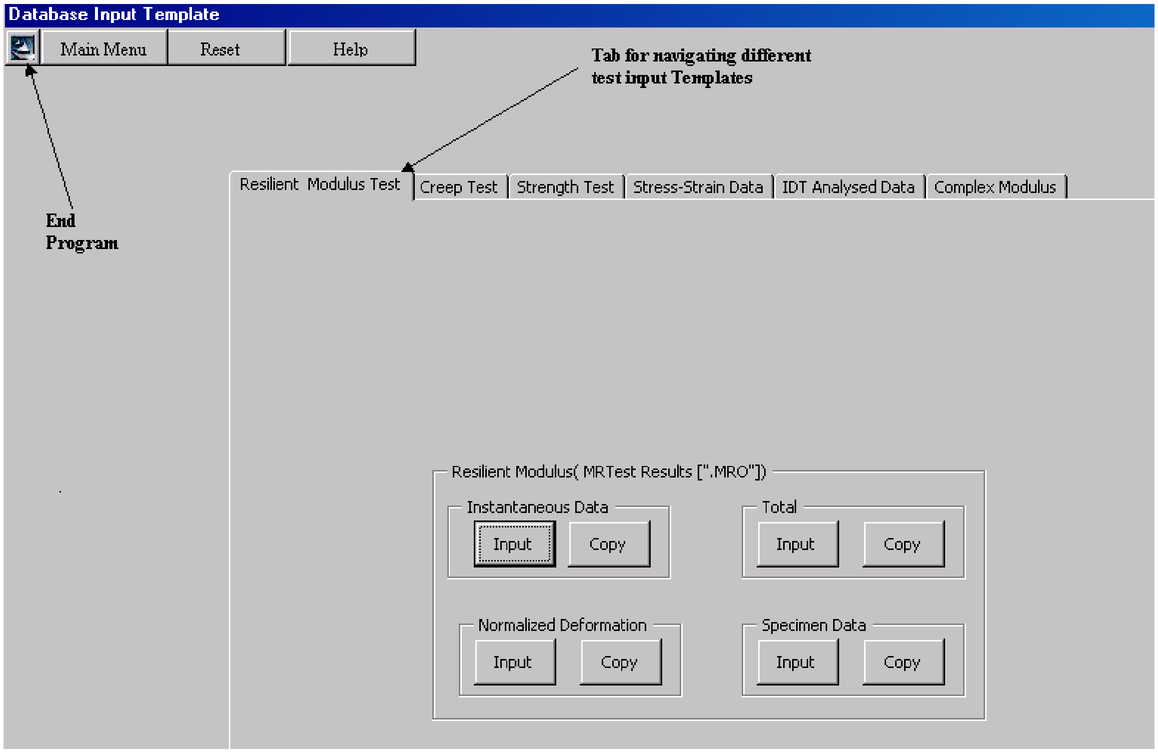


Figure 5-6. MS-DOS Base text file input template

Step 3: - Once input button is pressed a dialog box is opened, for navigating your computer system, which is designed to open only assigned file type. In current example assigned file type is .MRO file. This provides user ease of searching file at his system. Refer Figure 5-4 for details.

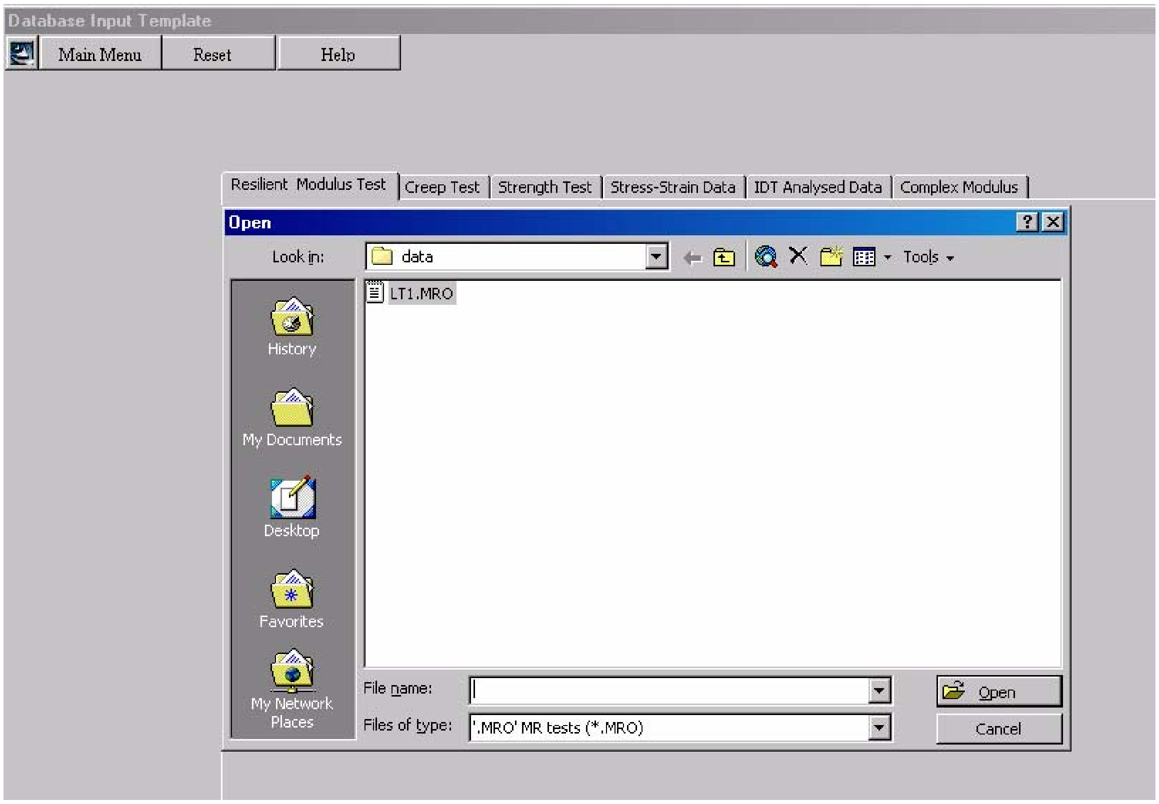


Figure 5-7. Input dialog box

Step 4: - Select file and then press open to continue. After the input process is completed a dialog box pops up (Figure 5-8) asking whether you want to save changes in opened file. Through out this program opt ‘No’ for such kind of dialog box. As we don’t want to change the main source files. Status of any activity is recorded and shown by changing color of button assigned. Sometimes while using this program you will face a dialog box as shown in Figure 5-6, where it asks whether to save clipboard contents. Always opt ‘Yes’ for such decision boxes.

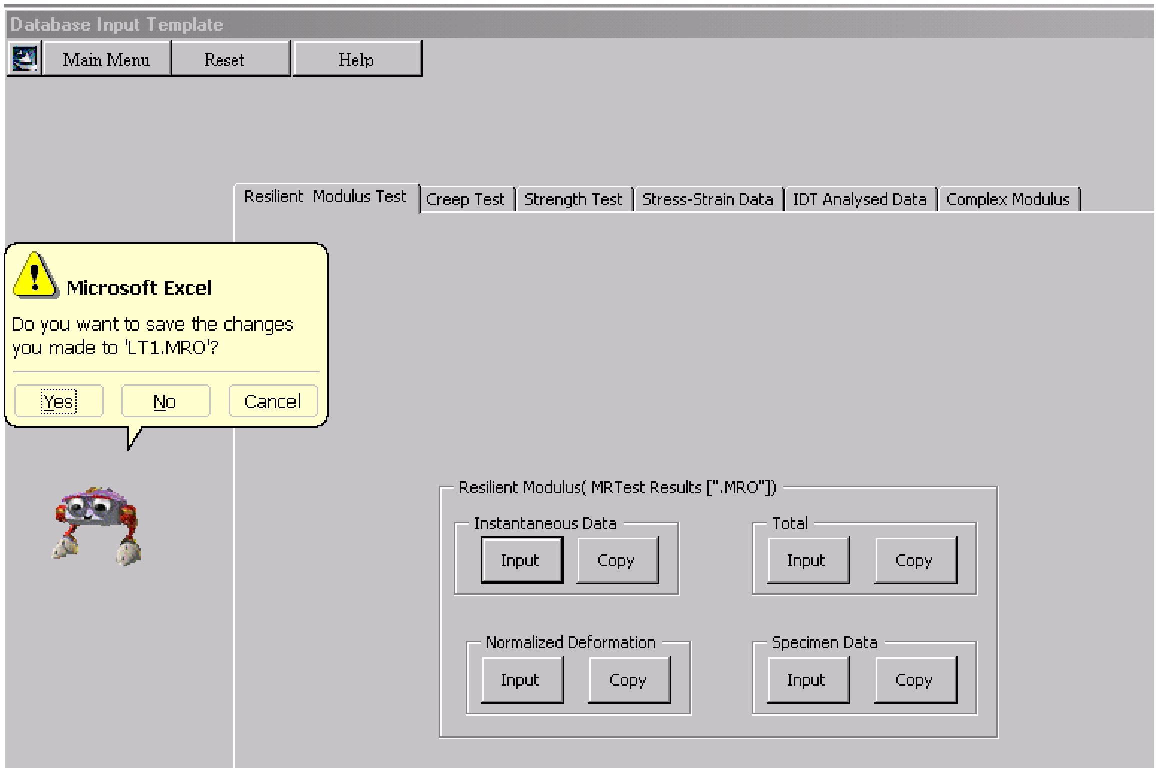


Figure 5-8. Save changes dialog box

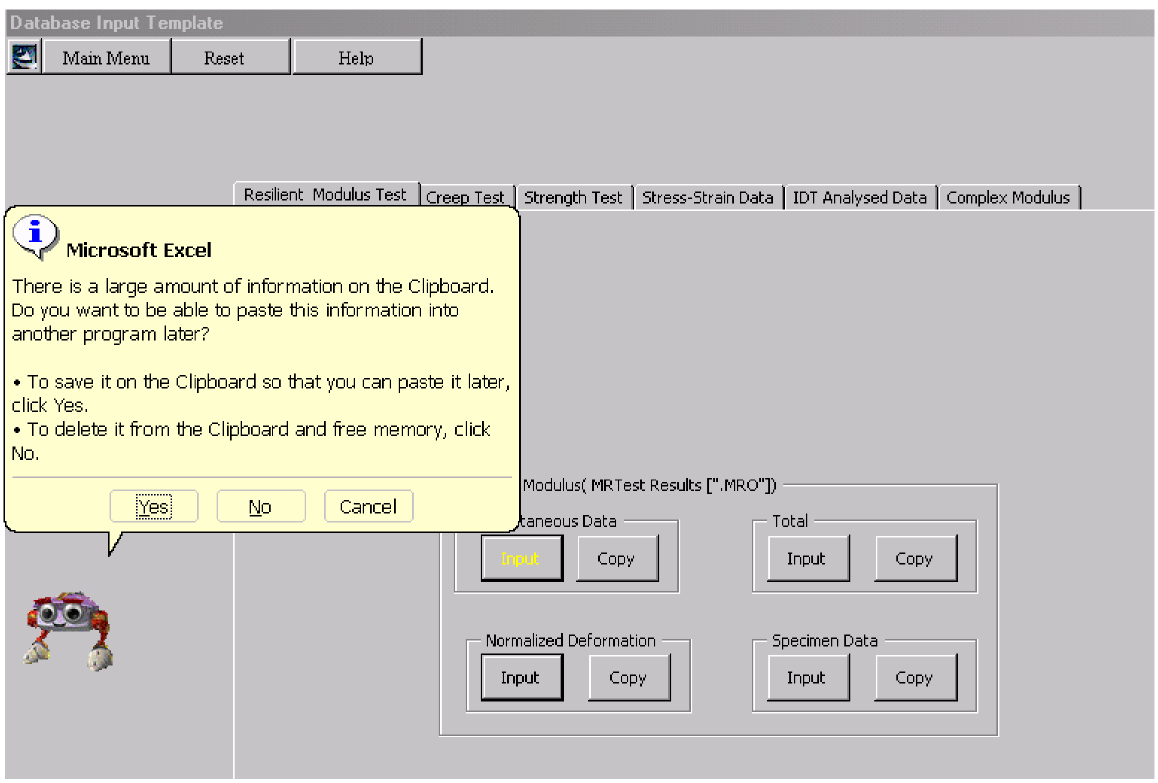


Figure 5-9. Decision Box for clipboard changes.

Step 5: - For extracting data from different text files same procedure needs to be followed. For analyzing Indirect Tensile Test data navigate to 'IDT Analyzed Data' using page tabs, then press analyze button which initiates an input box for applied tensile stress, as shown in Figure 5-10. The applied tensile stress is taken at the bottom of the AC layer and is very much dependent on the stiffness of the AC layer.

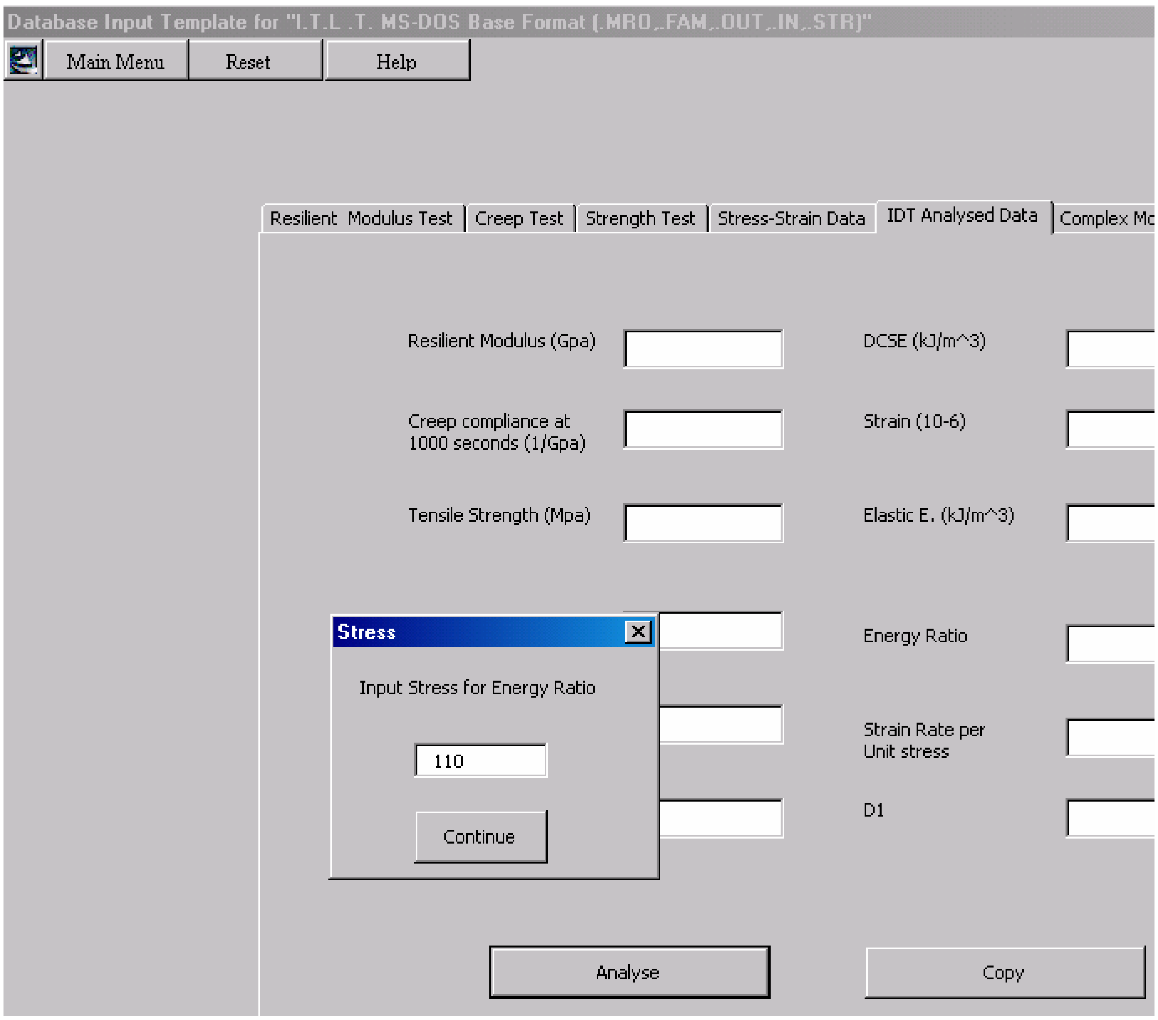


Figure 5-10. Applied tensile stress input box

5.4.4 Navigation through Input Templates and Database

Once you have inputted data for all tests, these analyzed and tabulated data need to be transferred to database. For navigation between database and inputted template press key F10 and then Windows key on Key Pad. For activating 'Database Input Mask' you have to click 'Input New Data' button at Database main menu (Ref Figure .

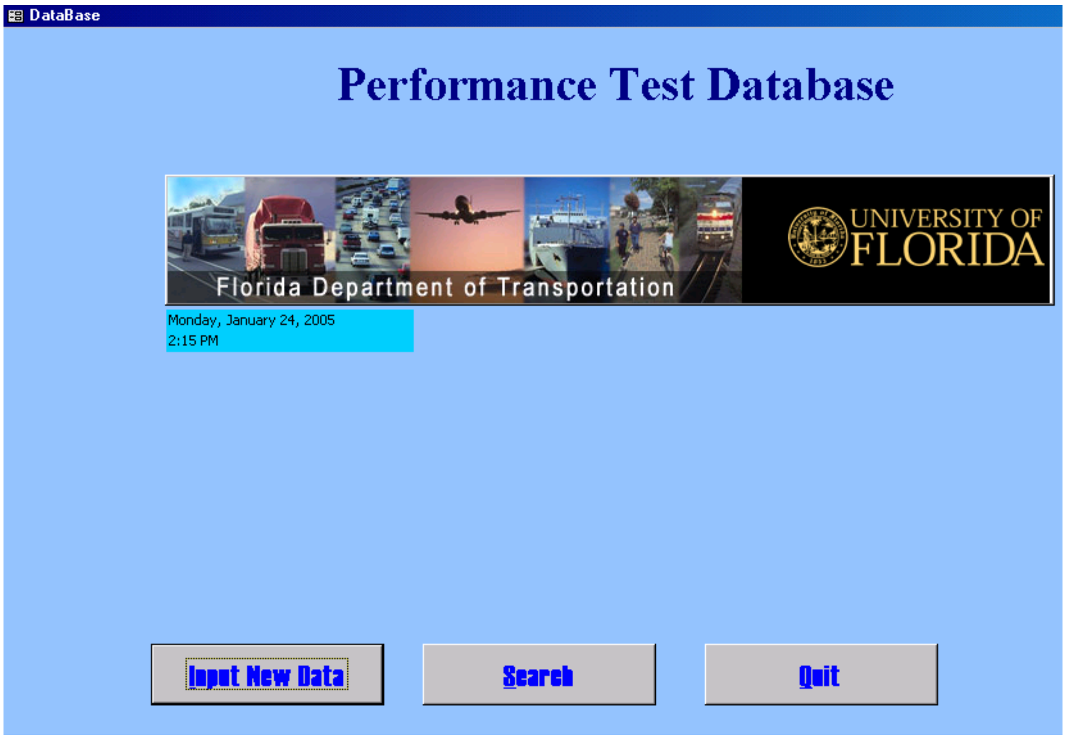


Figure 5-11. Database Main Menu

5.4.5 Data transfer to Database

Input mask (Figure 5-12) contains a set of field, which has to be entered manually. Data for particular mixture, which need to be entered in those fields, can be easily found on logbook. Use Main Menu button for closing input mask and return to database main menu.

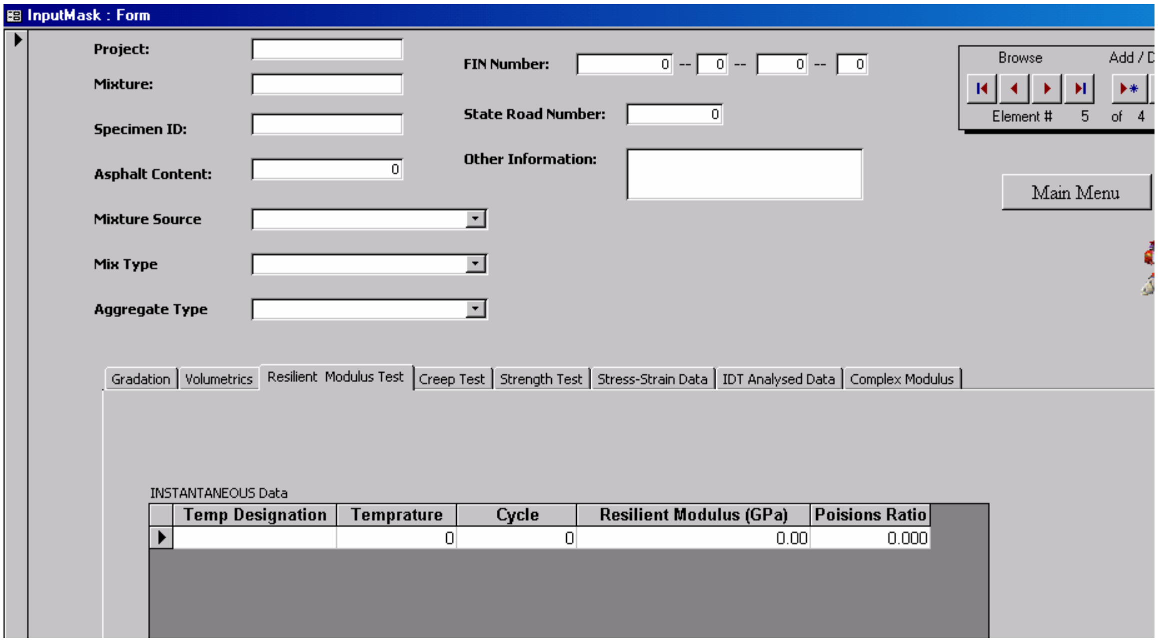


Figure 5-12. Database Input Mask

While inputting data to any table in this database the correct form of tables is shown in Figure 5-13 (a). It is very essential that there is no data in input table. When there is data in table its form looks as shown in Figure 5-10 (b). Delete the data by selecting arrow head shown and right click and thereafter selecting delete option.

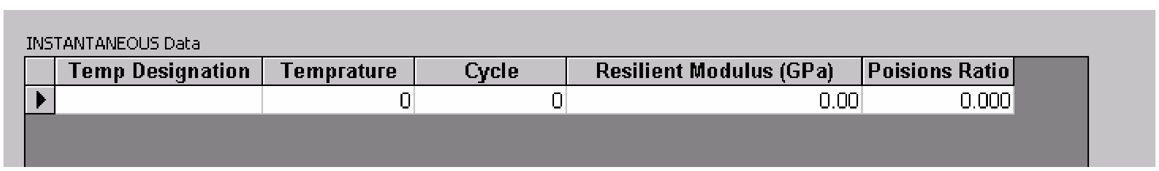


Figure 5-13. (a) Correct state of input tables for data entry

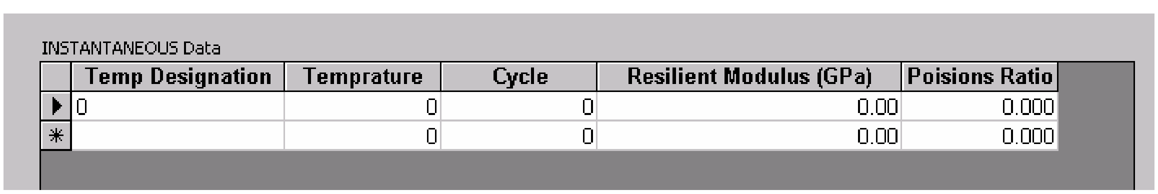


Figure 5-13. (b) Incorrect state of input tables for data entry

For inputting data right click on the arrow at left side to open paste option. Select the paste option for transferring data in clipboard to the screen table linked to internal database storage area. Figure 5-13 (c) shows this process.

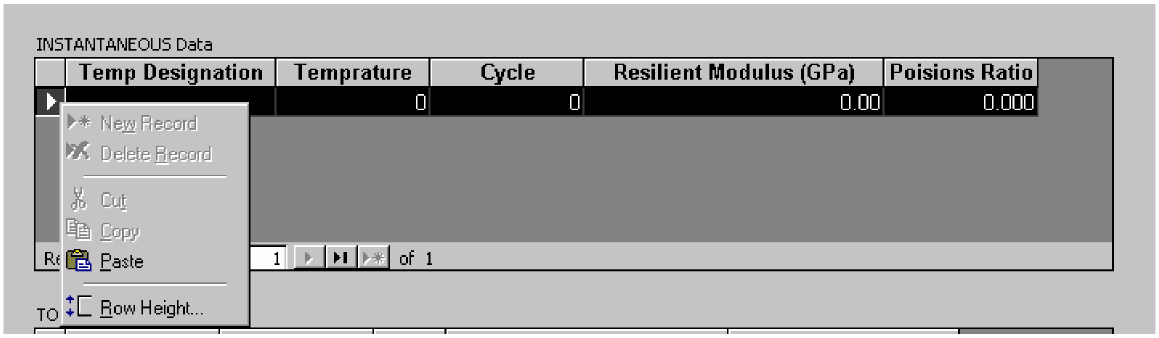


Figure 5-13. (c) Right click projected arrow for opening paste option

Figure 5-13 (d) shows confirmation of pasting data asked by Microsoft assistance. Press yes to complete the data transfer process.

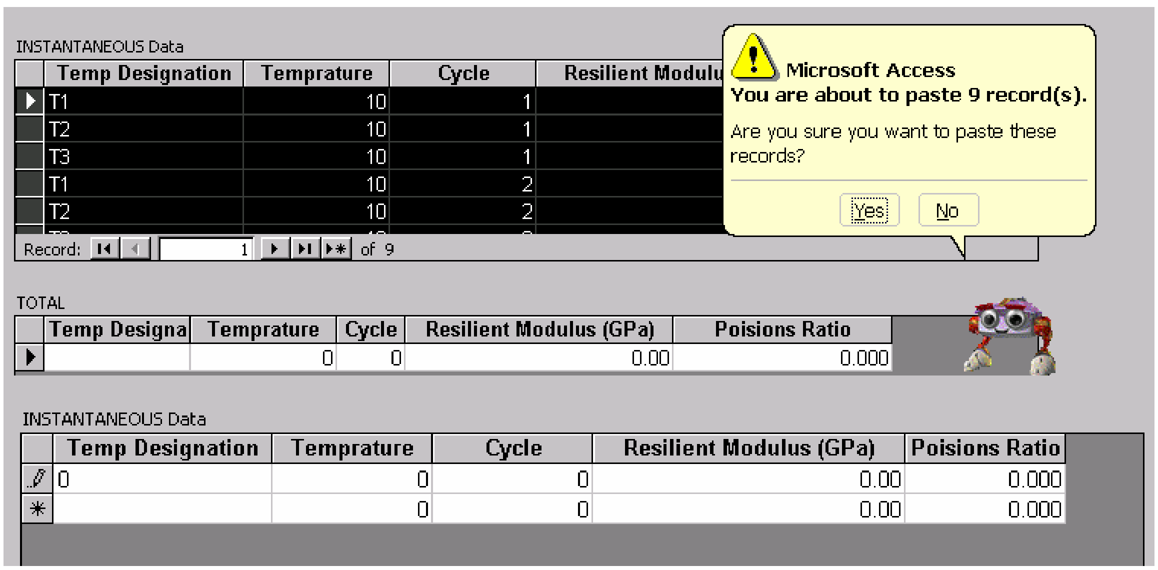


Figure 5-13. (d) Dialog box: - After selecting paste option. Opt 'Yes'

<u>5.4.6 Data Search</u>

Data stored in database needs haul out in proper presentable format. Following steps describes process of data search and report generation and transferring report to different output format as per required.

Step 1: - Press Search button at Main Database Menu Form. Customized Microsoft assistance pops up with a dialog box. Select the type of search criteria, which is to be carried out of ‘Materials Properties’ and ‘Test Data file’. Ref. Figure 5-11 for this process demonstration.

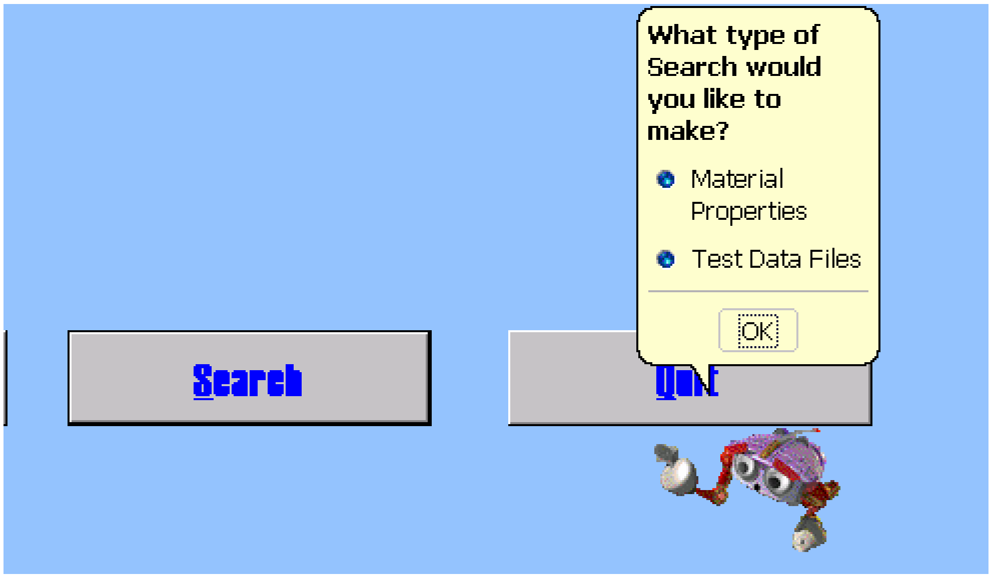


Figure 5-14. Search dialog box ‘Select type of search’

Step 2: - Once the type of search is selected corresponding Search Form (Figure 5-15) comes on screen for entering the search criteria. Search can be made based on, ranges for quantitative parameters like Asphalt content, air voids etc, fix criteria by selecting option commands and variables. Search Button clicked with out any data entry will display all mixtures details. Figure 5-16 shows search results. Upper part of form shows properties of individual mixture in frame, and at bottom bar chart are generated comparing properties of all mixture satisfying the search criteria. Set of navigation button at right top side allows to navigate to properties of other mixture.

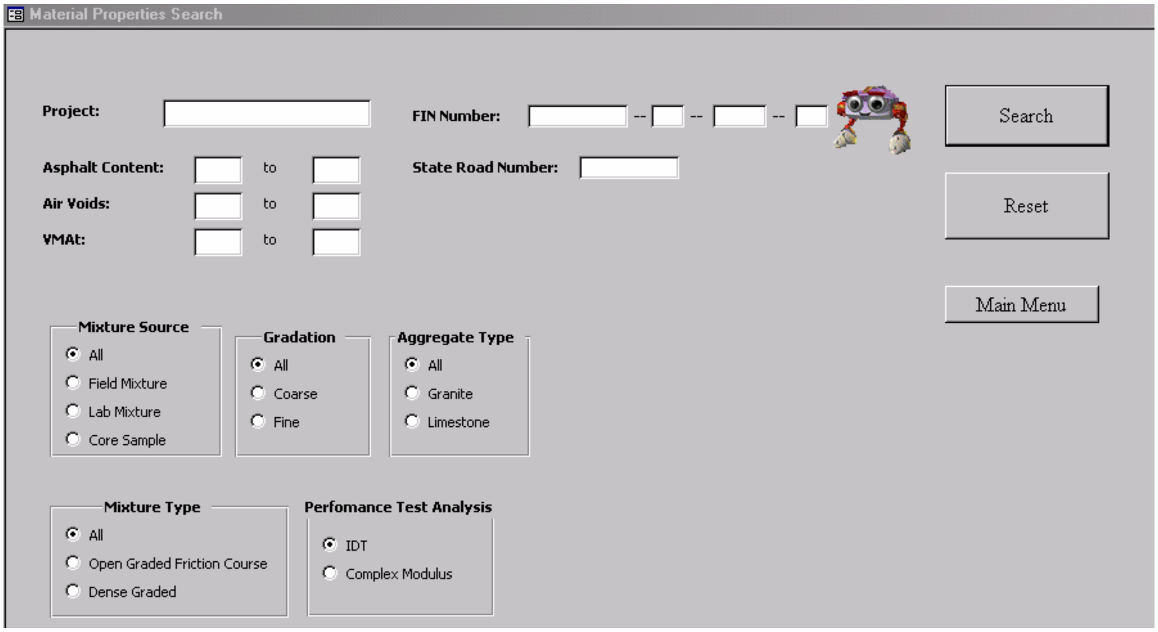


Figure 5-15. Search form

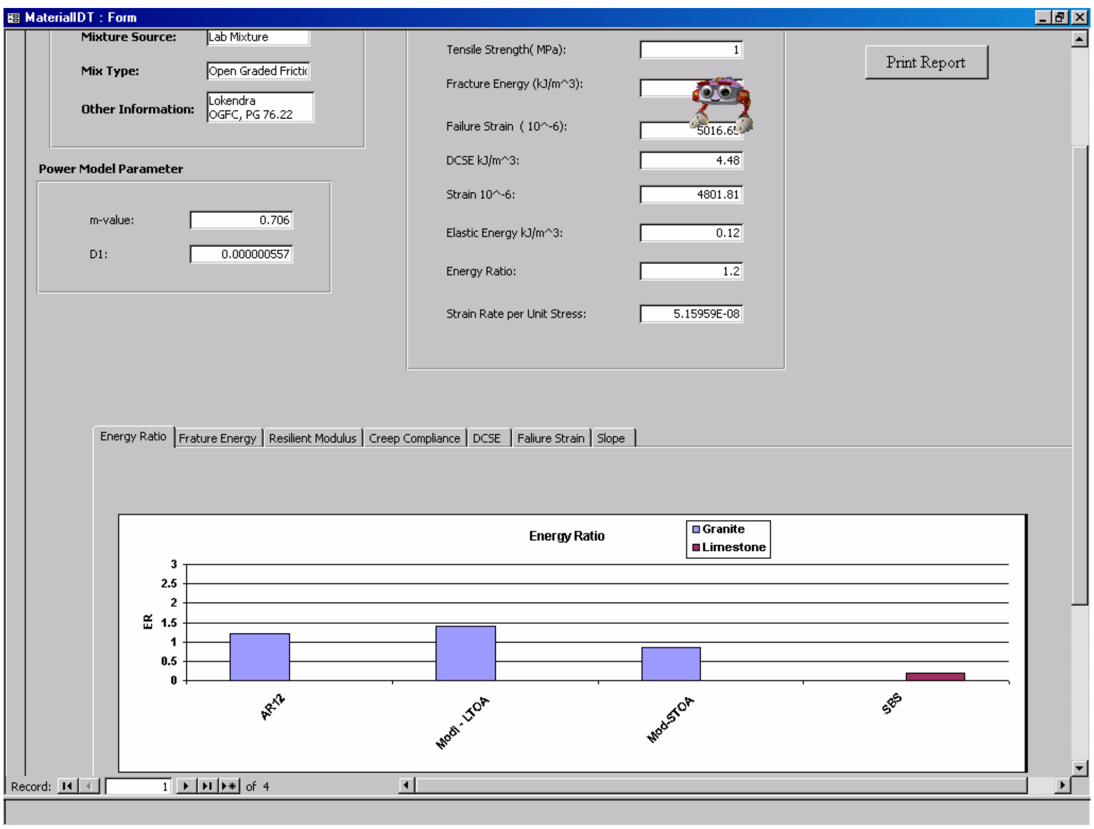


Figure 5-16. Search Result Form

5.4.7 Report Generation

For presentation of results produced by query, report generation and its output in desired format is developed, as shown in Figure 5-17, by pressing Print Report button and following the Microsoft Assistance directions.

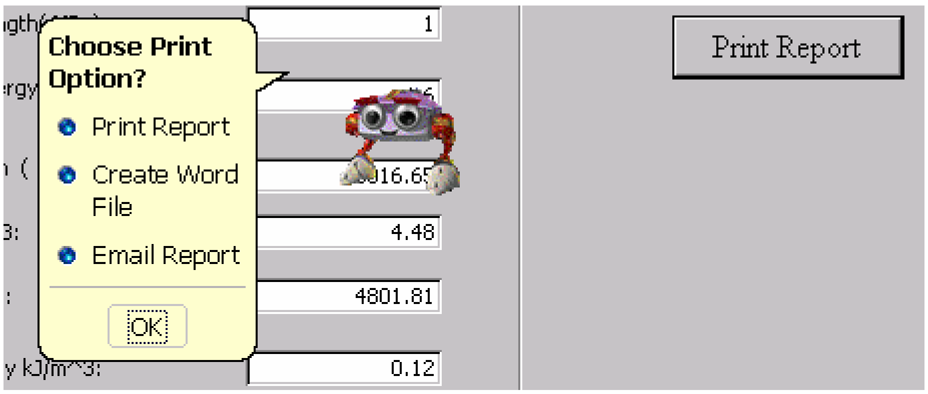


Figure 5-17. Report delivery option

Following report delivery format are available through this software: -

1. Print Report: - Selection of this option leads to print of report through printer using default printer setting.

2. Create File Word: - This option create rich text format file at desired location on system.

3. Email Report: - For web transfer of report this option is designed. Figure 5-18 shows different types of format can be selected which are attached to automatically generated email.

   Note: - Microsoft Snapshot format is the recommended output format for best bar chart and other graphic details.

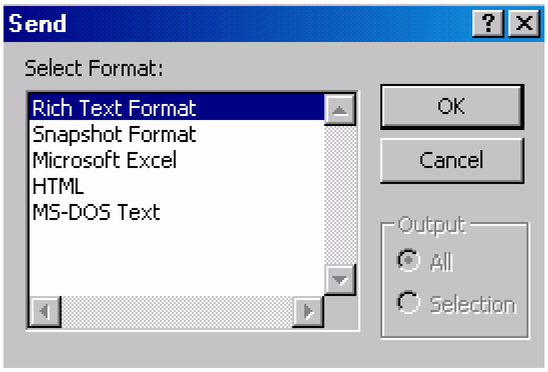


Figure 5-18. Email Report

5.4.8 Repair and Remove Program

For repairing or removing the program from your PC, double click the same setup.msi file. The options on template developed on screen direct the repair and remove process. For any assistance regarding this program use, program extension and suggestion please email to 'contact@lokendra.us'. Your queries and suggestion are important of us to improve the quality and performance of "Performance Test Database", and any other software development.

5.5 Summaries and Recommendation

This software is capable to support all kind of data generated for Superpave^{TM} Indirect Tensile Test text files, Mixture properties, Volumetric properties, Gradation details, APA rut depth, and Complex modulus data. Software has a separated interface, which calculates fracture test parameters like energy ration, DCSE and Strain rate. Therefore it can be used has analyzes software. This software has capability to produce report in Rich text format, Snapshot format, HTML format, and Direct Print document.

It is recommended to develop a 'Storage Area Network (SAN)' for this software (P.T.D.) for developing 'Distributed Database Management System'. This will ease data input and availability of certain information in database to global users. A 'Storage Area Network (SAN)' is any high-performance network whose primary purpose is to enable storage devices to communicate with computer systems and with each other. Basically from single user P.T.D., data is transferred to globally accessible P.T.D. interface so that there is common set of data stored in all databse.

CHAPTER 6
MOISTURE CONDITIONING ON I-295 PFC PROJECT

The AASHTO T283 (2003) moisture conditioning protocol was adopted to evaluate the moisture sensitivity of the I-295 PFC mixture. The Superpave IDT test and associated fracture parameters were used to quantify the effects of moisture damage.

6.1 Objective

Due to high air voids and dense graded pavement at bottom these porous mixtures retain water for long time. This continuous exposure to moisture at high temperature affects coarse aggregate arrangement and also causes stripping. PFC mixture if does not have sufficient resistance towards these effects, then it will lead to decrease in tensile strength. The main objective of moisture conditioning is to measure damage due to conditioning and predict resistance of mixture against moisture in actual field conditions.

6.2 Scope

The scope of project for determination of moisture sensitivity is tabulated as following: -

- Optimum asphalt content of I-295 PFC project gradation was determined and six pills of 6-inches diameter were prepared. Three for moisture conditioning and three as control samples, i.e. Unconditioned samples.
- Moisture conditioning was conducted, as per AASHTO T-283 (2003) protocol with modification, on three 6-inches diameter pills compacted in laboratory using Superpave gyratory compactor.
- SuperPave™ IDT was used to perform Resilient Modulus (M_R), Creep Compliance, and Strength tests (13, 14, 15) for determining fracture parameters.

6.3 Materials and Methodology

6.3.1 Aggregate and Hydrated Lime

The final aggregate blend for Gradation (1) and Gradation (2) is composed of #67 Granite stone from Pit No TM-579/NS-315, #78 Granite Stone from Pit No GA-383 and Granite Screens from Pit No. TM-579/NS-315. The F.D.O.T. code for this source stone stockpiles #67 Granite, #78 Granite and Granite Screens are 54, 54 and 23 respectively. Producer of these aggregates is 'Martin Marietta Aggregate'. Table 6-1 shows JMF used for I-295 PFC project and Figure 6-1 plot this gradation along with control points as per FDOT specification SECTION 337. Hydrated lime is added to mixture as antistrip agent, 1% by weight of aggregate. 'Global Stone Corporation' provided hydrated Lime and its Pit No. is Luttrel Co. TENN.

6.3.2 Binder and Mineral Fiber

An electrometric type of polymer modified asphalt cement PG 76-22 with 0.5% antistrip agent was used in this project. Mineral fiber used was regular FIBERAND ROAD FIBERS. 'Atlantic Coast Asphalt Co.' supplied asphalt and mineral fiber. The dosage rate of mineral fiber was 0.4% by weight of total mix.

Table 6-1. Gradation of I-295 PFC Project

Sieve Size	Percent Passing (%)
11/2 in. (37.5mm)	100
1 in. (25.0mm)	100
3/4 in. (19.0mm)	100
1/2 in. (12.5mm)	89
3/8 in. (9.5mm)	62
No. 4 (4.75mm)	15
No. 8 (2.36mm)	10
No.16 (1.18mm)	7
No.30 (600μm)	5
No.50 (300μm)	5

Table 6-1. Continued

Sieve Size	Percent Passing (%)
No.100 (150μm)	3
No.200 (75μm)	2

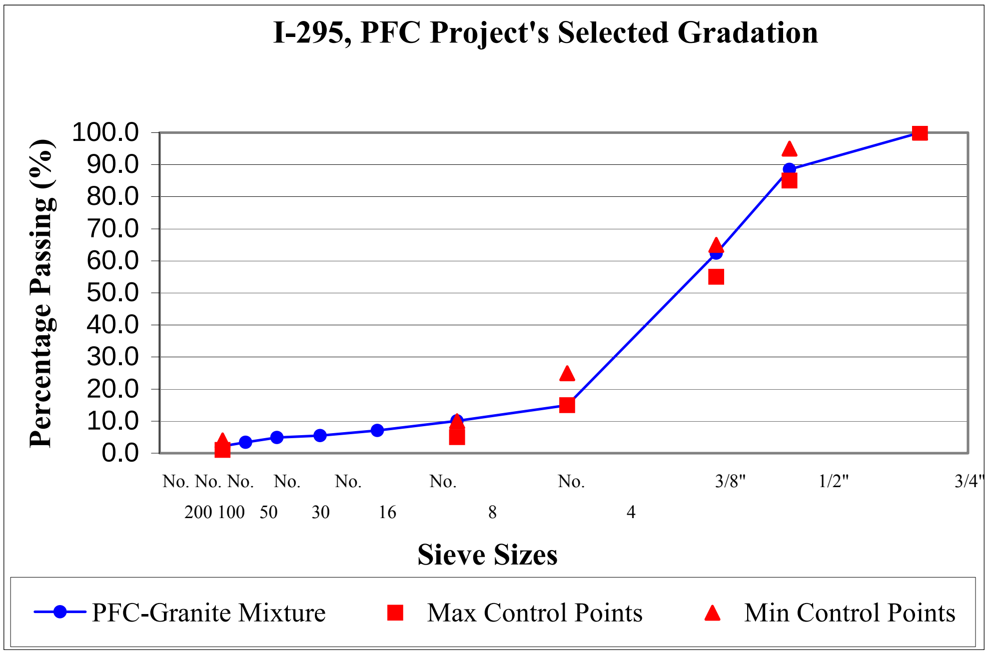


Figure 6-1. Plot of I-295 PFC mixture's gradation

6.4 Specimen Preparation and Testing

Based on number of experiments, the Georgia DOT suggested that if the gradation is within the specific limits, the initial estimate comes out to be 6%. Therefore, for gradations that control points the surface capacity (Kc) determination is not needed. The probable optimum asphalt content with in this gradation band is 6%. Depending on surface texture and angularity of aggregates and change in JMF might cause changes in optimum asphalt content. Four trial percentages (5.5%, 5.8%, 6.2% and 6.5%), and two piles for each trial percentage are produced in this project.

6.4.1 Mixing and Determination of Asphalt Content

Sieved and batched aggregates, asphalt and mineral fiber are preheated for 3 hours in oven before mixing. Due to viscous asphalt and addition of mineral fiber temperature of mixing selected was 330 º F, to maintain enough flow during mixing. All tools and mixing drum were also preheated to maintain desired temperature.

While mixing, asphalt is added to mix of aggregate and mineral fiber. These mixes are very sticky due to which it makes mixing very difficult. Ensure that while retrieving material from mixing drum there is no lose of fines. Mixing procedure was same both Rice and servopac samples. Avoid over heating of binder during mixing, as it causes aging of binder.

Before compaction, mixes are subjected to Short Term Oven Aging (STOA) for two hours, which includes stirring after one hour. Compaction temperature is reduced

to 320 º F, for avoiding draindown of binder during compaction. As already stated, 50 gyration were used to attain compaction level similar to field. The angle of gyration kept during compaction was 1.25. Essentially, because of sticky nature of these mixture oil is sprayed in molds.

From prior experience, compacted samples are not retrieved from molds immediately. They are allowed to cool from 1hr 30 min before retrieving from molds. Once the specimen is ejected from the mold let it cool for 5 min before holding specimen. Especially in granite mixtures if cooling after ejection is not allowed small aggregates due to high air voids stick to gloves and comes out causing discontinuity in specimen. Allow piles to cool for 24 hr before processing any other activity over it.

Determination of Rice specific gravity (Gmm) on loose PFC mixes in accordance with AASHTO T209, Refer Appendix B, was conducted. Calculations of all volumetric properties are shown in Appendix B. The determination of the optimum asphalt content as per recommended, as specified in chapter 3, was done by selecting AC at lowest point at VMA curve. 6% is the determined optimum asphalt content for this PFC-granite mixture.

6.4.2 Volumetric Properties

Figure 6-2 summarizes the volumetric properties for the mixture studied. The maximum specific gravity (Gmm) and Bulk specific gravity (Gmb) of mixture at optimum asphalt content are 2.485 and 1.957 respectively. The total air voids is designed mixture is 21.27 %. It should be noted that the effective film thickness (EFT) was developed by Nukunya et al. (9) to account for the nature of the coarse aggregate-to-aggregate contact structure in coarse-graded mixtures. Film thickness calculated as per Nukunya et al (9) is 35.4 microns. Film thickness is above specified minimum film thickness requirement, i.e. 35 microns, for 0%- 0.5% asphalt absorption. The minimum film thickness requirement is to ensure resistance against stripping and asphalt hardening. This indicates mixture have sufficient asphalt content.

6.4.3 Moisture Conditioning and Testing

Three samples were then subjected to saturation according to the AASHTO T-283 (2003) procedure, with the following modifications:

9. Since the PFC mixture has air voids around 21%, it is possible that the specimens creep during or fail during moisture conditioning. To over come this problem, the specimens were wrapped in 1/8' mesh and two clamps are provided without exerting pressure.

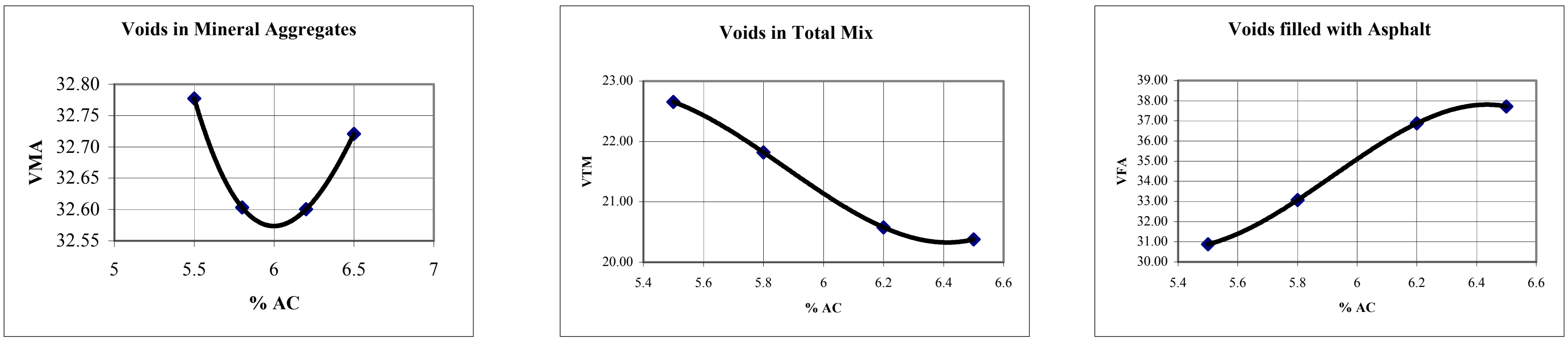
17. Wire mesh wrapped specimen is vacuum saturated at 25 inches of Hg absolute suction pressure for 30 minutes at a temperature of 25ºC. This allows water to penetrate into specimen, intercepting pocket of mastic. The vacuum saturation setup is shown in Figure 6-4.

18. Vacuum saturated samples are immersed in preheated water bath at 60ºC   1ºC temperature. Samples are conditioned in hot water bath for 24 ± 1 hour.

19. After 24 hours samples are moved to water bath with temperature 25 ± 0.5ºC for 2 hours. Conditioned samples are kept 36 hours for draining all water before removing the wire mesh.

Once the specimens had drained for 36 hours, both the conditioned and unconditioned specimens were cut, by a wet saw, into 2-inch thick specimens. The specimens were placed in a dehumidifier chamber for 48 hours. This ensured that the surface of the specimen was dry. SuperPave™ IDT was used to perform Resilient Modulus (M_R), Creep Compliance, and Strength tests (13, 14, 15) from which the following properties were determined: tensile strength, resilient modulus, fracture energy limit (FE), dissipated creep strain energy limit (DCSE), creep compliance, and m-value. The FE and DCSE values and the modulus can be accurately determined using the SuperPave™ Indirect Tensile Test following the procedures developed by Roque and Buttlar, and Buttlar and Roque (16, 17). Using these mixture properties and the HMA fracture mechanics framework developed at the University of Florida (Roque et al., 2004), the Energy Ratio was calculated.

Effective Sp Grav of Agg	% AC[6]	Gmm[1]	Gmb[2]	VMA[3] (%)	VTM[4] (%)	VFA[5] (%)
2.732	5.5	2.513	1.944	32.777	22.655	30.883
	5.8	2.501	1.955	32.603	21.820	33.073
	6.2	2.473	1.964	32.600	20.578	36.877
	6.5	2.470	1.966	32.721	20.379	37.718



Optimum Asphalt Content: - 6.0%

Gmm at Optimum Asphalt Content:- 2.485

Mineral Fiber: - 0.4% of Total Mix

VMA at Optimum Asphalt Content: - 32.69%

Effective Film Thickness (EFT) as per Nukunya et al for PFC-mixture with optimum asphalt content: - 35.4 microns

Figure 6-2. Mix Design of I-295 PFC-Granite mixture

Gmm[1] = Maximum specific gravity of mixture, Gmb[2] = Bulk specific gravity of mixture, VMA[3] = Voids in Mineral Aggregates, VTM[4] = Voids in Total Mix, VFA[5] = Voids filled with Asphalt, AC[6] = Asphalt Content

Figure 6-3. Compacted pill rolled in 1/8" inch sample placed in vacuum chamber

Figure 6-4. Vacuum Saturation of sample prior to moisture conditioning

6.5 Fracture Test on Moisture condition

Moisture conditioning causes sever damage to strength of mixture therefore it is essential to handle sample carefully during testing for obtaining consistent results.

In order to avoid end effects due to porous nature of OGFC and PFC mixtures, the Superpave IDT specimen thickness to be cut from compacted pill was kept around 1.5 –2 inches.After cutting, all specimens were allowed to dry in a constant humidity chamber for a period of two days. Figure 9.5 shows a picture of the dehumidifying chamber used. Four brass gage points (5/16-in. diameter by 1/8-in. thick) were affixed with epoxy to each specimen face. The strain gage extensometers were mounted on the specimen. Horizontal and vertical deformations were measured on each side of the specimen. Since the PFC air voids content is very high (around 18-22%), handling of the specimens at room temperature could cause specimen damage. Therefore specimens with glued gauge points were placed in a cooling chamber at a temperature 10 ± 0.5 °C for at least 3 hours before attaching the strain gage extensometers to the specimens. Without this step, occasional loss of gauge points, along with stone or mastic, was experienced, thus compromising the specimen for further testing. The test specimen was placed into the load frame. A seating load of 5 to 8 pounds was applied to the test specimen to ensure proper contact of the loading heads. As mentioned earlier, a 45-minute rest period was allowed between tests at different frequencies. Start up load for resilient modulus test was kept around 60 % of load applied on unconditioned sample during resilient modulus test to obtain resilient deformation of 100 microns (instead of 100-180 microns). If initial load applied is high it damages specimen in resilient test itself.

6.5.1 Findings and Analysis

Moisture conditioning was done in water bath of 60ºC for 24 hours on I-295 PFC samples. At such a high temperature and due negligible surface absorption capacity of granite mixture asphalt tends to flows with in mixture. Table 6-2 shows summary of fracture testing result of the conditioned and un-conditioned sample.

Creep compliance of conditioned mix is 17.66 1/Gpa, which is not a significant change as compared to unconditioned sample i.e. 17.53 1/Gpa. The strain rate per unit stress of unconditioned sample, i.e. 7.9 x 10^-8 1/psi-sec, remains same after conditioning. This indicates that the asphalt with in is not affected from the conditioning substantially. Where as, the threshold limit DCSE had reduced from 3.45 KJ/m^3 to 1.03 KJ/m^3 due to conditioning. Fracture energy also plummet from 3.6 KJ/m^3 to 1.1 KJ/m^6 as result of conditioning. Probably, as granite is not absorbing asphalt and asphalt at such a high temperature is in liquid state, the reinforcement of mixture due to stone to stone contact is affected as shown in Figure 6-5. Therefore the failure strain is reducing around half as compared to unconditioned sample.

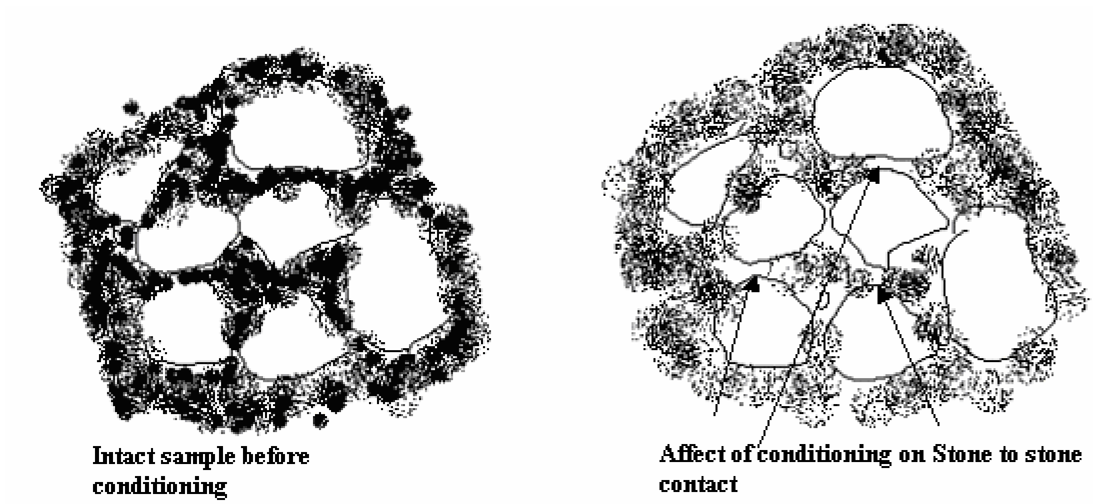


Figure 6-5. Affect of conditioning over stone to stone contact of PFC mixtures

Resilient modulus is increased to 5.25 Gpa from 4.41 Gpa, due to conditioning but this change is not significant. This confirms the constant strain rate and creep compliance.

The energy ratio, calculated as per Roque et al (2004), of conditioned specimen is 0.6, which is good value as compared with energy ratio, i.e. 1.67, of unconditioned sample.

Table 6-2. Summary of fracture test on moisture condition sample compared with unconditioned sample

Sample	**Property**												
	Resilient Modulus (Gpa)	**Creep compliance at 1000 seconds (1/Gpa)**	**Tensile Strength (Mpa)**	**Fracture Energy (kJ/m^3)**	**Failure Strain (10-6)**	**m-value**	**D_1**	**DCSE (kJ/m^3)**	**$e_0(10^{-6})$**	**Elastic E. (kJ/m^3)**	**Energy Ratio**	**Strain Rate per Unit stress (1/psi-sec)**	**Creep Rate (1/psi-sec)**
Unconditioned	4.41	17.53	1.15	3.6	3940	0.66	1.16E-06	3.45	3679.32	0.150	1.67	7.916E-08	8.86E-08
Conditioned	5.25	17.67	0.84	1.1	1827	0.73	7.9E-07	1.03	1666.89	0.067	0.60	8.827E-08	8.91E-08

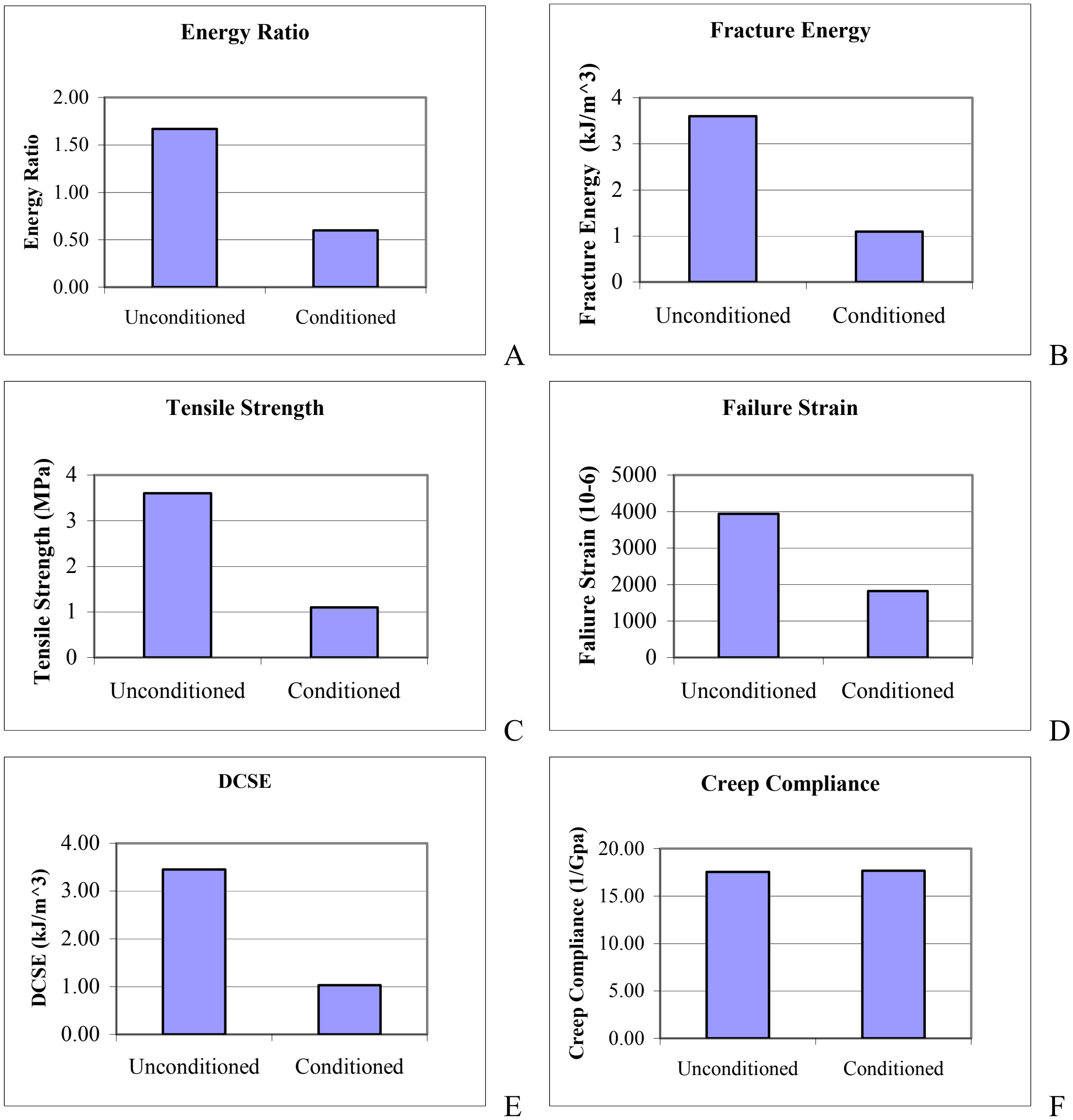
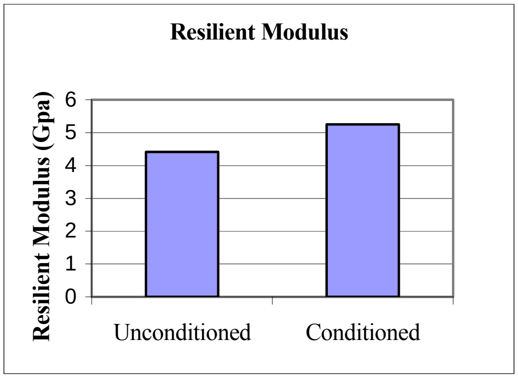


Figure 6-6. Comparison of Fracture Test rsults A) Energy ratio, B) Fracture energy, C) Tensile strength, D) Failure strain, E) DCSE, F) Creep compliance, G) Resilient modulus, H) Strain rate, I)Creep rate



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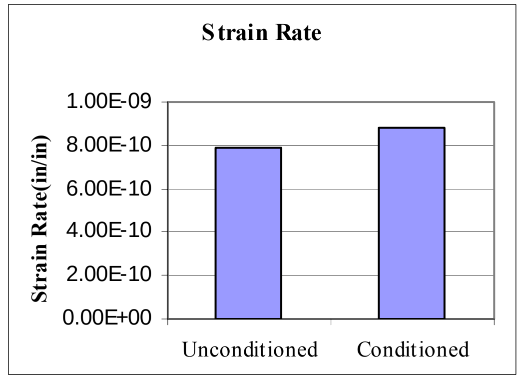

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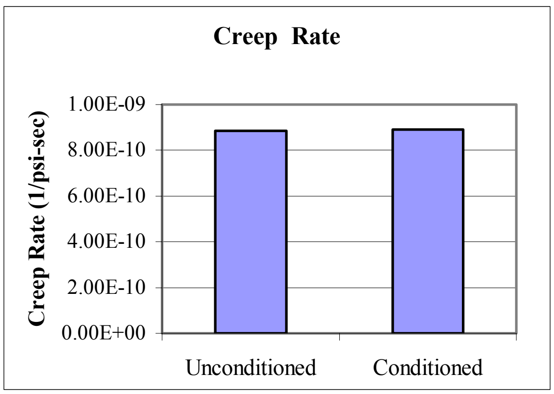


.I)

Figure 6-6. Continued

6.6 Summary and Conclusion

The energy ratio is reduced 0.6 from 1.67. Initial energy ratio of unconditioned indicates good field performance. Moisture conditioning procedure was to sever because of the warm water soaked in vacuum saturated specimen. This could have developed internal water pressure. Even though, after under going this conditioning liberation of energy ratio 0.6 is indicting good field performance. Finally, sample is still in good shape to with stand further conditioning, indicating good field performance of mixture for I-295.

CHAPTER 7
SUPERPAVE IDT FRACTURE TEST RESULTS

In this chapter, all Superpave IDT fracture test results from US-27 and I-295 project are presented and compared with an aim to evaluate the fracture performance of these mixtures.

7.1 Materials

7.1.1 Aggregate and Hydrated Lime

Two types of aggregate are used for the development of Georgia PEM for Florida condition i.e. Granite and Limestone. Nova Scotia granite and oolitic limestone from South Florida (White Rock) were used for preparing the mixtures. Same JMF is used for both granite and limestone mixture composing of aggregates from different stockpiles. Job mix formula of granite was composed of aggregates from stockpiles #7, #789 and Granite Screens. Job mix formula of limestone was composed of aggregates from stockpiles S1A, S1B and limestone screens. Hydrated lime (1% by weight of aggregate) was used as anti stripping agent for granite aggregates. FC-5 limestone and FC-5 granite are composition of stockpiles as shown in Appendix F. Hydrated lime is added to FC-5 Granite mixture with a dosage rate of 1%. Table F.2 of appendix show JMF of FC-5 granite with 1 % limestone.

The final aggregate blend for I-295 Permeable Friction Course (PFC) project is composed of #67 Granite stone from Pit No TM-579/NS-315, #78 Granite Stone from Pit No GA-383 and Granite Screens from Pit No-TM-579/NS-315. The F.D.O.T. code for this source stone stockpiles #67 Granite, #78 Granite and Granite Screens are 54, 54 and 23 respectively. Producer of these aggregates is 'Martin Marietta Aggregate'. Hydrated lime is added to mixture as antistrip agent, 1% by weight of aggregate. 'Global Stone Corporation' provided hydrated Lime and its Pit No. is Luttrel Co. TENN. Figure 7-1 shows Gradation used for Georgia PEM and I-295 PFC project.

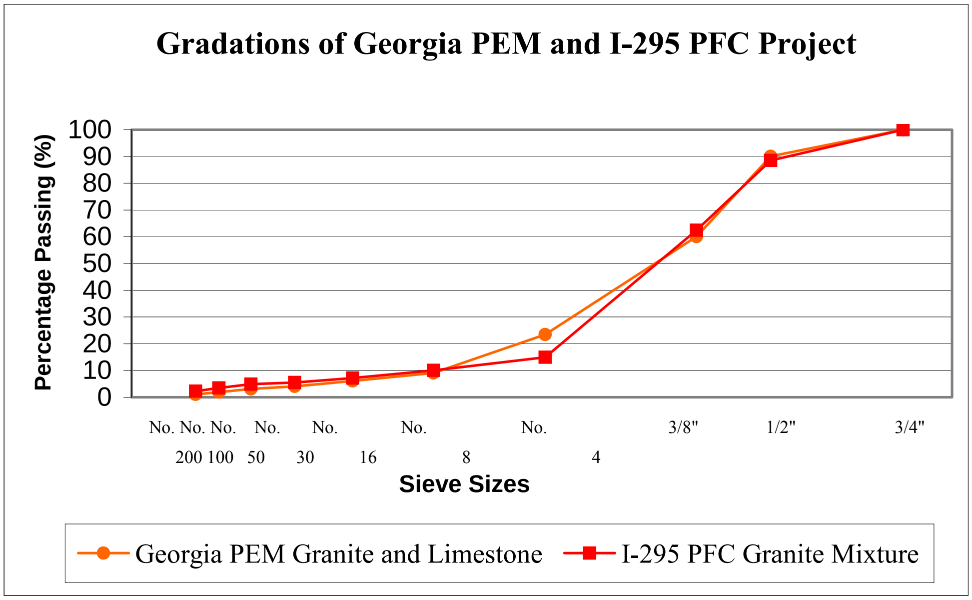


Figure 7-1. Gradation Band of Georgia PEM and I-295 PFC Project

7.1.2 Binder and Mineral Fiber

SBS modified PG 76-22 asphalt, with 0.5% anti strip agent was used in the mixture design. Mineral fiber (Fiberand Road Fibers) supplied by "SLOSS Industries, Alabama", 0.4% by weight of total mix, was added to mix in order to avoid binder drain drown. Chemical composition of mineral fiber is Vitreous Calcium Magnesium Aluminum Silicates. Mineral fibers were shredded into fine fragments before adding to mix.

An electrometric type of polymer modified asphalt cement PG 76-22 with 0.5% antistrip agent was used in I-295 PFC project. Mineral fiber used was regular FIBERAND ROAD FIBERS. 'Atlantic Coast Asphalt Co.' supplied asphalt and mineral fiber. The dosage rate of mineral fiber was 0.4% by weight of total mix.

7.2 Test Method

SuperPave^{TM} IDT was used to perform Resilient Modulus (MR), Creep Compliance, and Strength tests (14, 15) from which the following properties were determined: tensile strength, resilient modulus, fracture energy limit (FE), dissipated creep strain energy limit (DCSE), creep compliance, and m-value. The FE and DCSE values and the modulus can be accurately determined using the SuperPave Indirect Tensile Test following the procedures developed by Roque and Buttlar, and Buttlar and Roque (16, 17). Using these mixture properties and the HMA fracture mechanics framework developed at the University of Florida, the Energy Ratio was calculated (Roque, et al, 2004).

7.2.1 Sample Preparation

Both OGFC and PFC mixtures are very porous. Therefore both the long-term oven aging procedure and the Superpave IDT test procedure that was developed for dense-graded mixtures by Roque and Buttlar (1992) cannot be used unmodified. In the following, the long-term oven aging procedure used will be discussed, followed by a discussion on the Superpave IDT sample preparation and test procedures used.

Long-Term Oven Aging Procedure

The PFC and OGFC mixtures were subjected to long-term aging according to AASHTO PP2 (1994). However, the mixtures being very course and open, there was a possibility of these mixtures flowing or even falling apart during aging. Hence, the following procedure was developed to contain the compacted pills from falling apart during aging:

1. A 1/8 inch opening wire mesh is rolled around pills, with two tightening clamps located on each side of the specimen, at a distance of 1 inch from the top and bottom of the specimen, respectively. The mesh size was chosen to ensure that

there is good circulation of air within the sample for oxidation and at the same time, to prevent the smaller aggregate particles from falling through the mesh.

2. Following AASHTO PP2, the specimens are kept in an oven with porous plate at bottom for 185º F ± 5.4º F (85º C ± 3º C) for 120 ± 0.5 hours.

3. After that time period, the oven is turned off and the doors are opened to allow the oven and specimens to cool to room temperature for 16 ± 0.5 hours.

7.2.2 Testing Equipment

The basics of the Superpave IDT test equipment and data acquisition system have been specified by Buttlar and Roque (1994), Roque et al., (1992), and AASHTO TP-9. Figure 7-2 shows a picture of the Superpave IDT testing setup used. Additional information on the specific testing system used in this study is as follows:

- An environmental chamber was used to control specimen temperature. The chamber is capable of maintaining temperatures between -30° C and 30° C with an accuracy of ±0.1° C. Figure 7-3 shows a picture of the environmental chamber used.

- Loads were controlled using a MTS Model 418.91 MicroProfiler.

- The data acquisition system used was Labtech Notebook Pro software. A data acquisition program written specially for complex modulus tests. Approximately 50 data points per loading cycle were obtained.

- Vertical and horizontal deformation measurements were obtained using extensometers designed by MTS specifically for use with the Superpave IDT. A gage length of 1.5 inches was used for all specimens. Figure 7-4 shows a picture of the extensometers used.

Figure 7-2. IDT testing device

Figure 7-3. Temperature controlled chamber

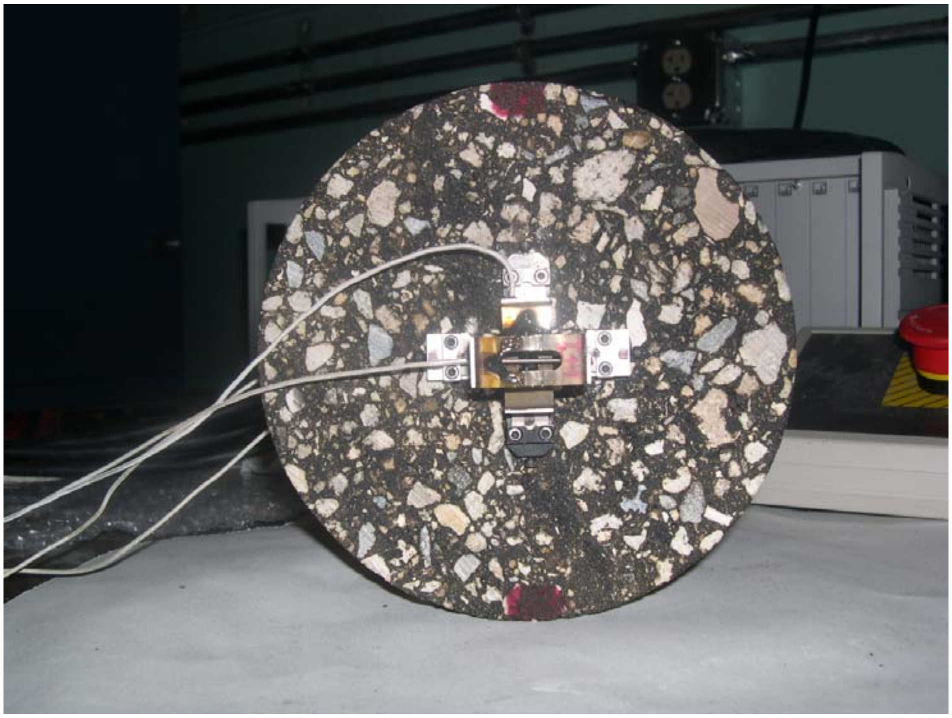


Figure 7-4. Typical Dense-Graded specimen with extensometers attached

7.2.3 Specimen Preparation and Testing Procedure

Test specimens were obtained from 6-in. diameter specimens that were compacted to 50 gyrations with the Superpave gyratory compactor. Each Superpave gyratory compacted specimen yielded two Superpave IDT specimens. Three specimens were tested at each of three test temperatures for each mixture.

Additional details on the testing procedure used are as follows:

- In order to avoid end effects due to porous nature of OGFC and PFC mixtures, the Superpave IDT specimen thickness to be cut from compacted pill was kept around 1.5 –2 in.
- After cutting, all specimens were allowed to dry in a constant humidity chamber for a period of two days. Figure 7-5 shows a picture of the dehumidifying chamber used.
- Four brass gage points (5/16-in. diameter by 1/8-in. thick) were affixed with epoxy to each specimen face.
- The strain gage extensometers were mounted on the specimen. Horizontal and vertical deformations were measured on each side of the specimen. Since the PFC

air voids content is very high (around 18-22%), handling of the specimens at room temperature could cause specimen damage. Therefore specimens with glued gauge points were placed in a cooling chamber at a temperature 10 ± 0.5 °C for at least 3 hours before attaching the strain gage extensometers to the specimens. Without this step, occasional loss of gauge points, along with stone or mastic, was experienced, thus compromising the specimen for further testing.

- The test specimen was placed into the load frame. A seating load of 5 to 8 pounds was applied to the test specimen to ensure proper contact of the loading heads.
- As mentioned earlier, a 45-minute rest period was allowed between tests at different frequencies.

Figure 7-5. Dehumidifying chamber

7.2.4 Test Procedures and Analysis of Test Results

Standard Superpave IDT tests, as specified by Roque & Butlar (1992) were performed on all mixtures to determine resilient modulus, creep compliance, m-value, D_1, tensile strength, failure strain, fracture energy, and dissipated creep strain energy to failure. The tests were performed at 10°C.

Resilient Modulus Test

The resilient modulus is defined as the ratio of the applied stress to the recoverable strain when repeated loads are applied. The test was conducted according to the system developed by Roque & Butlar (1992) to determine the resilient modulus and the Poisson's ratio. The resilient modulus test was performed in load control mode by applying a repeated haversine waveform load to the specimen for a 0.1 second followed by a rest period of 0.9 seconds. The load was selected to keep the horizontal strain in the linear viscoelastic range, in which horizontal strain is typically 100 to 180 micro-strains. The procedures for resilient modulus test are as follows:

1. The specimens compacted are cut parallel to the top and bottom faces using a water-cooled masonry saw to produce 2 inches thick specimens having smooth and parallel faces.

2. Four aluminum gage points are affixed with epoxy to each trimmed smooth face of the specimen.

3. Test samples are stored in a humidity chamber at a constant relative humidity of 60 percent for at least 2 days. In addition, specimens are cooled at the test temperature for at least 3 hours before testing.

4. Strain gauges are mounted and centered on the specimen to the gage points for the measurement of the horizontal and vertical deformations.

5. A constant pre-loading of approximately 10 pounds is applied to the test specimens to ensure proper contact with the loading heads before test loads are applied. Applying a repeated haversine waveform load for five seconds to obtain horizontal strain between 100 to180 micro-strains then tests the specimen. If the horizontal strains are higher than 50 micro-strains, the load is immediately removed form the specimen, and specimen is allowed to recover for a minimum 3minutes before reloading at different loading level.

6. When the applied load is determined, data acquisition program begins recording test data. Data are acquired at a rate of 150 points per seconds.

7. The resilient modulus and Poisson's ratio are calculated by the following equations, which were developed based on three dimensional finite element analysis by Roque and Buttlar (11). The equation is involved in the Superpave Indirect Tensile Test at Low Temperatures (ITLT) program, which was developed by Roque & Butlar (1994).

$$M_R = \frac{P \times GL}{\Delta H \times t \times D \times C_{comp}}$$

Where,

M_R = Resilient modulus

P = Maximum load

GL = Gauge Length

ΔH = Horizontal Deformation

t, D = Thickness, Diameter

$C_{comp} = 0.6354\times (X/Y)^{-1}-0.332$

Creep test

Creep compliance is a function of time-dependent strain over stress. The creep compliance curve was originally developed to predict thermally induced stress in asphalt pavement. However, because it represents the time-dependent behavior of asphalt mixture, it can be used to evaluate the rate of damage accumulation of asphalt mixture. As shown in Figure 5-5, D0, D1, and m-value are mixture parameters obtained from creep compliance tests. Although D1 and m-value are related to each other, D1 is more related to the initial portion of the creep compliance curve, while m-value is more related to the longer-term portion of the creep compliance curve.

The m-value has known to be related to the rate of damage accumulation and the fracture resistance of asphalt mixtures. In other words, the lower the m-value, the lower the rate of damage accumulation. However, mixtures with higher m-value typically have higher DCSE limits. The creep compliance is a time dependant strain, $\varepsilon(t)$, divided by a constant stress. That is, the inverse of the creep compliance, which is called creep stiffness, is a kind of stiffness. According to the analysis conducted by Roque & Butlar (1994), MR is higher than creep compliance stiffness at 1 second.

The Superpave Indirect Tensile Test at Low Temperatures (ITLT) computer program was used to determine creep properties of the mixtures. The test was conducted in a load control mode by applying a static load. The load was selected to keep the horizontal strain in the linear viscoelastic range, which is below a horizontal strain of 180 micro strains at 100 seconds and 750 microns at 1000 seconds.

The test procedure was presented by Roque & Butlar (1992). The procedures for indirect tensile creep test consist of the following steps:

- The preparation of test samples and the pre-loading are same as those for resilient modulus test
- Apply a static load for 1000 seconds. If the horizontal deformation is greater than 180 micro inch at 100 seconds, the load is immediately removed from the specimen, and specimen is allowed to recover for a minimum 3 minutes before reloading at a different level. At 100 sec, the horizontal deformation should be less than 750 micro inches
- When the applied load is determined, the data acquisition program records the loads and deflections at a rate of 10 Hz for the first 10 seconds, 1Hz for the next 290 seconds, and 0.2 Hz for the remaining 700 seconds of the creep test.
- The computer program, ITLT, was used to analyze the load and deflection data to calculate the creep compliance properties. Creep compliance and Poisson's ratio are computed by the following equations.

$$D(t) = \frac{\Delta H \times t \times D \times C_{comp}}{P \times GL}$$

$$\nu = -0.1 + 1.480 \times (X/Y)^2 - 0.778 \times (t/D)^2 \times (X/Y)^2$$

Where, D (t) = Creep Compliance

Strength test

Failure limits such as tensile strength, failure strain, and fracture energy were determined from strength tests using the Superpave IDT. These properties are used for estimating the cracking resistance of the asphalt mixtures. The strength test was conducted in a displacement control mode by applying a constant rate of displacement of 50 mm/min for field mix and 100 mm/min for saturated mix until the specimens failed. The horizontal and vertical deformation and the applied load are recorded at the rate of 20 Hz during the test.

The maximum tensile strength is calculated as the following equation.

$$S_t = \frac{2 \times P \times C_{sx}}{\pi \times b \times d}$$

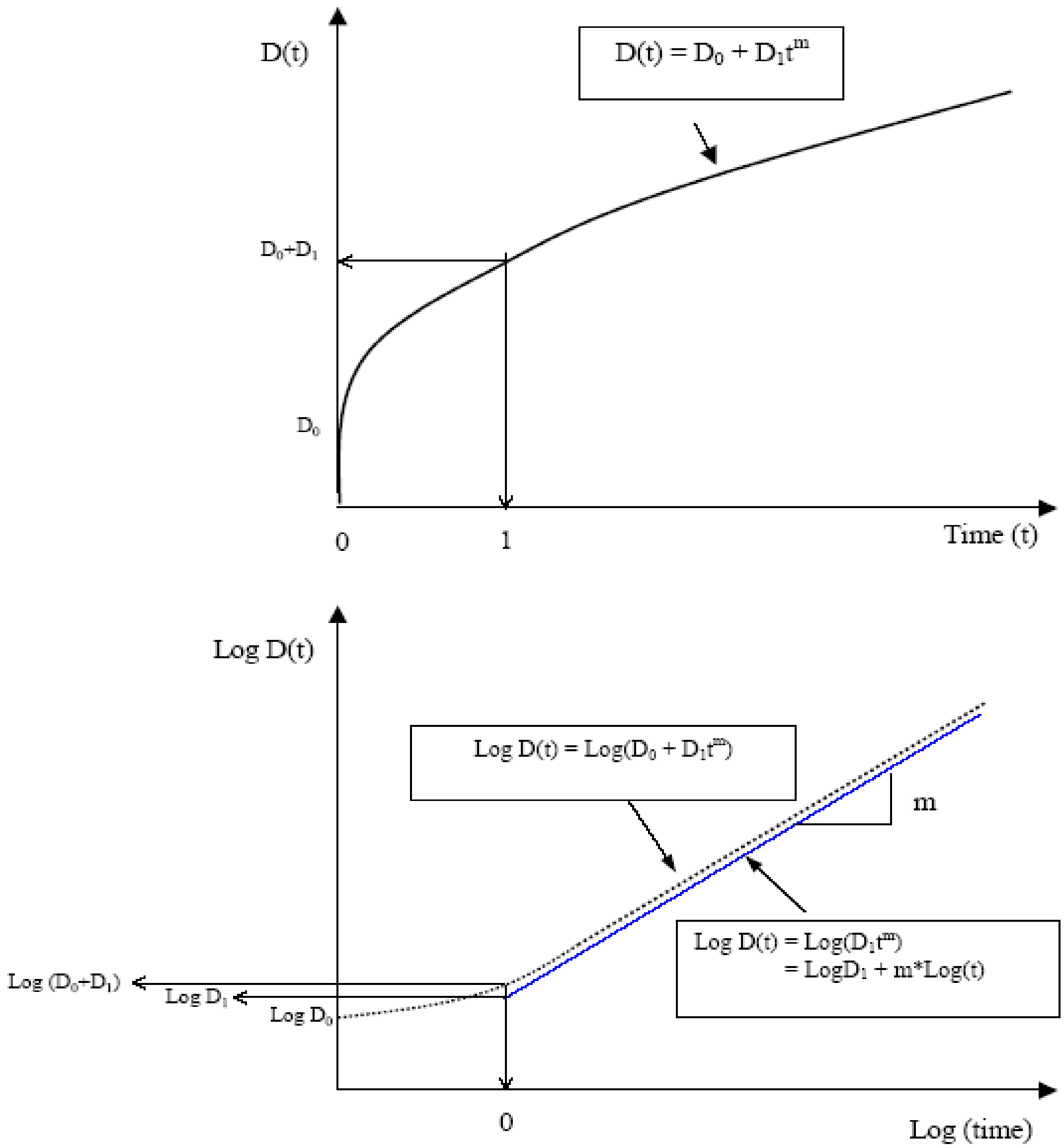
Where,

S_t = Maximum Indirect tensile Strength

P = Failure load at first crack

$C_{sx} = 0.948 - 0.01114 \times (b/D) - 0.2693 \times \nu + 1.436 \times (b/D)\nu$

b, D = Thickness, diameter



where:

$D(t)$ = Creep compliance at time, t

D_0, D_1, m = Power model constants

Figure 7-6. Power Model for Creep Compliance

From the strength test and the resilient modulus test, fracture energy and dissipated creep strain energy can be determined. Fracture energy is a total energy applied to the specimen until the specimen fractures. Dissipated creep strain energy (DCSE) is the absorbed energy that damages the specimen, and dissipated creep strain energy to failure is the absorbed energy to fracture ($DCSE_f$). As shown in the Figure 7-7, fracture energy and $DCSE_f$ can be determined as described below. The ITLT program also calculates fracture energy automatically.

$$M_R = \frac{S_t}{\varepsilon_f - \varepsilon_0} \quad \& \quad \varepsilon_0 = \frac{M_R \times \varepsilon_f - S_t}{M_R}$$

Elastic Energy (EE) = $(½) \times S_t \times (\varepsilon_f - \varepsilon_0)$

Fracture energy (FE) = $\int_0^{\varepsilon_f} St(\varepsilon)\, d\varepsilon$ (Upper Limit of strain is Faliure strain ε_f, Refer Figure 7-7)

Dissipated Creep Strain energy (DSCE) = FE – EE

Where, S_t = Tensile Strength

ε_f = Failure Tensile Strain

ε_0 = Elastic Strain

MR = Resilient Modulus

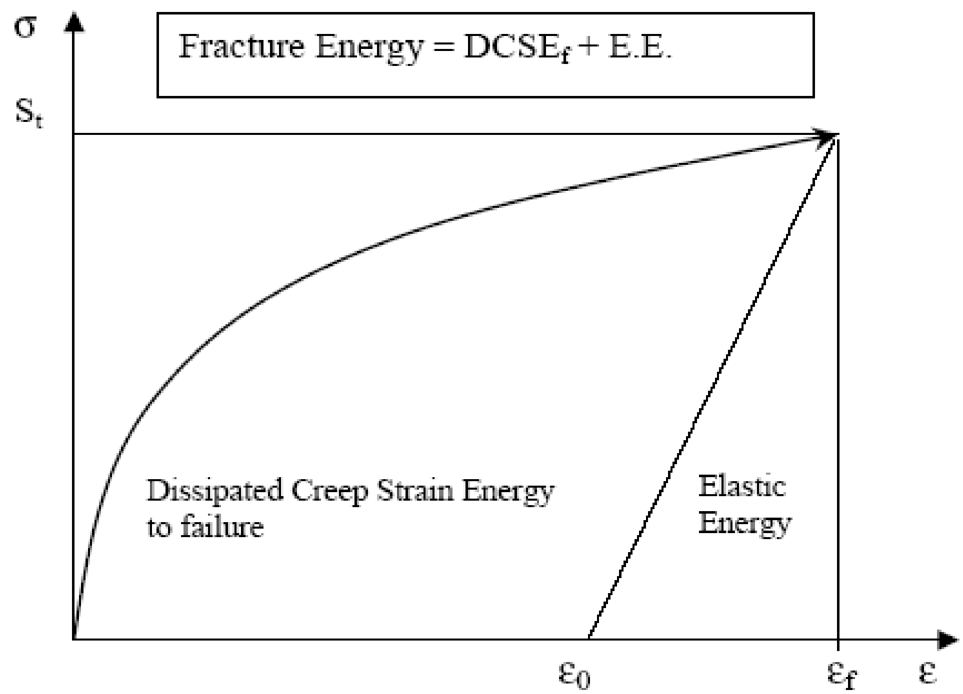


Figure 7-7. FE and DCSE from Strength Test

7.2.5 Results of Fracture Testing on PFC Mixtures

The short-term oven aged and long-term oven aged test results for the PFC friction courses are presented in Table 7-1 and Figure 7-8 through 7-16, along with a comparison with results from the OGFC mixtures from US Hwy 27, Highlands County. Below, the short-term oven aged and the long-term oven aged results are discussed briefly.

Discussion of results for short-term oven aged mixtures

The original GPEM mixture designs in this project used NS315 aggregate from Nova Scotia and oolitic limestone from South Florida, with an existing gradation obtained from the GDOT. Hence, these two mixtures are entitled "GPEM (Granite) and GPEM (Limestone)", respectively. The mixture entitled PFC (granite) is the mixture that was designed for the test section on I-295, Jacksonville. Finally, the granite and limestone OGFC mixtures from US Hwy 27, Highlands County are shown for comparison purposes.

The Energy ratio for short-term oven aged Georgia PEM-G (Granite) and PFC-G (Granite) ranges from between 1.5 and 2, which indicates good field performance. Similarly, for the GPEM (Limestone) mixture, the short-term oven aged energy ratio is around to 3.5. In the case of GPEM (Granite), the short-term oven aged failure strain is around 4000 micro strain and the DCSE limit is close to 4 KJ/m^3. In comparison, the short-term oven aged GPEM (Limestone) had a DCSE limit of 3.28 KJ/m^3. This lower DCSE limit is primarily due to the low failure strain 2735 micro strain as compared with granite mixture (4000 micro strain). For the short-term oven aged PFC-G the DCSE limit is 3.5 KJ/m^3 with a failure strain of 3940 micro strains.

Discussion of results for long-term oven aged mixtures

All granite mixtures showed a decrease in the energy ratio due to long-term aging. As shown in Figure 7-10 the failure-strain of the granite mixtures was reduced by half, as compared to the short-term oven aged mixtures. This decrease in the failure strain led to a decrease in the DCSE limit. The resilient modulus for the long-term oven aged mixtures is not affected significantly when compared with short-term oven aged mixtures.

Interestingly, limestone mixtures in general have a rough texture, with a lot of crevices and pores on the aggregate surfaces. During the long-term oven aging, the temperature is around 85° C, and at such a high temperature, the asphalt will flow, further enhancing the absorption of the asphalt into the crevices and the pores in the aggregate. This absorption mechanism may result in a mixture with enhanced ductility and failure strains, thus resulting in higher energy ratios. For example, in the extreme, the FC-5 Limestone mixture showed a significant increase in the energy ratio from 1.62 to 3.57, due to an increase in both failure strain and fracture energy. This shows that FC-5 limestone has sufficient cavities to absorb flowing asphalt. Interestingly, the GPEM-Limestone has a high-energy ratio for short-term oven aged conditions of about 3.3, and only a slightly reduced energy ratio of 3.09 for the long-term oven aged conditions. It is possible that the added mineral fiber is playing a role in reducing the absorption during long term oven aging, along with the SBS modified asphalt, which tends to be “stickier” than the ARB-12 asphalt.

Table 7-1. Summary of Fracture Test results on Short-Term and Long-Term Oven Aged Mixtures of Georgia PEM, PFC Project and OGFC Mixture

Sample	**Property**											
	Resilient Modulus (Gpa)	**Creep compliance at 1000 seconds (1/Gpa)**	**Tensile Strength (Mpa)**	**Fracture Energy (kJ/m^3)**	**Failure Strain (10-6)**	**m-value**	**D_1**	**DCSE (kJ/m^3)**	**$e_0(10^{-6})$**	**Elastic E. (kJ/m^3)**	**Energy Ratio**	**Strain Rate per Unit stress (1/psi-sec)**
Short-Term Oven Aged Mixtures												
GPEM-G	4.97	19.93	1.24	4.2	4383	0.74	8.35E-07	4.05	4133.73	0.154	1.95	1.061E-07
GPEM-L	5.81	3.54	1.59	3.5	2735	0.51	6.75E-07	3.28	2461.61	0.22	3.32	1.161E-08
FC-5 G	4.98	7.23	1.16	3	3248	0.60	7.84E-07	2.86	3014.79	0.14	1.59	2.896E-08
FC-5 L	7.35	1.88	1.11	0.9	982.1	0.48	4.29E-07	0.82	831.50	0.08	1.62	5.808E-09
PFC-G	4.41	17.53	1.15	3.6	3940	0.66	1.16E-06	3.45	3679.319	0.150	1.67	7.916E-08
Long-Term Oven Aged Mixtures												
GPEM-G	4.9	10.93	0.97	1.1	1552	0.70	5.86E-07	1.00	1354.31	0.10	0.86	5.127E-08
GPEM-L	6.27	2.47	1.57	2.3	2026	0.34	1.59E-06	2.10	1775.57	0.20	3.09	5.536E-09
FC-5 G	4.81	8.74	0.89	1	1454	0.77	2.80E-07	0.92	1268.76	0.08	0.68	4.567E-08
FC-5 L	7.57	1.81	1.69	2.1	1609	0.43	5.92E-07	1.91	1385.89	0.19	3.57	4.972E-09
PFC-G	3.28	27.91	0.94	1.6	2349	0.692	1.56E-06	1.47	2062.21	0.135	0.49	1.283E-07

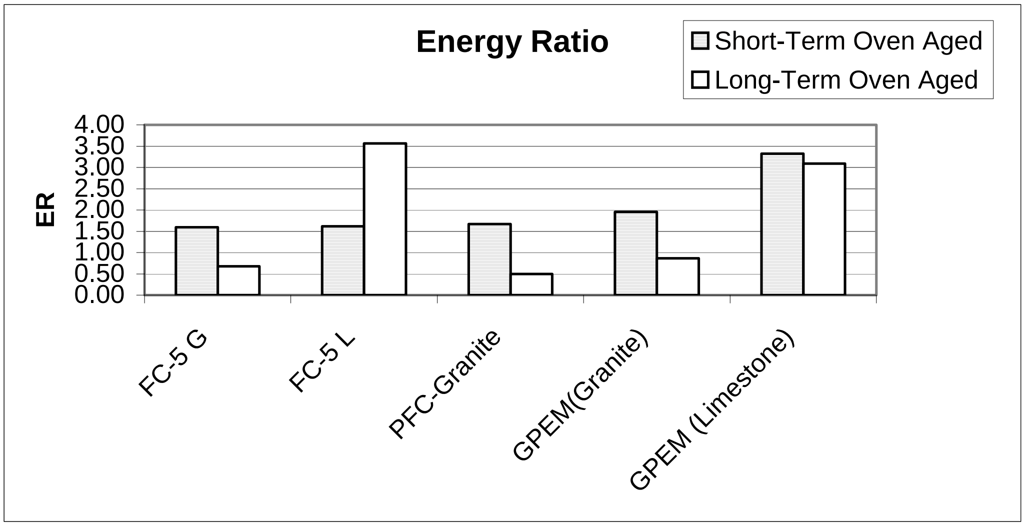


Figure 7-8. Energy Ratio

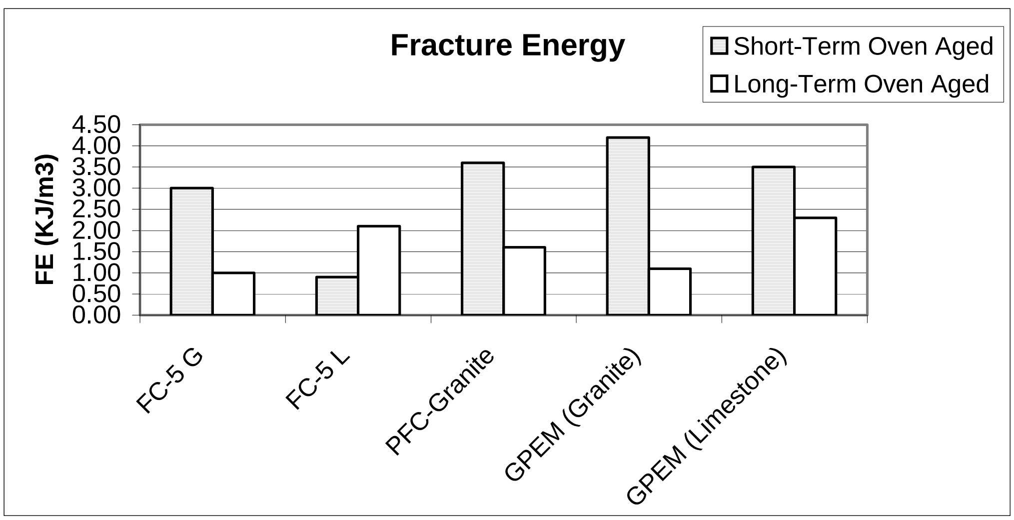


Figure 7-9. Fracture Energy

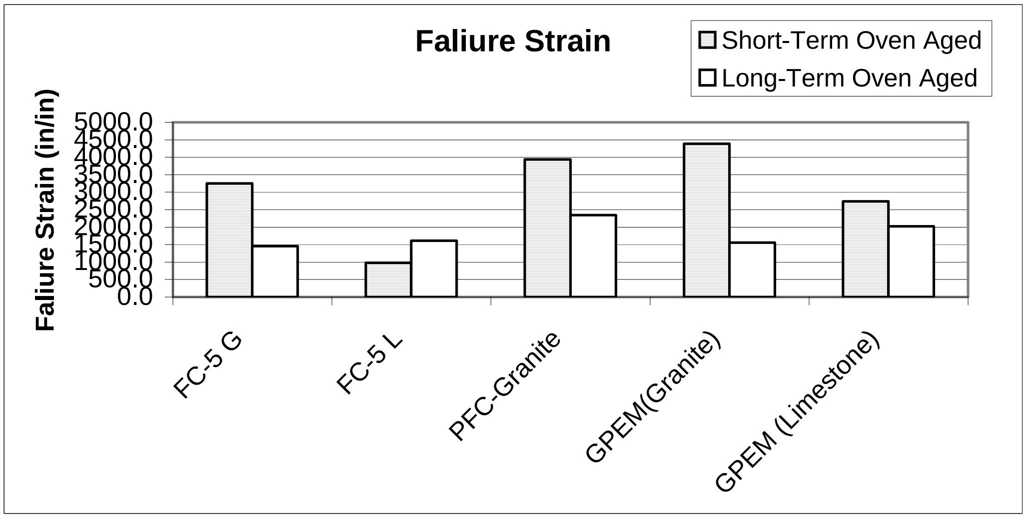


Figure 7-10. Failure Strain

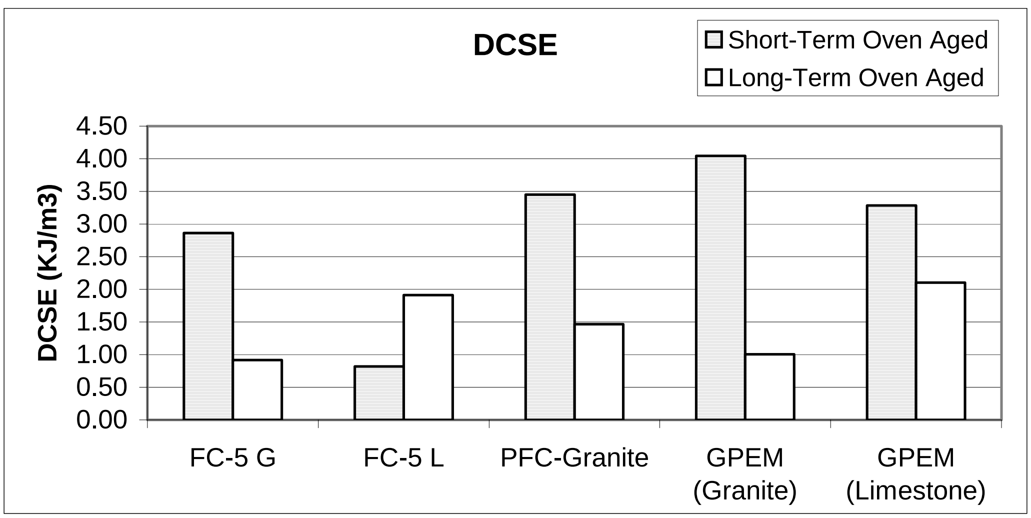


Figure 7-11. DCSE

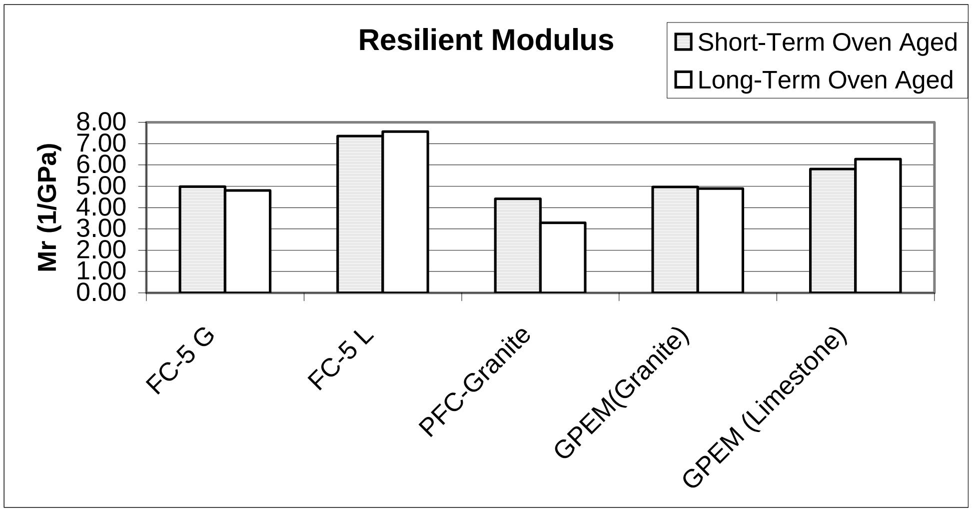


Figure 7-12. Resilient Modulus

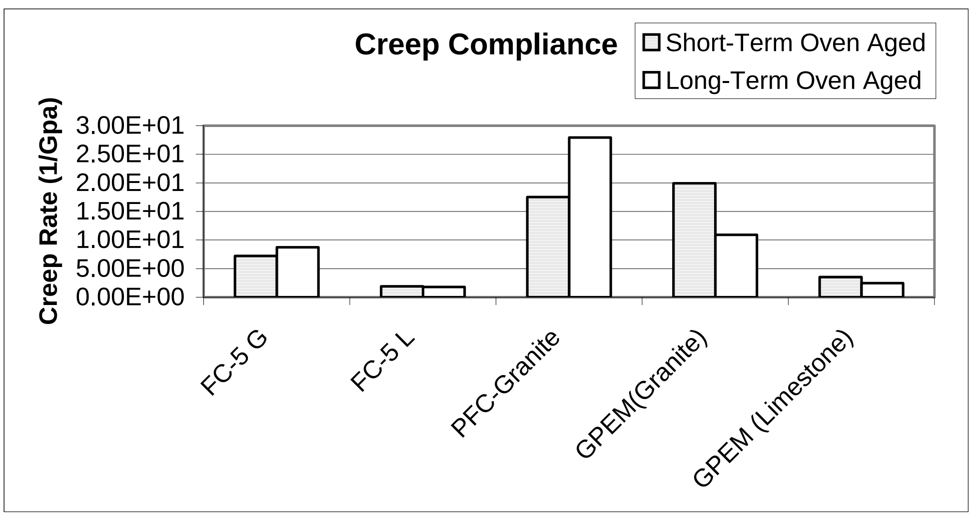


Figure 7-13. Creep Compliance

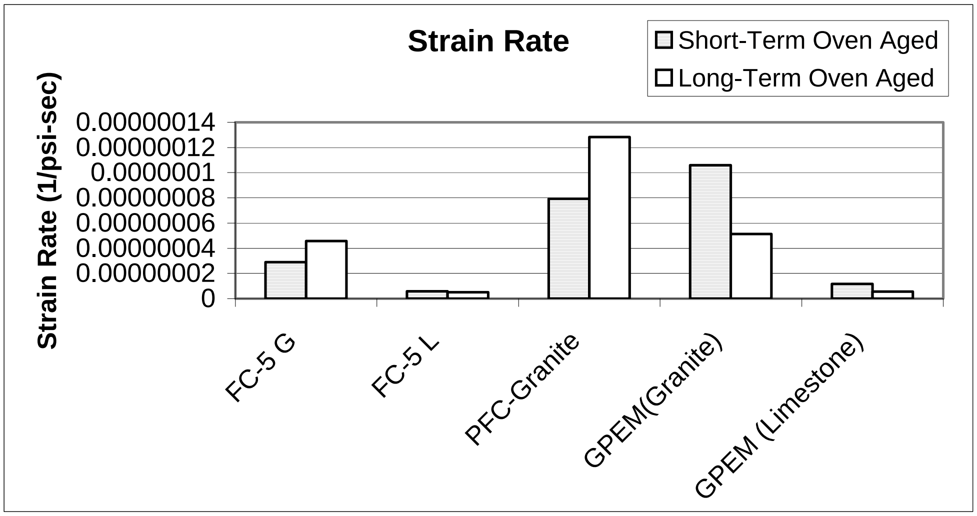


Figure 7-14. Strain Rate

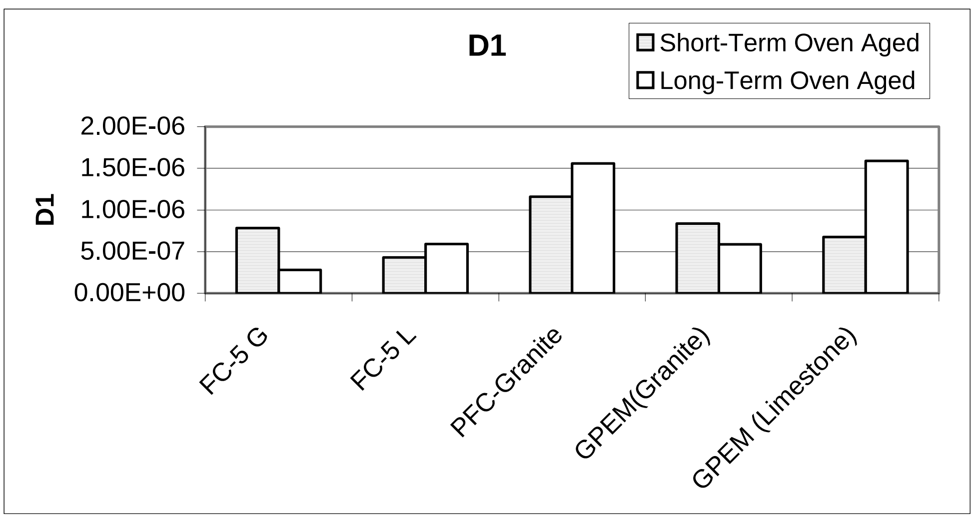


Figure 7-15. Power Model Parameter (D1)

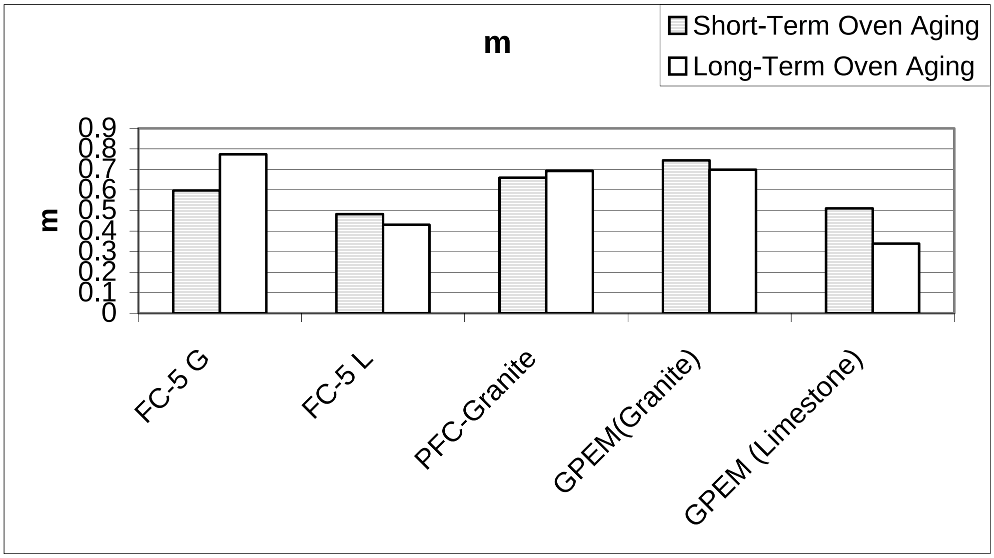


Figure 7-16. Power Model Parameter (m)

7.3 Summary and Conclusion

Summary and conclusion of findings and analysis of Superpave IDT fracture test results are as follows: -

- All limestone short-term oven aged mixtures are showing higher energy ratio as compared with granite short-term oven aged mixture.
- Due to absorption of asphalt in FC-5 limestone mixture during long-term oven aging, ductility is increased resulting in higher failure strain and energy ratio. Where as in GPEM limestone mixture use of SBS modified mixture, which is stickier than AR-12, and mineral fiber is reducing absorption of flowing asphalt at high temperature. Therefore, there is slight reduction in failure strain and energy ratio with approximately same tensile strength as compared with short-term oven aged samples.
- All granite mixture show substantial drop in failure strain, failure energy and energy ratio due to long-term oven aging.
- GPEM-granite and PFC-granite short-term oven aged mixture posses highest failure strain, fracture energy and energy ratio, as compared with FC-5 granite. Same mixtures is showing highest drop, more than 50%, in energy ratio, failure strain and fracture energy ratio.

APPENDIX A
SAMPLE CALCULATION OF VOLUMETRICS FOR GPEM AND PFC MIXTURE

Table A-1. Gradation for Georgia PEM-Granite

Type		#7	#789 Granite	Granite Screens	Lime	JMF	Control Points	
% Amount		55	37	7	1	100	Max	Min
Sive Size	Size^0.45							
37.5	5.11	100	100	100	100	100		
25	4.26	100	100	100	100	100		
19	3.76	100	100	100	100	100	100	100
12.5	3.12	82	100	100	100	90	100	80
9.5	2.75	28	99	100	100	60	60	35
4.75	2.02	2	39	99	100	23	25	10
2.36	1.47	2	6	69	100	9	10	5
1.18	1.08	2	2	46	100	6		
0.6	0.79	1	1	30	100	4		
0.3	0.58	1	1	17	100	3		
0.15	0.43	0	1	7	100	2		
0.075	0.31	0	0	1	100	1	4	1

Table A-2. Bulk Specific Gravity for Georgia PEM-Granite

AC (%)	Number	Height (cm)	Weight (gms)	Bulk Specific Gravity	Avg Bulk Specific Gravity
5.5	1	13.668	4659.3	1.930	1.936
	2	13.618	4657.1	1.936	
	3	13.586	4658.3	1.941	
6.0	1	13.539	4682.0	1.958	1.961
	2	13.557	4683.0	1.956	
	3	13.468	4681.5	1.968	

Table A-2. continued

AC (%)	Number	Height (cm)	Weight (gms)	Bulk Specific Gravity	Avg Bulk Specific Gravity
6.5	1	13.583	4704.9	1.961	1.967
	2	13.449	4701.8	1.979	
	3	13.598	4707.1	1.960	

Table A-3. Rice Test for Georgia PEM-Granite

% A/C	5.5		6		6.5	
Wt. Flask+Sample	2876	2867.6	2884.5	2851.7	2892	2892.6
Wt Flask	1872.9	1872.9	1875.7	1844.8	1872.9	1872.9
Wt Sample (A)	1003.1	994.7	1008.8	1006.9	1019.1	1019.7
Wt Flask+Water(D)	6126	6126	6125	6117.6	6126.1	6075.6
Wt Flask+Water+Sample(E)	6719.5	6714.7	6715.8	6707.4	6720.6	6671.4
SSD(B)	1005.4	995.4	1009.2	1007.2	1022.2	1022.2
Multiplier	1.00061	1.00038	1.00095	1.00095	1.00084	1.00084
Gmm	2.437	2.447	2.413	2.415	2.385	2.393
Avg Gmm	2.442		2.414		2.389	
% Agg	0.945		0.940		0.935	
Gse	2.647	2.660	2.640	2.641	2.625	2.636
Avg Gse	2.641					

Table A-4. Drain-down Test for Georgia PEM-Granite

%AC:	6.0	Mix Type: GPEM
Sample:	A	B
M_i, (g) Weight of mix before 1-hr aging	1274.2	1275.3
P_f, (g) (weight of paper disc + asphalt after draindown)	10.4	10.3
P_i, (g) (Initial Wt. Of paper Disc)	10.3	10.2
D (%Draindown)	0.01	0.01

Table A-4. continued

%AC:	6.0	Mix Type: GPEM		
D_{avg} (Avg)	0.01			
Drain-down test:	Passes	X	Fails	

Table A-5. Film Thickness for Georgia PEM-Granite

Sieve	Percent	Surface Area Factor		SurfaceArea	
Size	Passing	ft.2/lb.	m2/Kg	ft2/lb.	m2/Kg
11/2 in.(37.5mm)	100				
1 in. (25.0mm)	100				
3/4 in. (19.0mm)	100				
1/2 in. (12.5mm)	90				
3/8 in .(9.5mm)	60			2.0	0.41
No. 4 (4.75mm)	23	2	0.41	0.5	0.10
No. 8 (2.36mm)	9	4	0.82	0.4	0.08
No.16 (1.18mm)	6	8	1.64	0.5	0.10
No.30 (600um)	4	14	2.87	0.6	0.12
No.50 (300um)	3	30	6.14	0.9	0.19
No.100 (150um)	2	60	12.29	1.1	0.23
No.200 (75um)	1	160	32.77	1.7	0.35

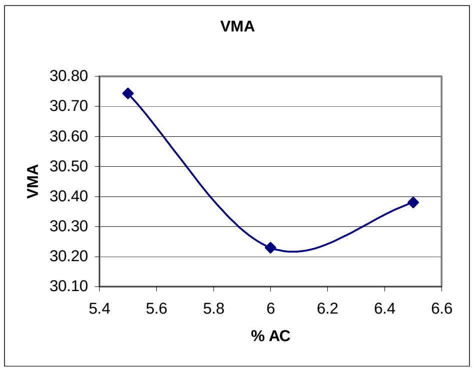
hrs

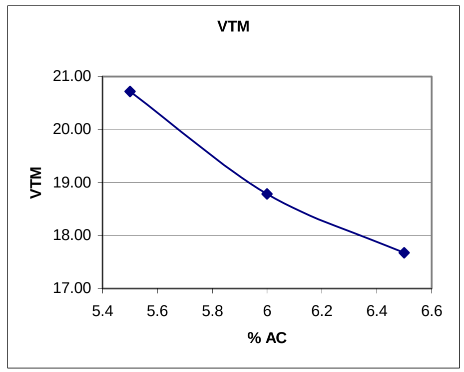
Total Surface Area	**7.6**	**1.57**
	AC % =	6.0

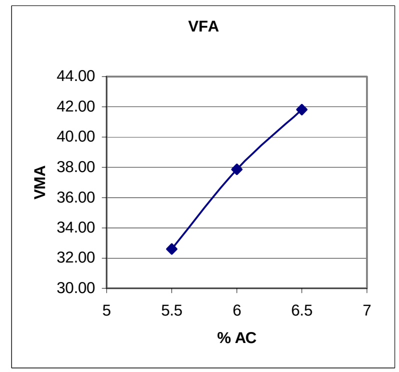
Table A-5. continued

Film Thickness =	[453.6 g per Pounds divided by % Aggregate] - [453.6 g per Pounds]				
	Surface area in square ft / lb * 0.09290Sq. m per sq. ft. * Sp. gr. of AC				
Or =	453.6	divided by	0.94	Minus	453.6
	28.953		divided by		0.731
Or =					
Film Thickness	**39.6**	Micron Coating			

Effective Sp Grav of Agg	% AC	Gmm	Gmb	VMA	VTM	VFA
2.641	5.5	2.442	1.936	30.74	20.72	32.60
	6	2.414	1.961	30.23	18.78	37.86
	6.5	2.389	1.967	30.38	17.68	41.82







Optimum AC	6%	**Mixing Temperature**	330 F
Mineral Fiber	0.4% of Total Mix	**Compaction Temperature**	325 F

Figure A-1. Final Mix Design for Georgia PEM-Granite

APPENDIX B
MAIN PROGRAMMING CODE OF PERFOMANCE TEST DATABSE (P.T.D.)

```
Option Compare Database
Option Explicit
Option Explicit
Rem     This software is developed on behalf of a partial fulfillment
Rem     of Master 's Thesis of Lokendra Jaiswal. The project concentrat
Rem     on development and evaluation of mixture design procedure. This
Rem     software helps in data extraction, analysis, and data storage
Rem     for report generation.
Dim CoarseGradationWhere As String
Dim FineGradationWhere As String
Dim GradationFrom As String
Dim GradationSt As String
Dim GradationWhere As String
Dim BasicSELECT As String
Dim LimestoneAggregateWhere As String
Dim GraniteAggregateWhere As String
Dim AggregateFrom As String
Dim AggregateWhere As String
Dim BasicFROM As String
Dim BasicWHERE As String
Dim ProjectNameWHERE As String
Dim FIN1rangeNumberWHERE As String
Dim FIN2rangeNumberWHERE As String
Dim FIN3rangeNumberWHERE As String
Dim FIN4rangeNumberWHERE As String
Dim StateRoadNumberWHERE As String
Dim FieldTypeWhere As String
Dim LabTypeWhere As String
Dim MixtureSourceWHERE As String
Dim FrequencyWhere As String
Dim FrequencySelect  As String
Dim FrequencyPunc  As String
Dim TempratureComplexSelect As String
Dim TempratureComplexPunc As String
Dim TempratureComplexWhere As String
Dim GradationSelect As String
Dim GradationPunc As String
Dim ExtractedDataPunc As String
Dim ExtractedDataSelect As String
Dim ExtractedDataFROM As String
Dim GradationEnd As String
Dim GradationEndLink As String
Dim Statementcomp As String
Dim QueryCount As Long
Dim choice
Dim ExtractedDataEnd As String
Dim ExtractedDataSt As String
Dim CoreTypeWhere As String
Dim MixtureTypeWHERE As String
Dim OpenGradedWhere As String
```

```
Dim AxialCreepPunc As String
Dim AxialCreepDataFROM As String
Dim AxialCreepSt As String
Dim AxialCreepEnd As String
Dim ComplexFROM As String
Dim ComplexSt As String
Dim ComplexEnd As String
Dim ComplexPunc As String
Dim ComplexSelect As String
Dim ACrangeminWHERE As String
Dim ACrangemaxWHERE As String
Dim AVrangeminWHERE As String
Dim AVrangemaxWHERE As String
Dim VolumetricsPunc As String
Dim VMArangeminWHERE As String
Dim VMArangemaxWHERE As String
Dim VolumetricsSelect As String
Dim VolumetricsFROM As String
Dim VolumetricsSt As String
Dim VolumetricsEnd As String
```

```
Private Sub QGen()
On Error Resume Next
    Set db = CurrentDb
    'Deletes the existing Search Query
    DoCmd.DeleteObject acQuery, "qryMain"
    On Error GoTo 0
    'Creates the new Search Query
    Set qdfSearch = db.CreateQueryDef("qryMain", SQL)
End Sub
```

```
Private Sub ACrangemin_AfterUpdate()
' Creates the Asphalt Content  Range minimum criteria
ACrangeminWHERE = " AND [Mix Defination].[Asphalt Content] > " & Me![ACrangemin] & ""

End Sub
```

```
Private Sub ACrangemin_BeforeUpdate(Cancel As Integer)
ACrangeminWHERE = ""
End Sub
```

```
Private Sub ACrangemax_AfterUpdate()
' Creates the Asphalt Content  Range minimum criteria
ACrangemaxWHERE = " AND [Mix Defination].[Asphalt Content] < " & Me![ACrangemax] & ""
End Sub
```

```
Private Sub ACrangemax_BeforeUpdate(Cancel As Integer)
ACrangemaxWHERE = ""
End Sub
```

```
Private Sub AVrangemin_AfterUpdate()
' Creates the Air Voids Range minimum criteria
AVrangeminWHERE = " AND [Mix Defination].[Va (%)] > " & Me![AVrangemin] & ""
End Sub
```

```
Private Sub ACrangemax_BeforeUpdate(Cancel As Integer)
ACrangemaxWHERE = ""
End Sub
Private Sub AVrangemin_AfterUpdate()
' Creates the Air Voids Range minimum criteria
AVrangeminWHERE = " AND [Mix Defination].[Va (%)] > " & Me![AVrangemin] & ""
End Sub

Private Sub AVrangemin_BeforeUpdate(Cancel As Integer)
AVrangeminWHERE = ""
End Sub
Private Sub AVrangemax_AfterUpdate()
' Creates the Air Voids  Range minimum criteria
AVrangemaxWHERE = " AND [Volumetrics].[Va (%)] < " & Me![AVrangemax] & ""

End Sub

Private Sub AVrangemax_BeforeUpdate(Cancel As Integer)
AVrangemaxWHERE = ""
End Sub
Private Sub VMArangemin_AfterUpdate()
' Creates the VMA criteria for SQL
VMArangeminWHERE = " AND [Mix Defination].[VMA (%)] > " & Me![VMArangemin] & ""
End Sub
Private Sub ProjectName_AfterUpdate()
'Creates the Project Name criteria
    ProjectNameWHERE = " AND [Mix Defination].[Project] Like '*" & Me![ProjectName] & "*'"
End Sub



Private Sub MainMenuButton_Click()
On Error Resume Next
        DoCmd.Close acForm, "frmSearchMaterials"
End Sub
Private Sub FIN2range_AfterUpdate()
'Creates the FIN Number criteria
    FIN2rangeNumberWHERE = " AND [Mix Defination].[FIN2] Like '*" & Me![FIN2range] & "*'"
End Sub
Private Sub FIN3range_AfterUpdate()
'Creates the FIN Number criteria
    FIN3rangeNumberWHERE = " AND [Mix Defination].[FIN3] Like '*" & Me![FIN3range] & "*'"
End Sub
Private Sub FIN4range_AfterUpdate()
'Creates the FIN Number criteria
    FIN4rangeNumberWHERE = " AND [Mix Defination].[FIN4] Like '*" & Me![FIN4range] & "*'"
End Sub

Private Sub FIN1range_AfterUpdate()
' Creates the FIN Number criteria
    FIN1rangeNumberWHERE = " AND [Mix Defination].[FIN1] Like '*" & Me![FIN1range] & "*'"
End Sub
```

```
Private Sub Form_Current()
   DoCmd.Maximize
   'Creates the basic Criteria for querying all records
    BasicSELECT = "SELECT DISTINCTROW [Mix Defination].[Index ID], [Mix Defination].[Project]," & _
    " [Mix Defination].[Specimen ID], [Mix Defination].[Mixture], [Mix Defination].[Aggregate]," & _
    "[Mix Defination].[Asphalt Content],[Mix Defination].[Other Information], [Mix Defination].[Mixture Source],"
    "[Mix Defination].[Mix Type], [Mix Defination].[IDT Temprature]," & _
    "[Mix Defination].[Complex Modulus Temrature]," & _
    "[Mix Defination].[Complex Modulus Frequency], [Mix Defination].[Complex Modulus Temrature]," & _
   "[Mix Defination].[FIN1],[Mix Defination].[FIN2],[Mix Defination].[FIN3],[Mix Defination].[FIN4]," & _
     "[Mix Defination].[State Road Number],[Mix Defination].[Asphalt Content]," & _
     "[Mix Defination].[VMA (%)],[Mix Defination].[Va (%)]"
  ExtractedDataPunc = ","
  ExtractedDataSelect = "[Extracted Data].[Resilient Modulus Gpa]," & _
  " [Extracted Data].[Creep compliance at 1000 seconds 1/Gpa], [Extracted Data].[Tensile Strength Mpa]," & _
  " [Extracted Data].[Fracture Energy kJ/m^3], [Extracted Data].[Failure Strain   10^-6]," & _
  " [Extracted Data].[m-value], [Extracted Data].D1, [Extracted Data].[DCSE kJ/m^3]," & _
  " [Extracted Data].[Strain 10^-6], [Extracted Data].[Elastic Energy kJ/m^3]," & _
  " [Extracted Data].[Energy Ratio], [Extracted Data].[Strain Rate per Unit Stress]"

  BasicFROM = "[Mix Defination] "
  BasicWHERE = "WHERE [Mix Defination].[Index ID]>0"
  ExtractedDataFROM = "INNER JOIN [Extracted Data] ON [Mix Defination].[Index ID] = [Extracted Data].[Index ID]"

  Statementcomp = ";"


End Sub
```

```
Private Sub Search_Click()
SQL = BasicSELECT & ExtractedDataPunc & ExtractedDataSelect & AxialCreepPunc & _
AxialCreepDataSelect & ComplexPunc & ComplexSelect & GradationPunc & GradationSelect & _
"FROM" & ExtractedDataSt & AxialCreepSt & ComplexSt & BasicFROM & _
ComplexFROM & ComplexEnd & AxialCreepDataFROM & AxialCreepEnd & ExtractedDataFROM & _
ExtractedDataEnd & GradationFrom & BasicWHERE & ProjectNameWHERE & FIN2rangeNumberWHERE & _
FIN3rangeNumberWHERE & FIN4rangeNumberWHERE & FIN1rangeNumberWHERE & StateRoadNumberWHERE & _
AggregateWhere & GradationWhere & MixtureSourceWHERE & MixtureTypeWHERE & ACrangeminWHERE & _
ACrangemaxWHERE & AVrangeminWHERE & AVrangemaxWHERE & VMArangeminWHERE & VMArangemaxWHERE & Statementcomp
'Calls the Query subprocedure
Call QGen
    QueryCount = DCount("[Index ID]", "qryMain")
    'Displays a message if no records matching the specified criteria are found
    If QueryCount = 0 Then
    MsgBox "No records were found. Please try a different search criteria"
    Exit Sub
    End If

Select Case Perfomance
Case 1

DoCmd.OpenForm "MaterialIDT", acNormal, , , , acWindowNormal

Case 2
ComplexSelect = "[ComplexModulusMain].[Temprature (*C)], [ComplexModulusMain].[Frequency (Hz)], [ComplexModulusMain]
  ComplexPunc = ","
  ComplexFROM = "INNER JOIN [ComplexModulusMain] ON [Mix Defination].[Index ID] = [ComplexModulusMain].[Index ID]"
  ComplexSt = "("
  ComplexEnd = ")"
DoCmd.OpenForm "MaterialComplex", acNormal, , , , acWindowNormal


End Select
End Sub
```

```
Select Case Perfomance
Case 1

DoCmd.OpenForm "MaterialIDT", acNormal, , , , acWindowNormal

Case 2
ComplexSelect = "[ComplexModulusMain].[Temprature (*C)], [ComplexModulusMain].[Frequency (Hz)], [ComplexModulusMain]
  ComplexPunc = ","
  ComplexFROM = "INNER JOIN [ComplexModulusMain] ON [Mix Defination].[Index ID] = [ComplexModulusMain].[Index ID]"
  ComplexSt = "("
  ComplexEnd = ")"
DoCmd.OpenForm "MaterialComplex", acNormal, , , , acWindowNormal


End Select
End Sub
```

```
Private Sub AggregateType_AfterUpdate()
 LimestoneAggregateWhere = " AND ([Mix Defination].[Aggregate])='Limestone'"
  GraniteAggregateWhere = " AND ([Mix Defination].[Aggregate])='Granite'"
     AggregateWhere = ""
     'Creates the Aggregate Type Criteria
      Select Case Gradation
        Case 1
        AggregateWhere = ""
        Case 2
        AggregateWhere = LimestoneAggregateWhere
        Case 3
        AggregateWhere = GraniteAggregateWhere
      End Select
End Sub
```

```
Private Sub Form_Current()
   DoCmd.Maximize
   'Creates the basic Criteria for querying all records
    BasicSELECT = "SELECT DISTINCTROW [Mix Defination].[Index ID], [Mix Defination].[Project]," & _
    " [Mix Defination].[Specimen ID], [Mix Defination].[Mixture], [Mix Defination].[Aggregate]," & _
    "[Mix Defination].[Asphalt Content],[Mix Defination].[Other Information], [Mix Defination].[Mixture Source],"
    "[Mix Defination].[Mix Type], [Mix Defination].[IDT Temprature]," & _
    "[Mix Defination].[Complex Modulus Temrature]," & _
    "[Mix Defination].[Complex Modulus Frequency], [Mix Defination].[Complex Modulus Temrature]," & _
   "[Mix Defination].[FIN1],[Mix Defination].[FIN2],[Mix Defination].[FIN3],[Mix Defination].[FIN4]," & _
     "[Mix Defination].[State Road Number],[Mix Defination].[Asphalt Content]," & _
     "[Mix Defination].[VMA (%)],[Mix Defination].[Va (%)]"
  ExtractedDataPunc = ","
  ExtractedDataSelect = "[Extracted Data].[Resilient Modulus Gpa]," & _
  " [Extracted Data].[Creep compliance at 1000 seconds 1/Gpa], [Extracted Data].[Tensile Strength Mpa]," & _
  " [Extracted Data].[Fracture Energy kJ/m^3], [Extracted Data].[Failure Strain   10^-6]," & _
  " [Extracted Data].[m-value], [Extracted Data].D1, [Extracted Data].[DCSE kJ/m^3]," & _
  " [Extracted Data].[Strain 10^-6], [Extracted Data].[Elastic Energy kJ/m^3]," & _
  " [Extracted Data].[Energy Ratio], [Extracted Data].[Strain Rate per Unit Stress]"

  BasicFROM = "[Mix Defination] "
  BasicWHERE = "WHERE [Mix Defination].[Index ID]>0"
  ExtractedDataFROM = "INNER JOIN [Extracted Data] ON [Mix Defination].[Index ID] = [Extracted Data].[Index ID]"

  Statementcomp = ";"


End Sub
```

```
Private Sub Form_Load()
Me!Perfomance.Value = 1
End Sub
```

APPENDIX C
EFFECTIVE ASPHALT CONTENT CALCULATION FOR FILM THICKNESS DETERMINATION

C-1 Water Absorption and Effective Asphalt Calculation

Specific Gravity of Aggregate (Fine and Coarse aggregate as per AASHTO T 84 and T 85 repectively)

Limestone sample is separated into fine (Passing on Sieve Size 4.75) and Coarse (Retained on Sieve Size 4.75) by Weight

a) Specific Gravity of Fine Aggregates T84

$A_{T84} := 1026gm$ ....Dry weight of Test Sample

$B_{T84} := 1095gm$ ....SSD

$C_{T84} := 3970.2gm - 3383.3gm$..........Weight in water

$C_{T84} = 586.9\ gm$

b) Specific Gravity of Coarse agrregate T85

$A_{T85} := 3378.2gm$..........................Dry weight of Test Sample

$B_{T85} := 3463.3gm$..........................SSD

$C_{T85} := 2924gm - 869.9gm$.............Weight in water

$C_{T85} = 2.054 \times 10^{3}\ gm$

$$Gsb := \frac{\left(A_{T84} + A_{T85}\right)}{\left[\left(B_{T84} + B_{T85}\right) - \left(C_{T84} + C_{T85}\right)\right]}$$ ....Gross Specific Gravity

$Gsb = 2.297$

$$Water_{abs} := \frac{(B_{T84} + B_{T85}) - (A_{T84} + A_{T85})}{(A_{T84} + A_{T85})} \cdot 100$$

$Water_{abs} = 3.499$ ....Percentage of Water by weight of dry aggregate absorbed

$$Water_{abs\_ml} := \frac{Water_{abs} \cdot \frac{4400}{100}}{1.03}$$

$Water_{abs\_ml} = 149.469$

$$V_{eff3} := Total_{Asphalt} - Water_{abs\_ml}$$

$V_{eff3} = 128.201$

Table C-1. Core-Lok Results calculation for Efffective asphalt content

	A	B	C	D	E	F	G	H	I	J
Sam-ple ID	Bag Weight (g)	Dry Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Dry Sample Weight After Water Submerdio	Ratio B/A	Bag Volume Correction From Table	Total Volume (A + D) - C	Volume of Sample A/F	Volume of Sample (G-H)	Bulk Specific Gravity B/I
I	50.7	4700.3	2328.8	4700	92.71	0.706	2421.9	71.813	2350.087	2.0001
II	50.7	4700.7	2312.5	4700.7	92.72	0.706	2438.9	71.813	2367.087	1.9859

$$Gmb := \frac{2.0001 + 1.9859}{2}$$

$Gmb = 1.993$

Table C-2. Minimum Film Thickness

Effective Asphalt content	Asphalt Absorption (%)	Effective asphalt (ml)	Film thickness (microns)
4.36	0.5	191.84	32.30
3.86	1	169.84	28.59
3.36	1.5	147.84	24.89
2.86	2	125.84	21.19
1.86	3	81.84	13.78
0.86	4	37.84	6.37

APPENDIX D
GEOMERTIC DETAILS OF FRACTURE TEST SPECIMEN AND MOLDS FOR ASPHALT MASTIC

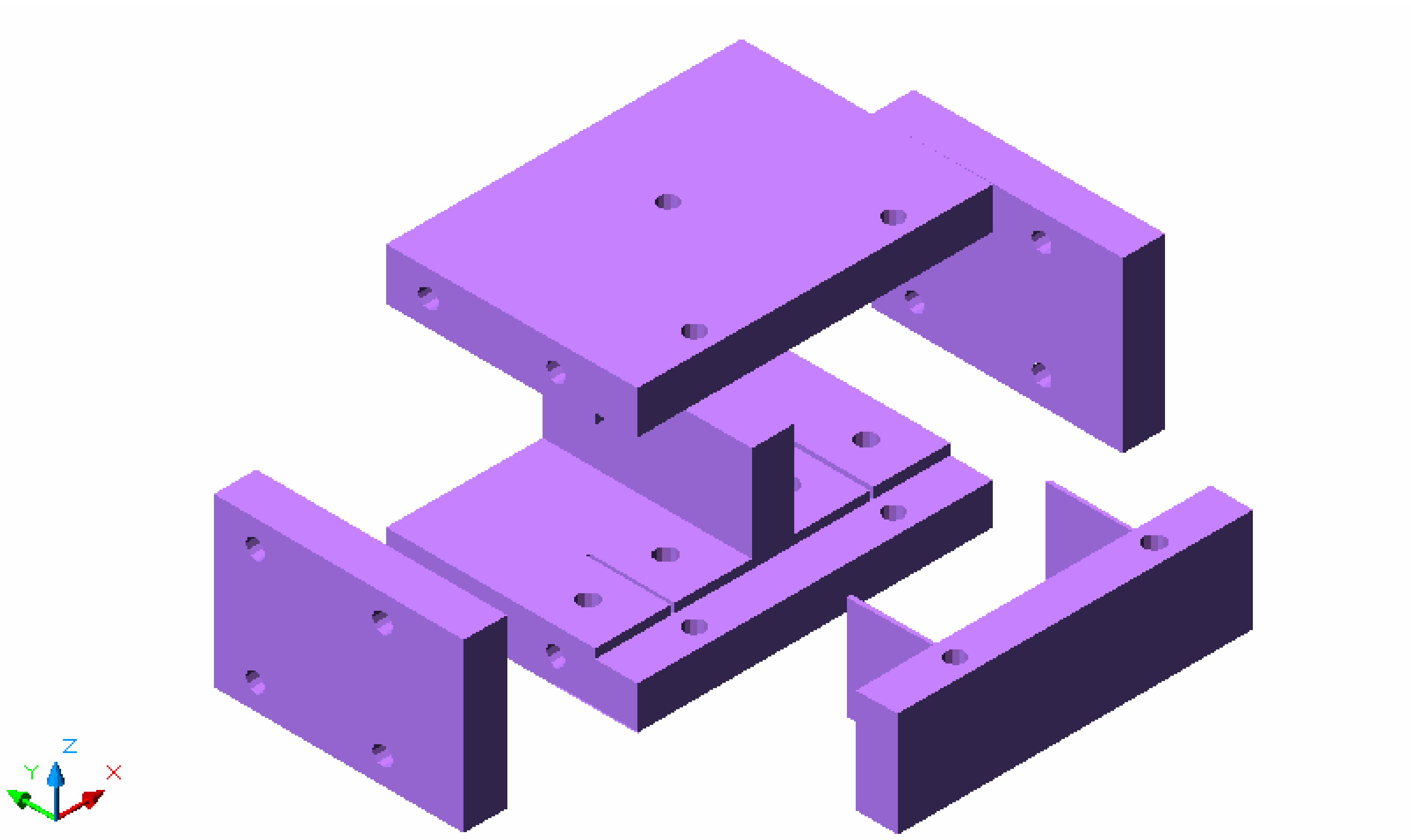


Figure D-1. Showing 3-D view of mold designed for preparing specimen for Asphalt Mastic

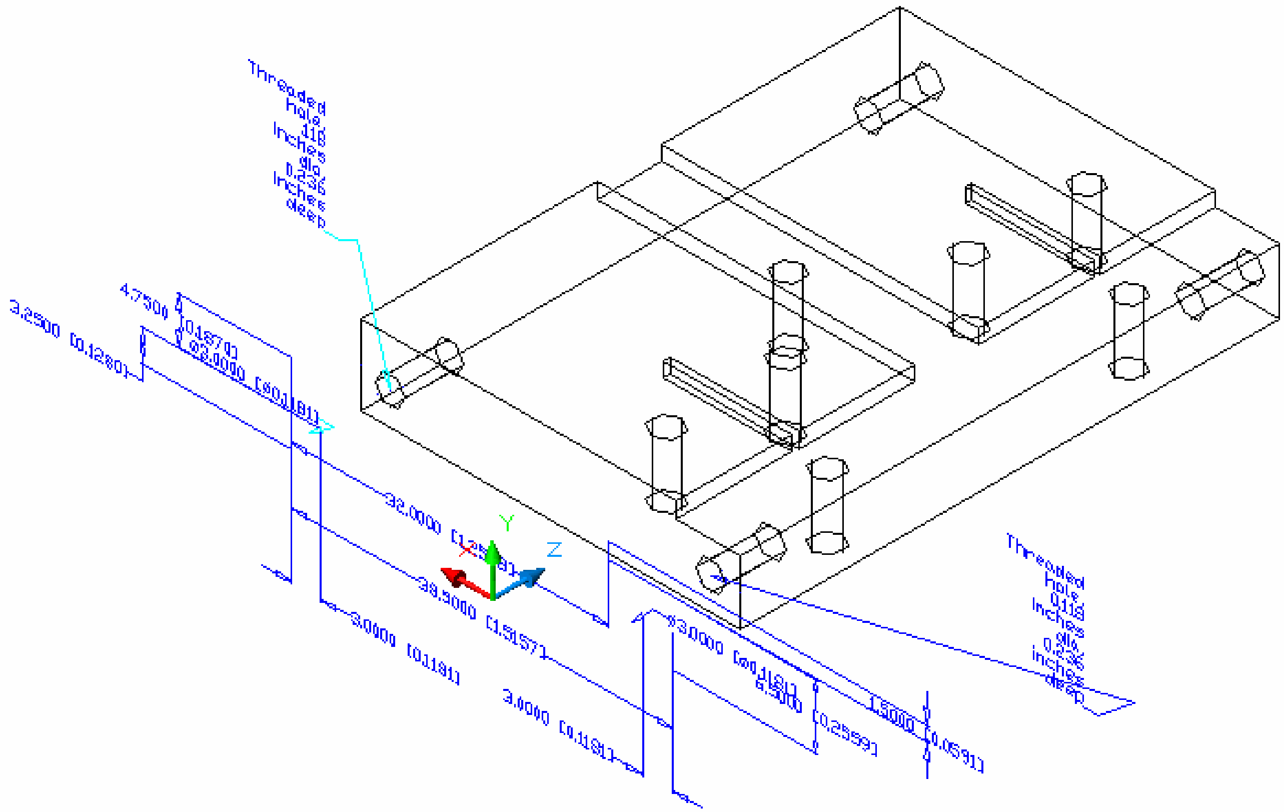


Figure D-2. Base plate 3-D wire view showing position of groves and notch

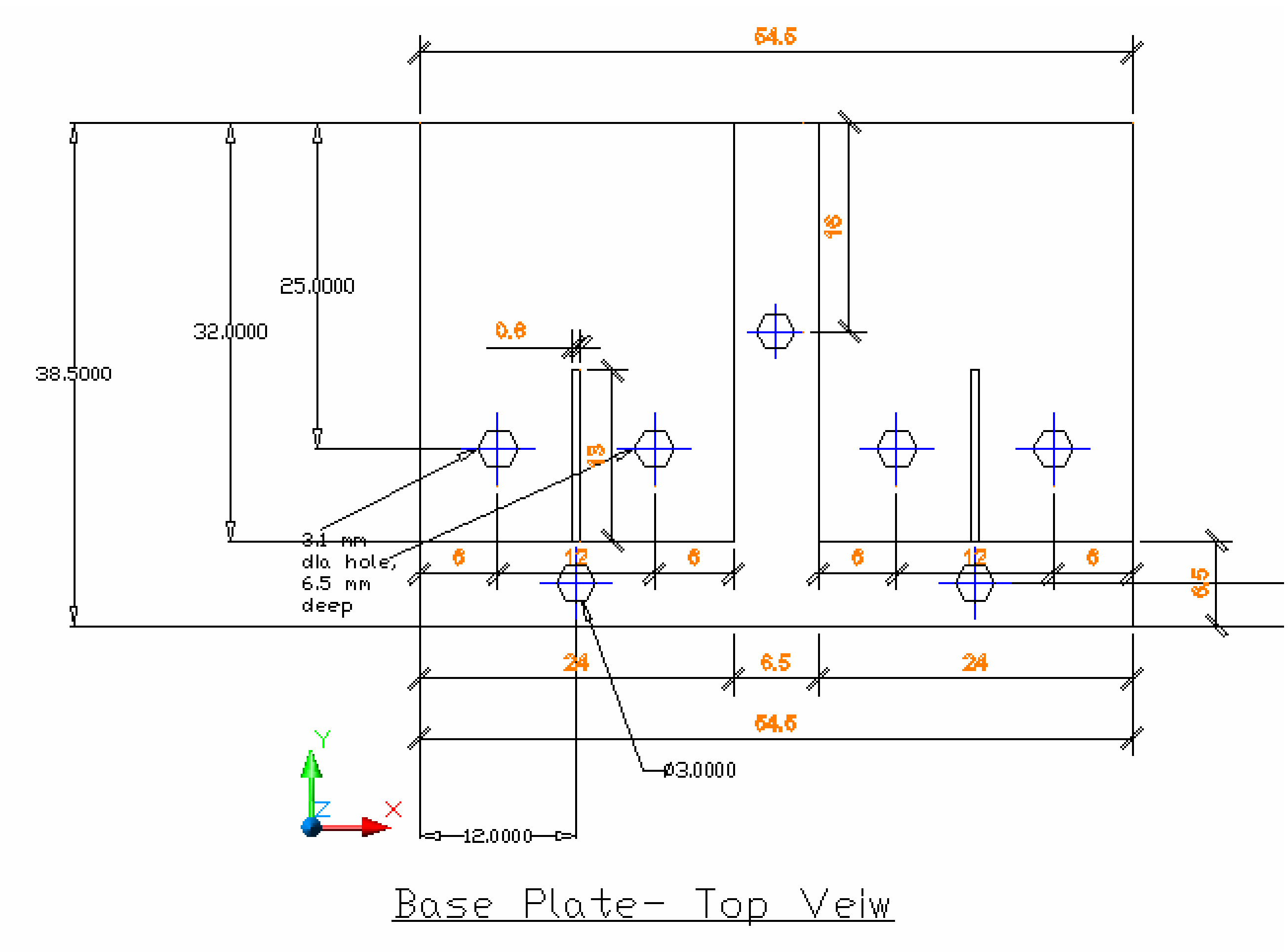


Figure D-3. Base plate geometry

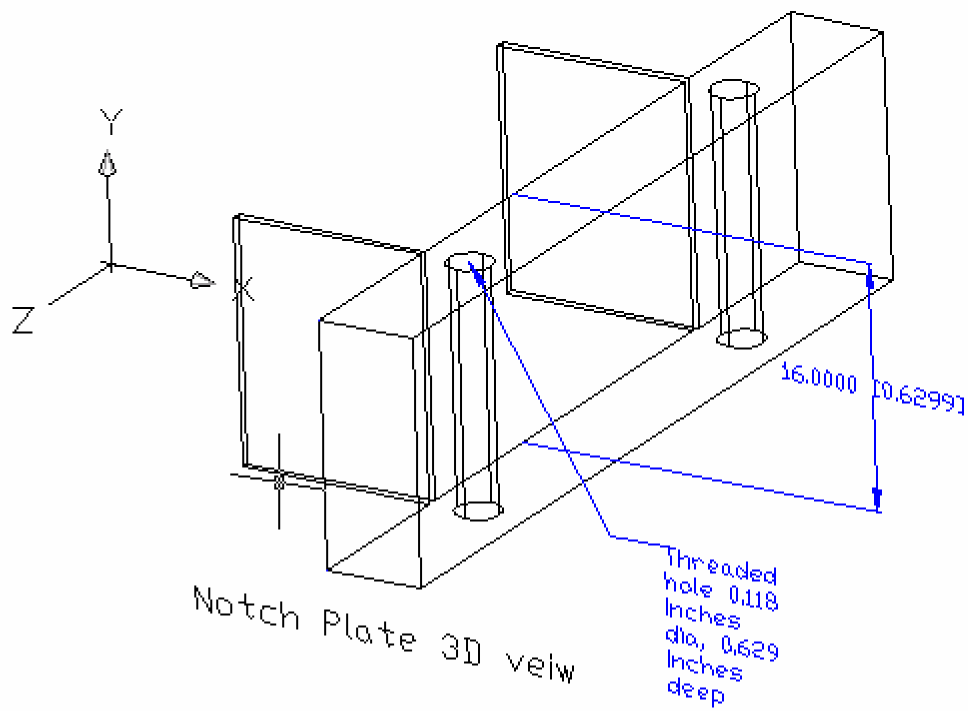


Figure D-4. Notch plate 3-D wire view.

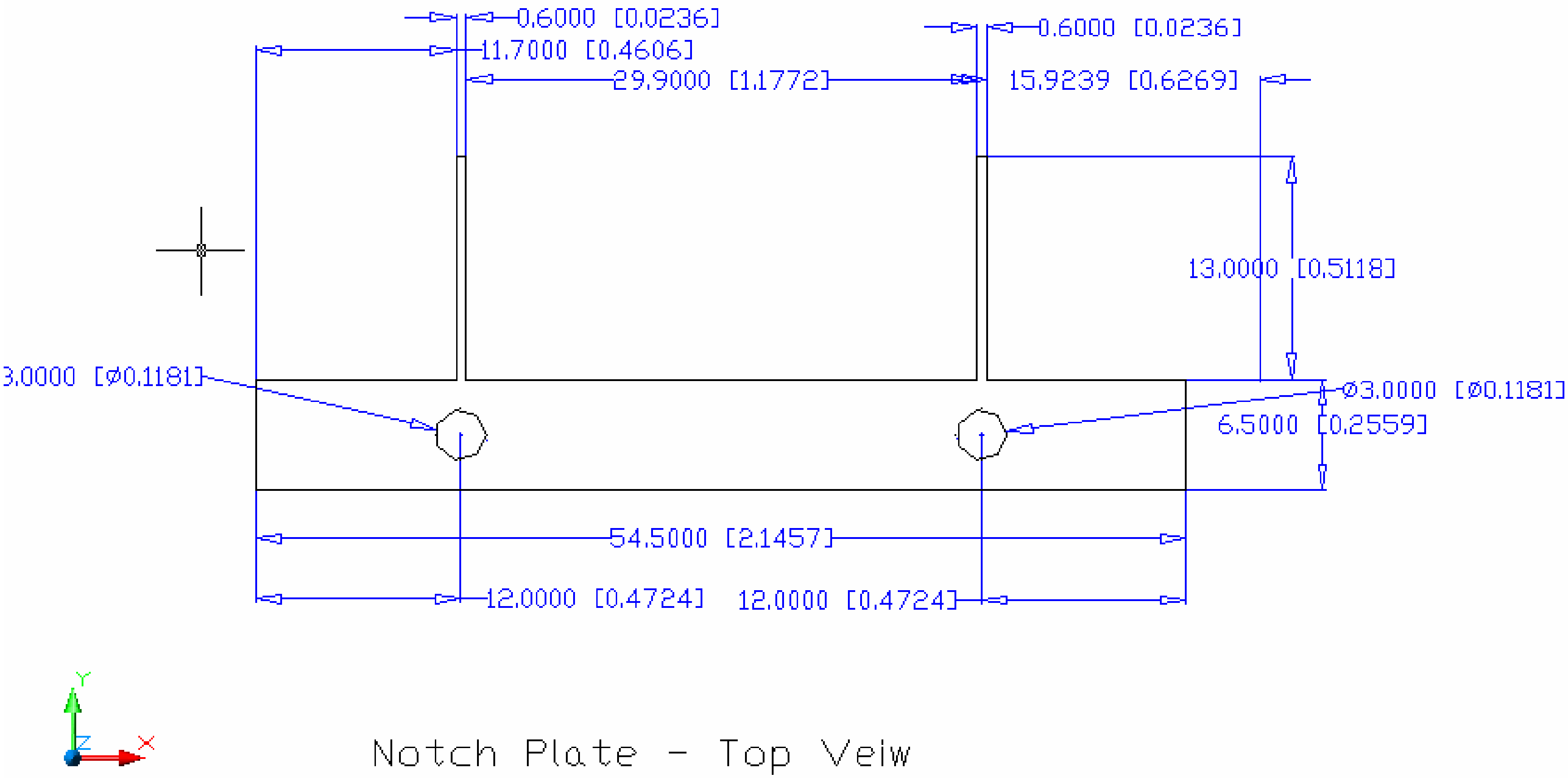


Figure D-5. Notch plate geometry

APPENDIX E
VOLUMETRIC PROPERTIES OF MIXTURES

Table E-1. Volumetric Properties of all the Mixtures

Volumetric Properties	Denotation	GPEM-Granite	GPEM-Limestone	I-295 PFC Granite Gradation (1)	I-295 PFC Granite Gradation (2)	FC-5 Granite	FC-5 Limestone
Bulk specific Gravity	Gsb	2.626	2.442	2.729	2.716	2.623	2.444
Maximum Specific Gravity	Gmm	2.414	2.298	2.485	2.491	2.441	2.336
Specific Gravity of Asphalt	Gb	1.03	1.03	1.03	1.03	1.03	1.03
Total Asphalt	Pb (%)	6.00	6.50	6.00	5.90	6.00	6.40
Effective Specific Gravity	Gse	2.640	2.513	2.731	2.734	2.675	2.558
Asphalt Absorption	Pab (%)	0.215	1.193	0.031	0.252	0.762	1.874
Effective Asphalt Content	Peff (%)	5.785	5.307	5.969	5.648	5.238	4.526
Bulk Specific Gravity of Compacted Gravity (Dimensional Analysis)	Gmb	1.961	1.927	1.957	1.945	1.916	1.923
Voids in Mineral Aggregates	VMA	30.23	28.3	32.69	32.76	32.67	29.64
Voids filled with Asphalt	VFA	3.86	42.89	34.94	33.05	34.17	40.34
Voids in Total Mix	VTM	18.78	16.16	21.27	21.93	21.51	17.68
Bulk Specific Gravity of Compacted Gravity (CoreLok)	Gmb	-	1.992	-	-	-	-

Table E-1. Continued.

Volumetric Properties	Denotation	GPEM-Granite	GPEM-Limestone	I-295 PFC Granite Gradation (1)	I-295 PFC Granite Gradation (2)	FC-5 Granite	FC-5 Limestone
Water Absorption	Wab (%)	-	3.38	-	-	-	-
Film Thickness (GDOT's method)	(Microns)	38.08	34.76	27.12	25.77	19.96	24.12
Effective Film Thickness (Nukunya, 2001)	(Microns)	54.58	50.07	33.12	31.65	23.95	32.19
Theoretical Film Thickness (Hveem, 1991)	(Microns)	36.94	33.89	26.26	25.03	19.48	23.71

APPENDIX F
JOB MIX FORMULA

Table F-1. Composition of Job Mix Formula of FC-5 Limestone

Blend			45	48	7	JMF
Number of StockPiles			S1A	S1B	Scrns	
SIEVE SIZE	3/4"	19.0mm	100	100	100	100.0
	1/2"	12.5mm	79	100	100	90.6
	3/8"	9.5mm	36	92	100	67.4
	No. 4	4.75mm	7	26	100	22.6
	No. 8	2.36mm	3	7	68	9.5
	No. 16	1.18mm	3	3	67	7.5
	No. 30	600µm	3	3	55	6.6
	No. 50	300µm	3	2	35	4.8
	No. 100	150µm	2	2	14	2.8
	No. 200	75µm	1	1	3	1.1
Specific Gravity			2.4252	2.4509	2.527	2.444

Table F-2. Composition of Job Mix Formula of FC-5 Granite

Blend			77	12	10	1	JMF
Number of Stockpiles			#7	#789 Granite	Granite Screens	Lime	
SIEVE SIZE	3/4"	19.0mm	100	100	100	100	100.0
	1/2"	12.5mm	95	100	100	100	96.2
	3/8"	9.5mm	64	92	100	100	71.3
	No. 4	4.75mm	11	20	97	100	21.6
	No. 8	2.36mm	3	5	68	100	10.7
	No. 16	1.18mm	2	3	43	100	7.2
	No. 30	600µm	2	3	28	100	5.7
	No. 50	300µm	2	3	18	100	4.7
	No. 100	150µm	2	3	11	100	4.0
	No. 200	75µm	1.1	2.5	8	100	2.9
Specific Gravity			2.627	2.633	2.58	2.69	2.624

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BIOGRAPHICAL SKETCH

Lokendra Jaiswal was born on August 27, 1981, in the city of Indore, India. He received his Diploma in Civil Engineering from Maharashtra State Board of Technical Education, Nagpur, India, May 1999. He received his bachelor's degree in civil engineering from University of Pune, Pune, in May 2002.

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