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ABSTRACT

This research describes an investigation of the use of polymer-modified aggregate (PMA) as a bomb damage repair material. PMA, an open-graded aggregate partially bonded with polymer at the particle interfaces, could be an economical repair material and provide a strong subgrade for repaired airfield surfaces. A PMA repair material would consist of a 6 to 18 in. layer of partially bonded, porous aggregates over push-back debris or over a layer of ballast stone base material. The select fill, an open-graded aggregate, would provide the primary load bearing capacity. Adding polymer would provide tensile strength to the aggregate matrix, which, in its unbonded state, would not exhibit any tensile strength. A PMA repair material would also provide FOD protection.

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The University of Texas at Austin

College of Engineering

ADVANCED CONSTRUCTION MATERIAL FOR AIRFIELD PAVEMENTS AND RAPID RUNWAY REPAIR

by

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and
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THE UNIVERSITY OF TEXAS AT AUSTIN

December 1990

ADVANCED CONSTRUCTION MATERIAL FOR AIRFIELD

PAVEMENTS AND RAPID RUNWAY REPAIR

APPROVED:

Co-supervisor: ______________________

Dr. David W. Fowler

Co-supervisor: ______________________

Dr. Ramon L. Carasquillo

DEDICATION

This research is dedicated
to Jesus Christ, my Lord and Savior, and
to my family, Betsy and Mark.

ADVANCED CONSTRUCTION MATERIAL FOR AIRFIELD PAVEMENTS AND RAPID RUNWAY REPAIR

by

Vincent Maurice Saroni, B.S.C.E.

THESIS

Presented to the Faculty of the Graduate School of

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in Partial Fulfillment

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for the Degree of

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I greatly appreciated the funding support from the Air Force Engineering and Services Center and the opportunity to try something new.

My thanks also go to Dr. Fowler's staff, Rose Rung, David Whitney, Fred Barth, Linda Rosales, Joy Suvunphugdee, and Don Dombroski, who not only helped me in the research, but also shared in the joyous occasion of my wedding.

I owe a special thanks to my lovely bride, Betsy, and my son, Mark, who have been a source of strength and encouragement to me. Also, I appreciated all the typing and proofreading Betsy did in preparing the thesis.

August 1, 1990

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CHAPTER 1

INTRODUCTION

1.1 Background

For the past 30 years, the United States Air Force (USAF) has researched and developed various methods to improve its bomb damage repair (BDR) capabilities. The Air Force Engineering and Services Center (AFESC) at Tyndall Air Force Base has taken a leading role in developing and managing a Rapid Runway Repair (RRR) program which will provide state-of-the-art BDR capabilities during modern and future conflicts. AFESC's RRR program includes research and development in the following areas:

a. Preattack construction of Alternate Launch and Recovery Surfaces (ALRS).

b. Postattack environmental assessments.

c. Bomb damage repair techniques, including:

 (1) Advanced materials for crater repair.

 (2) Precast concrete slabs for crater repair.

 (3) Fiberglass membranes (i.e. foreign object damage (FOD) covers) for crater repair.

(4) Advanced materials for scab repair.

d. Equipment modifications and new equipment developments.

e. Other areas:

(1) Computer modeling of p tattack environment and sequencing of base recovery work activities.

(2) Assessing potential FOD to aircraft in the postattack environment.

(3) Establishing surface roughness criteria for repaired surfaces.

(4) Developing crater lip removal procedures and improving concrete cutting capabilities.

1.2 Previous Research

Previous AFESC research concluded that the method of percolating resin to form a polymer structural cap was one of the fastest and most effective ways of meeting the USAF's BDR criteria because it used less manpower and equipment, and completed the repair on or ahead of schedule (References 5 & 6). A life cycle cost (LCC) analysis showed the startup costs for the percolation method to be less than that of the premix methods (Reference 6). However, the 20-year LCC of the percolation method was more than the premix method, because the large quantity of chemicals needed and the replacement costs of those chemicals, due to a finite shelf life, increased the expense significantly.

Previous AFESC research also concluded that most methods of crater repair explored to date have had problems with the strength of the subgrade. Because of a weak subgrade, either additional material was needed to thicken the structural cap resulting in a more expensive repair, or additional compaction was needed to strengthen the subgrade thus resulting in a more expensive and time intensive repair. Conclusions from some of the previous research are summarized as follows:

a. Polymer structural cap: Cap thickness is governed by deflection characteristics rather than strength for polyurethane structural caps on weak subgrades and with flexural strengths greater than 700 psi. (Reference 6).

b. Polymer structural cap: Cap deflections are significantly affected by subgrade consolidation near the center of caps, by load transfer near the edges, and by elastic/nonelastic characteristics of the cap at the time it is loaded (Reference 6).

c. Polymer structural cap: Results indicate that cap thickness, elastic modulus, and subgrade strength are the primary factors controlling repair stresses and deflections (Reference 6).

d. Fiberglass mat system: The thickness of fill material should be increased to improve the performance under traffic (Reference 1).

e. Fiberglass mat system: Durability of the mat fulfilled the stated requirement, but the performance of the crushed stone was poor. All maintenance required during loadcart trafficking was related to the crushed stone base course, not the mat (Reference 7).

f. Precast slabs: To reduce initial slab movement, some compactive effort should be applied to the base and bedding material placed in the crater (Reference 1).

1.3 Scope of Research

This research had the objective of investigating a new repair material, one that is economical and provides a strong subgrade. Polymer-modified aggregate (PMA), an open-graded aggregate partially bonded with polymer at the particle interfaces, fulfills both requirements. A PMA repair material consists of a 6 to 18 in. layer of partially-bonded, porous aggregate over push-back debris or over a layer of ballast stone base material. The select fill, an open-graded aggregate, provides the primary load bearing capacity. Adding polymer provides tensile strength to the aggregate matrix which, in its unbonded state, does not exhibit any tensile strength. A PMA repair material would also provide FOD protection.

This research is presented as follows:

a. Chapter 2 describes the variables.

b. Chapter 3 outlines the preparation and casting of the PMA specimens.

c. Chapter 4 outlines the testing procedures.

d. Chapter 5 describes the data reduction.

e. Chapter 6 discusses the test results.

f. Chapter 7 presents a summary, conclusions and recommendations.

1.4 Objective of Research

The objective of this research was to investigate PMA as a bomb damage repair material. This objective was accomplished by:

a. Constructing a mold, casting the specimen and establishing procedures for testing PMA in flexure.

b. Measuring the flexural strength of PMA beams.

c. Comparing flexural strengths of PMA beams at 6-, 12-, and 18-in. depths.

d. Comparing flexural strengths of PMA beams with varying aggregates, levels of compaction, and resin content.

CHAPTER 2

EXPERIMENTAL DESIGN

2.1 Variables

Casting and testing data were collected for the 24 conditions listed in Table 2.1. The variables studied included: aggregate type (siliceous gravel and crushed limestone), compaction (compacted and uncompacted), resin loading (maximum and minimum), and depth of specimen (0 to 6 in., 6 to 12 in., and 12 to 18 in.). The specimens were tested in flexure for each combination of variables. At least three specimens at the 0- to 6-in. depth were tested for each combination. In most cases, three specimens at 6- to 12-in. and 12- to 18-in. depths were tested, depending on availability resulting from the depth of penetration of the resin.

2.2 Numbering

Each specimen was assigned an identification number of the form ABC.XY. Each number represents a specific variable, as shown in Table 2.2 and Fig. 2.1. For example, specimen 212.32 refers to a specimen composed of crushed limestone, compacted, maximum

Table 2.1 Specimen Variables.

Variables				Number of specimens tested in flexure
Aggregate Type	Compaction	Resin Loading	Specimen Depth, in.	
Gravel	compacted	min	0 to 6	3
Gravel	compacted	min	6 to 12	3
Gravel	compacted	min	12 to 18	1
Gravel	compacted	max	0 to 6	6
Gravel	compacted	max	6 to 12	5
Gravel	compacted	max	12 to 18	5
Gravel	uncompacted	min	0 to 6	3
Gravel	uncompacted	min	6 to 12	3
Gravel	uncompacted	min	12 to 18	3
Gravel	uncompacted	max	0 to 6	3
Gravel	uncompacted	max	6 to 12	3
Gravel	uncompacted	max	12 to 18	3
Limestone	compacted	min	0 to 6	5
Limestone	compacted	min	6 to 12	5
Limestone	compacted	min	12 to 18	2
Limestone	compacted	max	0 to 6	3
Limestone	compacted	max	6 to 12	3
Limestone	compacted	max	12 to 18	3
Limestone	uncompacted	min	0 to 6	3
Limestone	uncompacted	min	6 to 12	3
Limestone	uncompacted	min	12 to 18	3
Limestone	uncompacted	max	0 to 6	3
Limestone	uncompacted	max	6 to 12	3
Limestone	uncompacted	max	12 to 18	3

Table 2.2 Specimen Designation.

A - First digit specifies type of aggregate.

- 1 = Siliceous gravel.
- 2 = Crushed limestone.

B - Second digit specifies compaction.

- 1 = compacted.
- 2 = uncompacted.

C - Third digit specifies resin loading.

- 1 = minimum loading (4060 ml).
- 2 = maximum loading (6090 ml).

X - Fourth digit specifies position of the specimen in the box.

- 1 = first specimen in the box.
- 2 = middle specimen in the box.
- 3 = last specimen in the box.

Y - Fifth digit specifies depth of the specimen from the surface.

- 1 = 0 to 6 in., or 6-in. depth.
- 2 = 6 to 12 in., or 12-in. depth.
- 3 = 12 to 18 in., or 18-in. depth.
- 4 = 18 to 23 in., or 23-in. depth.

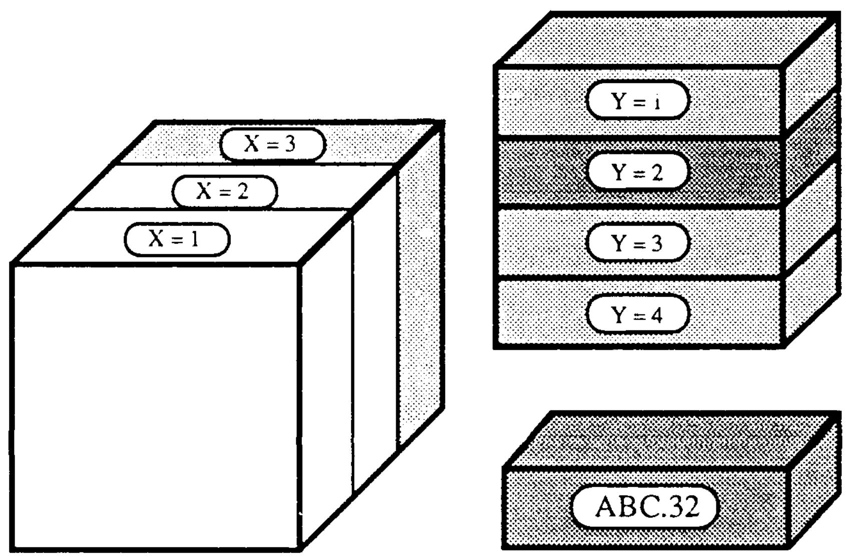


Figure 2.1 Specimen Identification Numbering.

resin loading, was the third specimen in the mold, and was cut from the 6- to 12-in. depth.

CHAPTER 3

SPECIMEN PREPARATION AND CASTING

3.1 General

The polymer concrete specimens were cast by pouring resin over aggregate placed in a partitioned box which served as the mold. The aggregate was oven-dried and weighed before being placed into each section of the partitioned box. The resin was measured, mixed and then poured over the aggregate in each mold. Casting and testing data are given in Appendix A.

3.2 Molds

A special mold was constructed for this test. To test the polymer-modified aggregate (PMA), the resin was allowed to freely percolate through the aggregate. A standard 6-in. x 6-in. x 20-in. mold would have caught any resin not retained by the aggregate resulting in a solid layer of polymer on the bottom of each specimen. A specimen with a layer of polymer on the bottom would have a higher flexural strength than possible under actual field conditions.

An alternate method of simulating field conditions was evaluated. Constructing a special mold with a screen as the bottom surface of the mold was considered. However, the gauge of wire or size of mesh required to simulate the effect of aggregate at lower levels was not known. Another concern was that the resin would form a solid layer of resin at the bottom of the mold, between the screen and the aggregate. Furthermore, a screen or wire mesh would deform under the weight of the aggregate and resin, and a screen would also be difficult to securely attach to the sides of the mold.

It was decided that a mold with a depth of about 2 ft. would best simulate field conditions, where the resin could freely percolate through the aggregate. A mold with a 2-ft. depth would also allow the flexural strength of the PMA at various depths to be evaluated.

Each mold was approximately 2 ft. x 2 ft. x 2 ft., as shown in Figs. 3.1, 3.2, 3.3 and 3.4. Two molds were constructed. The sides and bottom were removable. The pieces of the mold were machine cut from an 8-ft. x 4-ft. x 3/4-in. sheet of high density polyethelyne and were grooved to allow easy, yet snug, assembly. A thickness of 3/4 in. was necessary to provide strength and stiffness to a mold this size. The resin could be easily cleaned from the polyethelyne without the use of a release agent. Bracing was added to hold the mold together

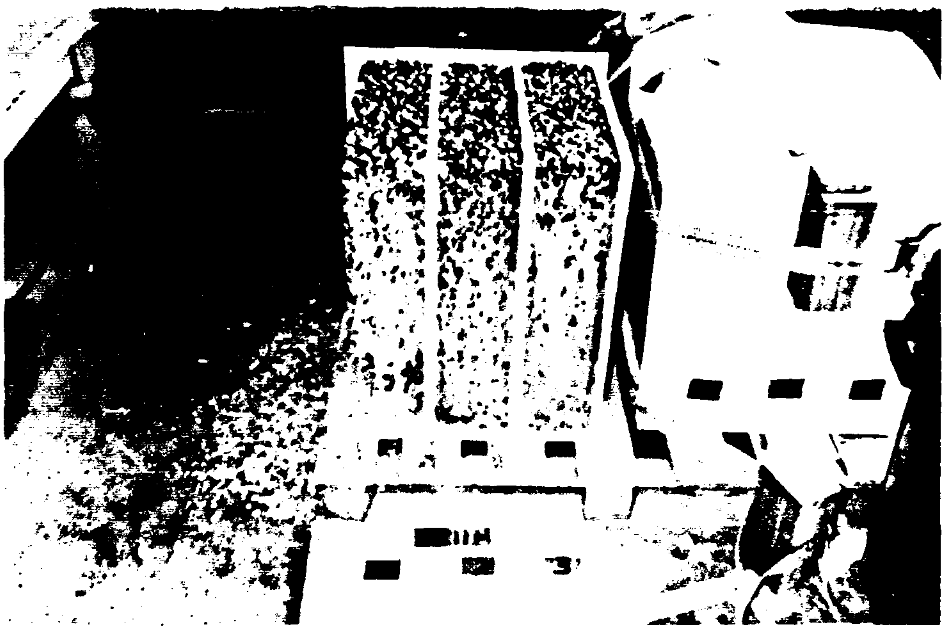


Figure 3.1 High Density Polyethelyne Molds Used in Casting PMA Specimens.

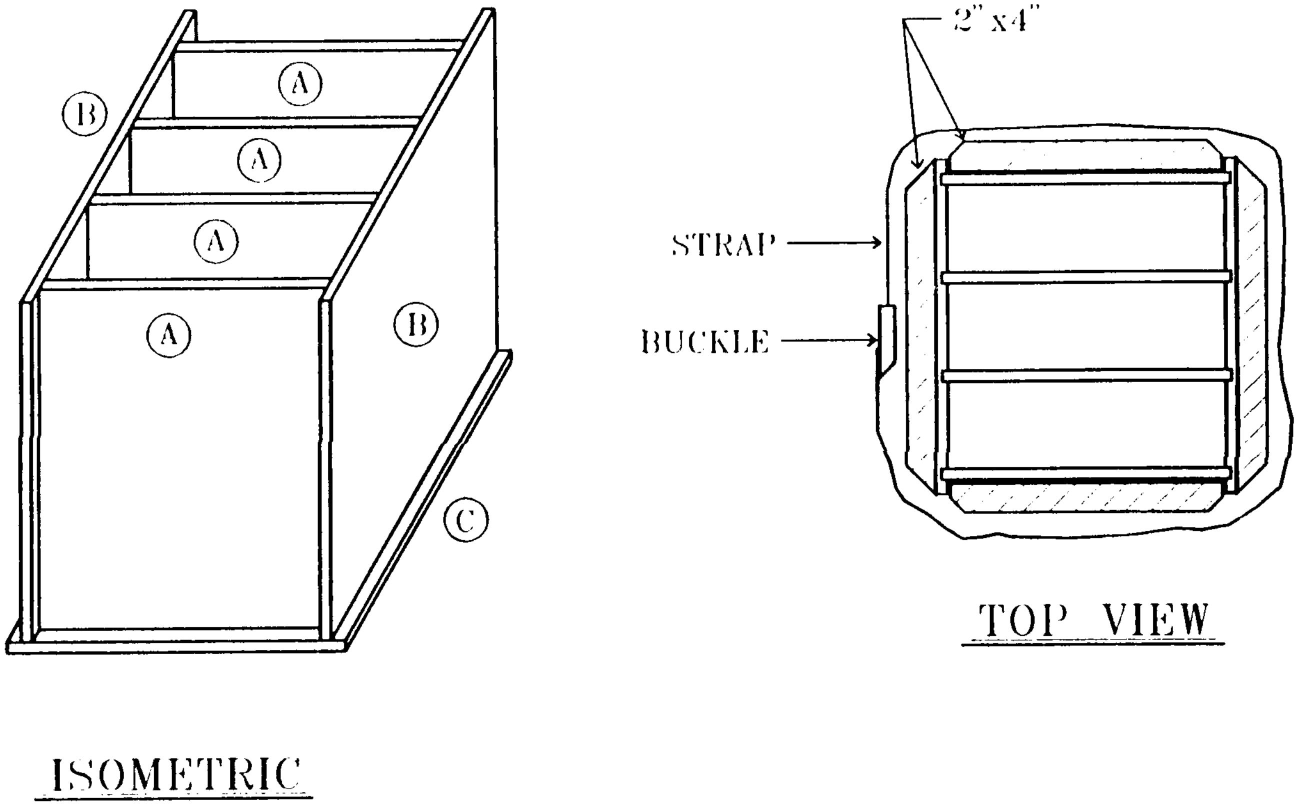


Figure 3.2 Drawing of High Density Polyethelyne Mold.

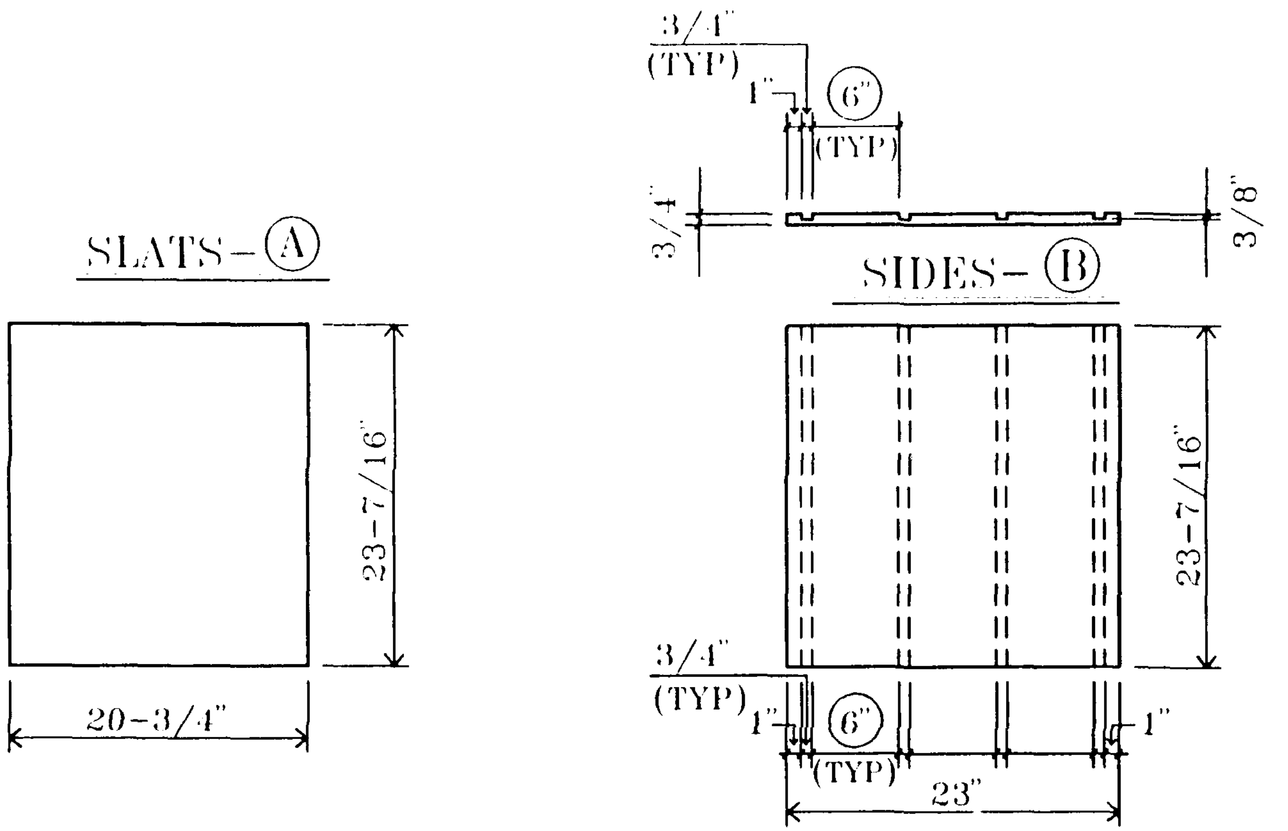
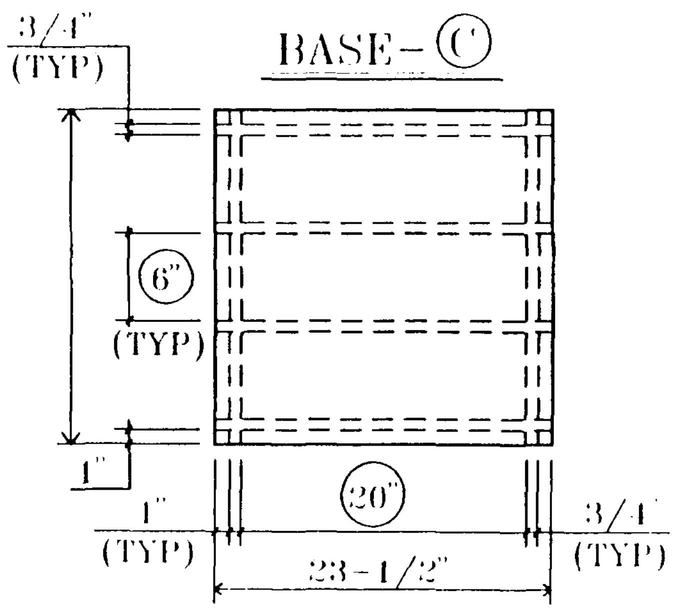


Figure 3.3 Diminsions for High Density Polyethelyne Mold.



NOTES:

1. ALL SLOTS ARE 3/8" DEEP.
2. ALL SLOTS ARE 3/4" WIDE.
3. CIRCLED NUMBERS MUST BE EXACT INTERIOR DIMENSIONS (i.e., (6") & (20")).
4. 1/16" TOLERANCE ON ALL OTHER DIMENSIONS.
5. DASHED LINES REPRESENT SLOTS OR GROOVES.

Figure 3.4 Diminsions Continued for High Density Polyethelyne Mold.

and to minimize deflection of the sides during compaction of the aggregate.

Each mold was partitioned into three separate sections. Each section acted as an individual mold. The interior dimensions of each section were 6 in. x 20 in. x 23 1/8 in.

3.3 Aggregate

Two types of aggregate were used in this test: siliceous gravel and crushed limestone. Both were procured from local suppliers and the gradation ranged from No. 57, nominal 1-in. diameter, to No. 4. Appendix B lists the aggregate gradations. The siliceous gravel had a dry-rodded unit weight (DRUW) of 101.9 pounds per cubic feet (lb/cf.), a dry-loose unit weight of 91.6 lb/cf., and a bulk specific gravity (BSG) of 2.61. The crushed limestone had a DRUW of 88.7 lb/cf., a dry-loose unit weight of 74.5 lb/cf., and a BSG of 2.48. The unit weight was determined in accordance with the American Society of Testing and Materials (ASTM) C-29-78. The BSG was provided by the local supplier of the aggregate.

The aggregate was oven-dried at about 275°F and then cooled at the ambient temperature, usually overnight. After cooling, the aggregate was either placed into the mold or was stored in sealed garbage bags until casting.

Once the molds were assembled, the aggregate was scooped into a metal bucket, weighed, and placed into a specific section of the mold. The weight of the aggregate was recorded before it was placed in each section. To ensure even distribution of the aggregate inside the mold and to minimize the deflection of the partitions, the aggregate was first placed in the middle section in a 4-in. lift, and then in the two side sections, also in 4-in. lifts. If the specimen was to be compacted, each 4-in. lift was compacted by 50 blows with a 2-in. x 4-in. x 4-ft. piece of wood. The top was leveled and compacted by striking a hammer on a short piece of wood. For uncompacted specimens, the aggregate was placed in 4-in. lifts and leveled.

3.4 Resin

The Air Force provided a polyurethane resin to be used in this test. Part A, the isocyanate, had a density of 1.112 gm/ml; Part B, the polyol, had a density of 1.054 gm/ml; Part C, the catalyst, had a density of 1.050 gm/ml.

For consistency, Part B was measured by weight to the nearest 0.01 gm. Part A was determined visually to ensure that an equal volume to Part B was used.

Through initial testing, it was found that Part C should be 3 percent of the weight of Part B to obtain a set time of about two minutes. Two minutes was just enough time to mix the resin, pour it, and allow it to percolate through the aggregate. As the ambient temperature increased, the weight percent of Part C had to be decreased by trial and error to avoid a "quick-set" of the resin. The catalyst amount was 3 percent by weight for all specimens unless otherwise noted in Appendix A. Part C was also measured by weight to the nearest 0.01 gm.

The maximum and minimum resin loadings were established by trial and error. The first three specimens used 4060 ml. for the resin loading: 2000 ml. of Part A, 2000 ml. of Part B and 60.20 ml. of Part C. Although resin percolated to a depth of 20 in., not enough resin percolated to the 12- to 18-in. depth to allow a specimen to be sawed and tested (Table A.3, specimens 111.00). As a result, it was decided that 4060 ml. would be the minimum resin loading and a greater quantity of resin would be used for the maximum loading conditions. For the maximum resin loading, the objective was to pour enough resin into the mold so that ample resin percolated to the

12- to 18-in. depth. This would allow a specimen at the 12- to 18-in. depth to be obtained for testing. A 50-percent increase in the resin loading, 6090 ml., accomplished this objective: 3000 ml. of Part A, 3000 ml. of Part B and 90.34 ml. of Part C.

3.5 Pouring the Resin

Safety was the top priority during the mixing and pouring of the resin. The lab was kept well ventilated by opening all doors and windows and by having a large fan constantly blowing the vapors out of the lab. Resins were never stored nor poured near a source of heat. All resins were stored in a chemical storage room. All lab assistants wore pants and aprons made of a Tyvek® material, two layers of gloves, and goggles. All waste contaminated by resin was properly disposed.

Two people helped in the pouring process. One person, the timekeeper, monitored the elapsed time from the start of mixing until the resin set. The other person, the mixer, was the only person to ever handle, mix, pour, or dispose of the resins. The mixer weighed the required amounts of Part B in 1000 ml. beakers and Part C in 100 ml. beakers. Part A was measured visually in 1000 ml. beakers.

Parts B and C were mixed together in an 8-qt. container. Part A was added, the stopwatch started, and all parts mixed together with a wooden stick. After thorough mixing, the container was sealed with a lid containing approximately twenty 3/8-in. holes that evenly dispersed the resin over the specimen surface. The mixing process took 20 to 30 seconds.

The container was then tipped upside down over one section of the mold and the resin was poured evenly over the specimen surface at a constant rate. A small air hole was located at the bottom of the container to allow the pressure inside the container to equalize. It was covered with tape during mixing and removed by the timekeeper at the beginning of pouring. The pouring process took 60 to 75 seconds.

3.6 Polymerizing and Mold Removal

The resin typically set 15 to 30 seconds after the pouring was completed. Appearance and pourability were used to define the set time. The resin started out with a viscosity nearly as low as water. After about two minutes, the resin became thicker in consistency. At about the same time, dark fibers, or chains, began to form in the resin mixture. A few seconds later, the mixture became solid and turned a light tan color. The moment it became unpourable and light tan in color was defined as the set time. Overall, the resin initially set about two minutes after the mixing began and was hard after seven minutes.

After the resin set, the amount of unused resin was measured. The empty weight of the beakers and the pouring container were subtracted from their weight after the mixing and pouring process. This gave the weight of the residual resin left in the various containers. The resin left on the wooden stick was also determined and an estimate was made on the weight of the resin spilled during the pouring process.

The specimens polymerized at least 12 hours before mold removal and sawing. All specimens polymerized at least 24 hours before testing. Specimens polymerized at the ambient temperature in the lab.

After removing the bracing around the mold, three side panels were removed. The first specimen was removed from the partition that separated it from the next specimen, and then the partition was removed. This was repeated until all specimens were removed from the mold.

Mold pieces were cleaned after every pour and care was taken not to scratch the interior surfaces. After reassembly, all inside seams were thoroughly caulked with a silicon rubber sealant.

3.7 Concrete Sawing

Starting at the top of the specimen, lines were drawn so that each specimen would be 6-in. deep after it was sawed. The minimum and maximum depths the resin percolated were measured prior to sawing.

A portable concrete saw was placed on top of a 4-in. high wooden platform as shown in Fig. 3.5. The specimen was held securely against the platform. The operator made a straight cut by lowering the saw blade through the specimen along the drawn line.

After the specimens were cut at 6-in. intervals, the 6-in. x 6-in. x 20-in. beams were transported approximately 10 miles to the testing lab. The truck was driven slowly and sheets of plywood were used to help minimize any damage to the specimens.

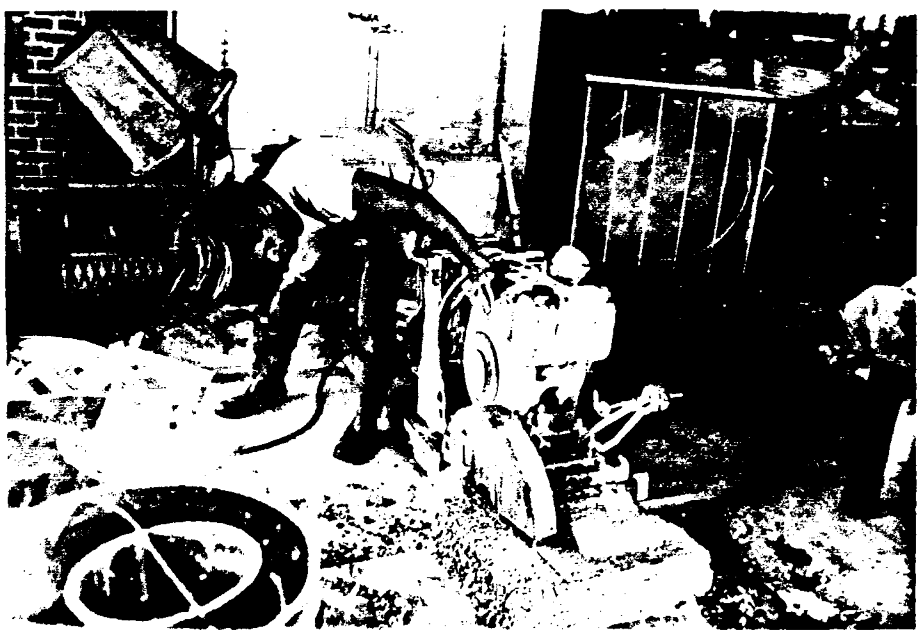


Figure 3.5 Concrete Sawing PMA Specimens into 6-in. x 6-in. x 20-in. Sections.

CHAPTER 4

TESTING

4.1 Specimen Measurements

As shown in Fig. 4.1, specimen measurements were taken just prior to actual testing so that the measurements accurately represented the specimen at the time of testing. Three measurements were taken for each dimension to the nearest 0.05-in. These measurements were used to determine the average width, depth and length of the specimen. When a resin-aggregate void existed at the edge of the specimen, a minimum dimension of 5.75-in. was used.

A resin-aggregate void is defined as a void which resulted when pieces of polymer-modified aggregate broke off. It is not a trapped air void in the PMA matrix. Regardless of the precautions taken while handling the specimens, pieces of polymer-modified aggregate broke off during mold removal, concrete sawing, and transporting but most often during sawing. Occasionally, voids resulted when resin failed to percolate completely through the aggregate.

To calculate the amount of resin retained by the specimen, the

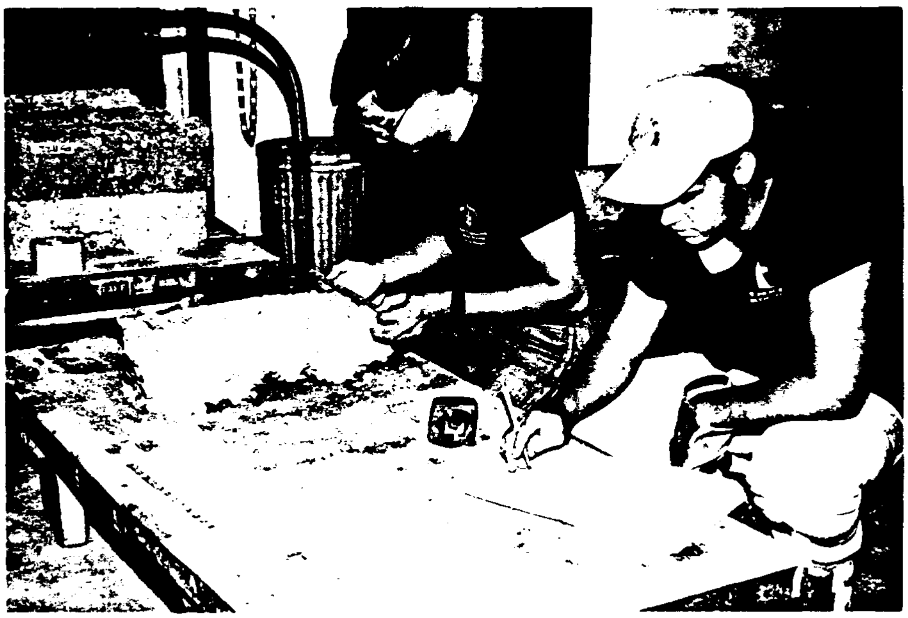


Figure 4.1 Measuring PMA Specimens for Average Dimensions, Resin-Aggregate Voids, and Weight.

volume of the resin-aggregate void was measured with a 3-in. x 2.5-in. x 2.5-in. block. This volume is recorded in Appendix A under the column "Voids," and Figs. 4.2 and 4.3 show resin-aggregate voids in PMA specimens. In addition to measuring resin-aggregate voids, specimens were weighed on a scale to the nearest 0.06 lb. prior to testing.

4.2 Flexural Testing

Flexural strength testing was conducted according to the American Society for Testing and Materials (ASTM) C-78-75. The first several specimens were tested using a hand-operated Rainhart Testing Machine. These specimens are identified in Appendix A. However, this machine could not accurately measure the flexural strength when it was less than 200 psi., so all remaining tests were conducted using a hydraulic testing machine.

As shown in Fig 4.4, the tests used the standard apparatus for third-point loading. The specimens had an 18-in. span and were loaded at the third-points. A few minor adjustments were made to ASTM C-78-75 to accommodate the unique characteristics of PMA. ASTM requires a loading rate of 125 psi/min. to 175 psi/min. after rapidly loading the specimen to 50 percent of its

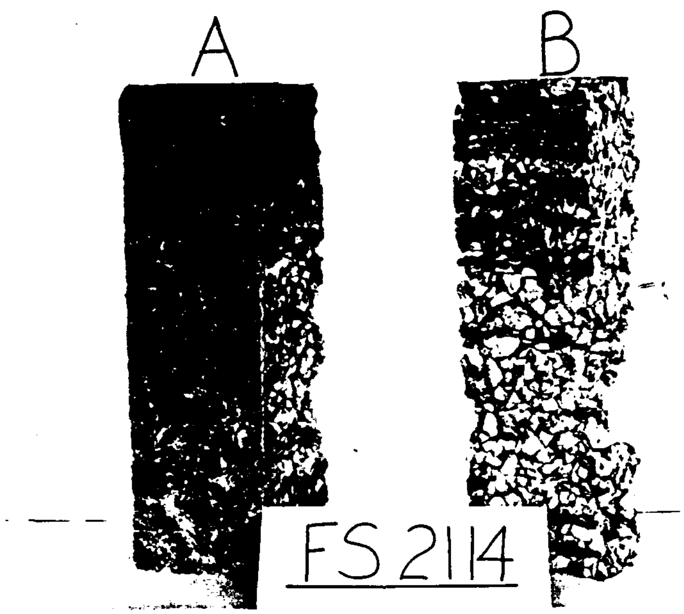


Figure 4.2 Crushed Limestone PMA Specimens Showing Resin-Aggregate Voids. Specimens (B = No. 211.42 and C = No. 211.43) are at the 12-in. and 18-in. Depths.

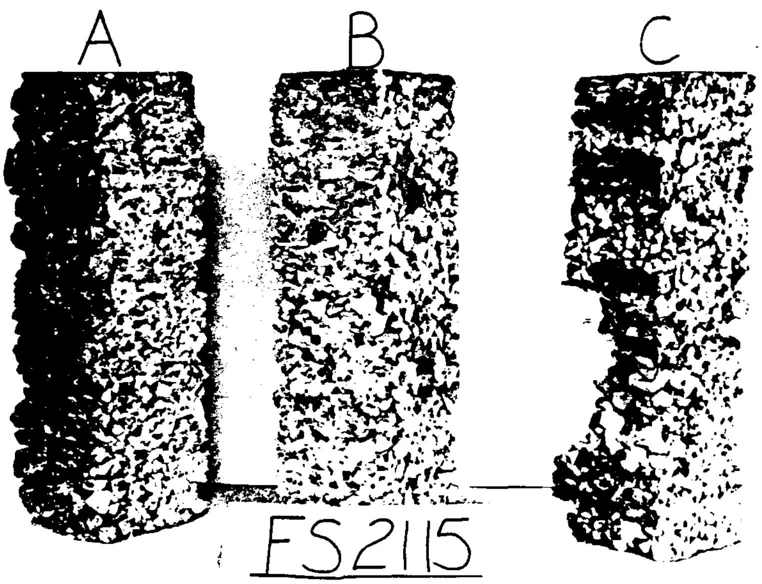


Figure 4.3 Crushed Limestone PMA Specimens Showing Resin-Aggregate Voids. Specimen A (No. 211.51) shows the top surface of PMA and Specimen C (No. 211.53) Shows Resin-Aggregate Voids.

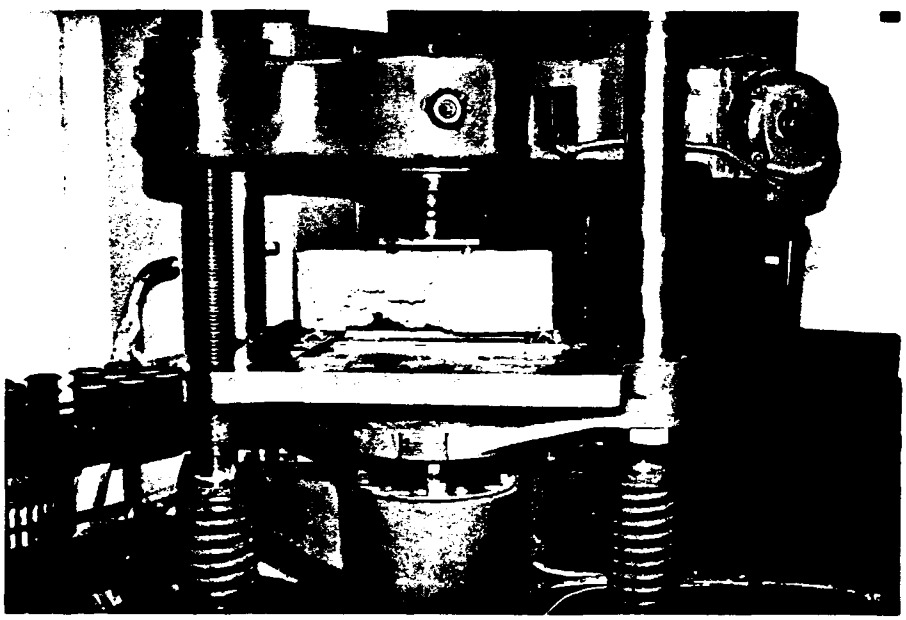


Figure 4.4 Measuring the Flexural Strength of PMA in a Hydraulic Testing Machine.

breaking load. This rate was too high for PMA specimens since the ultimate load was so low. A loading rate of 40 psi/min. to 45 psi/min. (i.e. 480 lb/min. to 540 lb/min.) was used instead. Also, thin strips of wood were used in place of leather shims.

Another adjustment was made to more accurately measure the flexural strength of the specimen. Whenever possible, the specimens were tested in the same position as they were cast. This adjustment was made because sometimes a thin layer of resin formed on the sides of the specimen where it was in contact with the mold. If the specimen had been tested on its side, the strength might have been slightly higher. When the top surface was too rough or had resin-aggregate voids, it was turned on its side for testing. Fig. 4.5 shows a typical PMA specimen after testing.

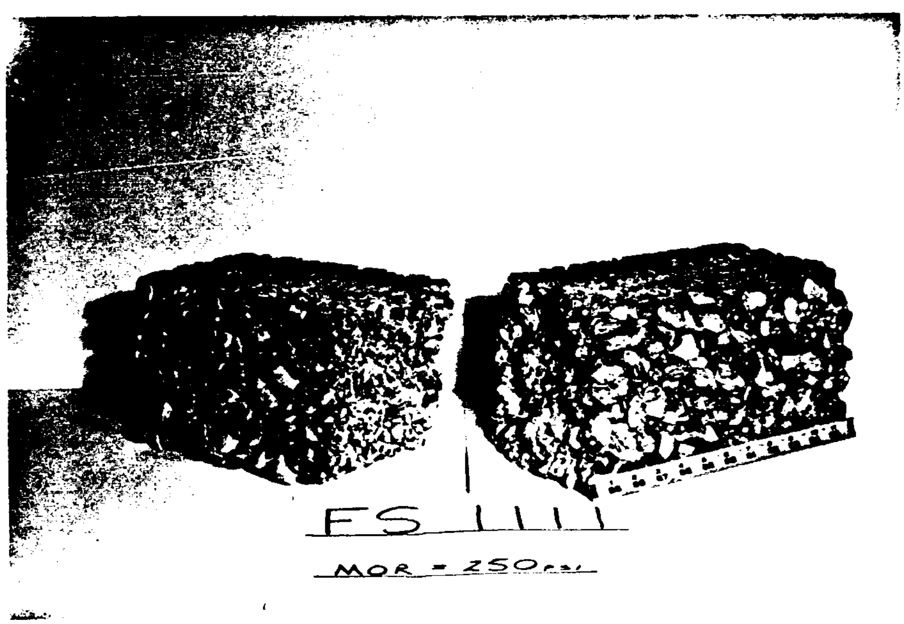


Figure 4.5 Siliceous Gravel PMA Specimen After Testing. Specimen No. 111.11 was under Maximum Compaction and Minimum Loading Conditions at the 6-in. Depth.

CHAPTER 5

DATA REDUCTIONS

5.1 Flexural Strength

The modulus of rupture (MOR) was used to define the flexural strength. The MOR was calculated to the nearest 5 psi. The equations listed in ASTM C-78-75 were used to calculate the MOR, except for the specimens tested on the Rainhart Testing Machine. If the location of the fracture line lay within the middle one-third of the span length, the following equation was used:

$$R = \frac{Pl}{bd^2}$$

where:

R = modulus of rupture, psi.,

P = maximum applied load, lb.,

l = span length, (18 in.),

b = average width of specimen, in.,

d = average depth of specimen, in.

The one occasion when the fracture line was outside the middle one-third of the span by not more than 5 percent, the following equation was used:

$$R = \frac{3Pa}{bd^2}$$

where:

a = average distance between the line of fracture and the nearest support, in.

5.2 Density

The density of the placed aggregate was calculated separately for each section of the mold and assumed to be the same through the full depth. The weight of the aggregate placed in each section was recorded as previously discussed. The volume of each section was 1.61 cf. In one test, there was not enough aggregate to fill the mold. In this case (Table A.7), the aggregate was placed to a level of 3 in. below the top of the mold. The volume of each section for this mold was 1.40 cf.

Density was calculated as follows:

$$D = \frac{W}{V}$$

where:

D = density, lb/cf.,

W = dry aggregate weight, lb.,

V = volume of mold section, cf.

5.3 Percent Voids

The following equation was used to calculate the percent voids for each mold section:

$$\text{Percent Voids} = \frac{(\text{BSG} \times 62.4 \text{ lb/cf.}) - D}{(\text{BSG} \times 62.4 \text{ lb/cf.})} \times 100 \text{ percent}$$

where:

BSG = bulk specific gravity,

D = density, lb/cf.

The aggregate supplier provided the BSG for each type of aggregate. In place of the DRUW, the section density was used because it was calculated for each specimen.

5.4 Percent Retained and Percent Weight

Percent retained and percent weight both indicated the amount of resin retained by the specimen. Percent retained compared the amount of resin retained by the specimen to the amount of resin poured into the mold section. Percent weight compared the adjusted weight of the specimen with resin to the initial weight of the specimen without resin. The equations were as follows:

$$\text{Percent Retained} = \frac{W_f - W_i}{W_r} \times 100 \text{ percent}$$

and:

$$\text{Percent Weight} = \frac{W_f - W_i}{W_f} \times 100 \text{ percent}$$

where:

W_f = final specimen weight, lb.

= [W_t + (number of resin-aggregate voids x 0.0875 lb/block)],

W_t = tested specimen weight, lb.

= specimen weight just prior to flexural test,

W_i = initial specimen weight (i.e., dry weight of aggregate), lb.

= [V_s x density],

V_s = specimen volume, cf.

= (average depth x average width x length)/

1728 in^3/cf.,

W_r = final resin weight, lb.

= weight of the resin poured into the section

= {[(intial resin weight) - (loss in beakers)

- (loss in container) - (loss from stick and spilling)]/

[453.6 gm/lb.]}.

5.5 Percent Resin Volume/Void Volume

Percent resin volume per void volume is the ratio between the volume of resin that was retained in the aggregate matrix after polymerization and the volume of voids in the specimen prior to pouring the resin. The equation used to determine this is as follows:

$$\text{Percent RV/VV} = \frac{Vr}{Vv}$$

where:

Vr = resin volume, cf.

= [(resin weight, gm)

/ (avg. density of resin, 1.083 gm/ml)

/ (1000 ml/ltr) / (28.32 ltr/cf)],

V_v = void volume, cf.

= [(percent voids) x (volume of specimen, cf.)].

CHAPTER 6

DISCUSSION OF RESULTS

6.1 Scope of Chapter

This chapter describes the results of the research. The graphs show flexural strength as a function of depth from surface, resin loading, density, percent voids, percent retained, percent weight, and percent resin volume/void volume. Results of data calculations are located in Appendix C. Data points and linear equations for the graphs are given in Appendices D and E.

6.2 Depth

The strength of the PMA material varied with the depth, as shown in Figs. 6.1, 6.2, 6.3, and 6.4.

In Fig. 6.1, siliceous gravel PMA and crushed limestone PMA had strengths of 112 psi. and 101 psi., respectively, at the 18-in. depth and under minimum compaction and maximum resin loading conditions. The strengths increased slightly up to the 6-in. depth.

Under maximum compaction conditions, siliceous gravel PMA and crushed limestone PMA had minimum strengths of 106 psi. and

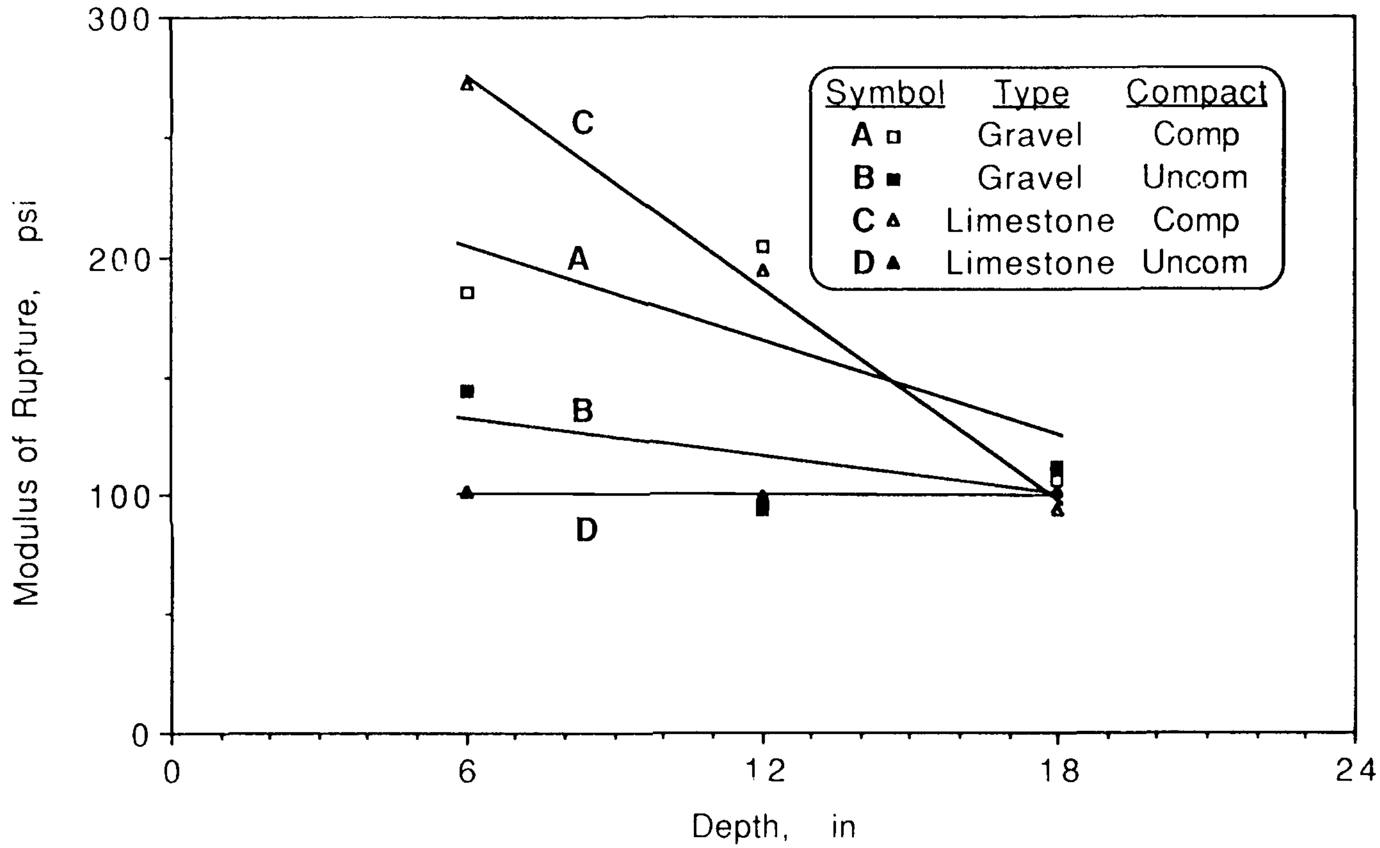


Figure 6.1 Flexural Strength of PMA as a Function of the Depth of the Specimen Under Maximum Resin Loading Conditions.

94 psi., respectively, at the 18-in. depth. As the depth decreased to 6 in., the PMA realized the benefits of compaction and increased 138 percent to maximum strengths of 185 psi. and 272 psi., respectively.

In Fig. 6.2, siliceous gravel PMA and crushed limestone PMA strengths increased by 68 percent as the depth decreased under uncompacted and minimum resin loading conditions. Under maximum compaction and minimum resin loading conditions, the strengths were under 100 psi. at the 18-in. depth. As the depth decreased to 6 in., the PMA realized the benefits of compaction, and the strengths increased significantly by 103 percent for siliceous gravel PMA and 298 percent for crushed limestone PMA.

In Fig. 6.3, siliceous gravel PMA, and in Fig. 6.4, crushed limestone PMA, the flexural strengths increased as the depth to the surface decreased under compacted/uncompacted and maximum/minimum resin loading conditions.

In summary, the flexural strength of PMA specimens increased an average of 133 percent as the depth to the surface decreased from 18 in. to 6 in. Also, PMA achieved a flexural strength average of 170 psi. at the 6-in. depth and an average of 130 psi. at all three depths.

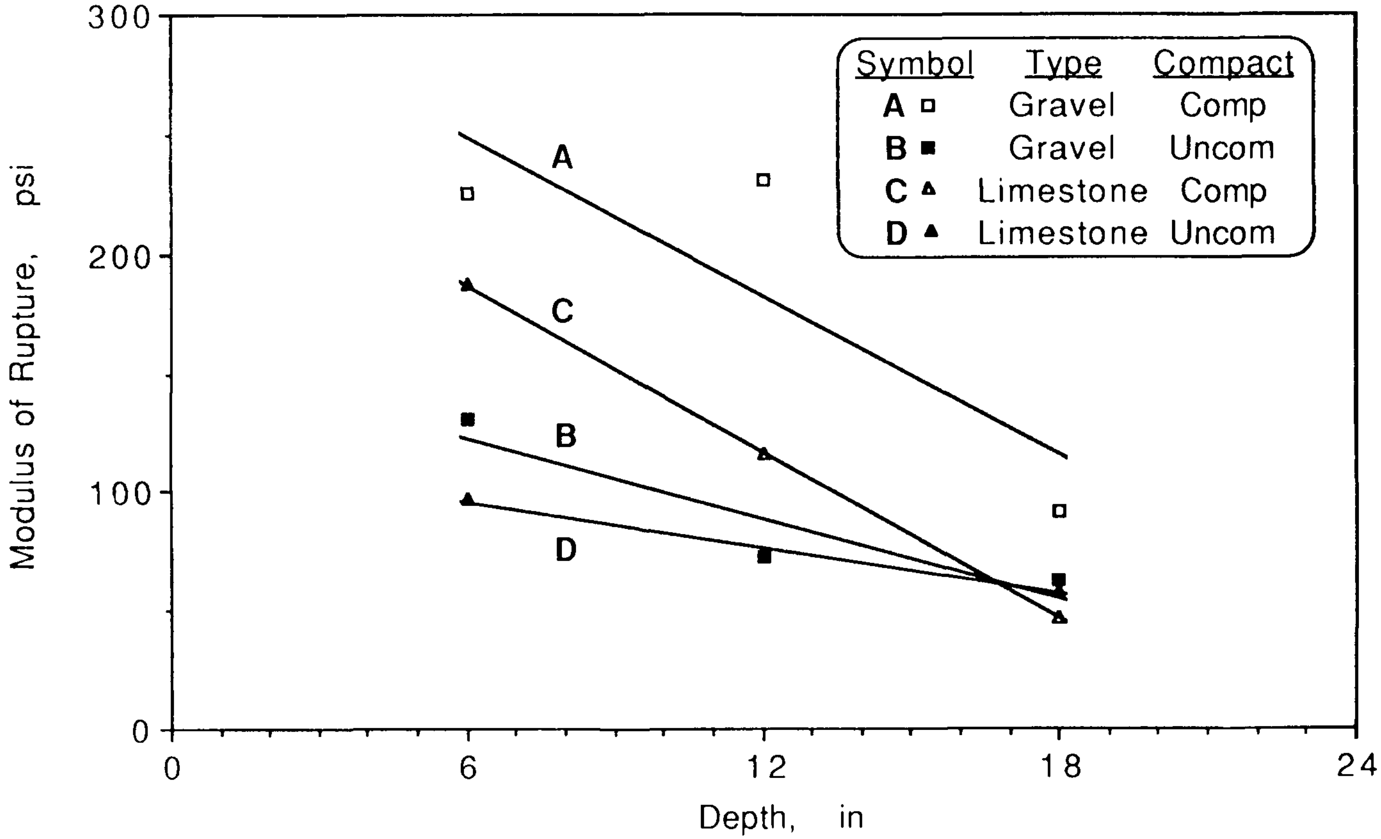


Figure 6.2 Flexural Strength of PMA as a Function of the Depth of the Specimen Under Minimum Resin Loading Conditions.

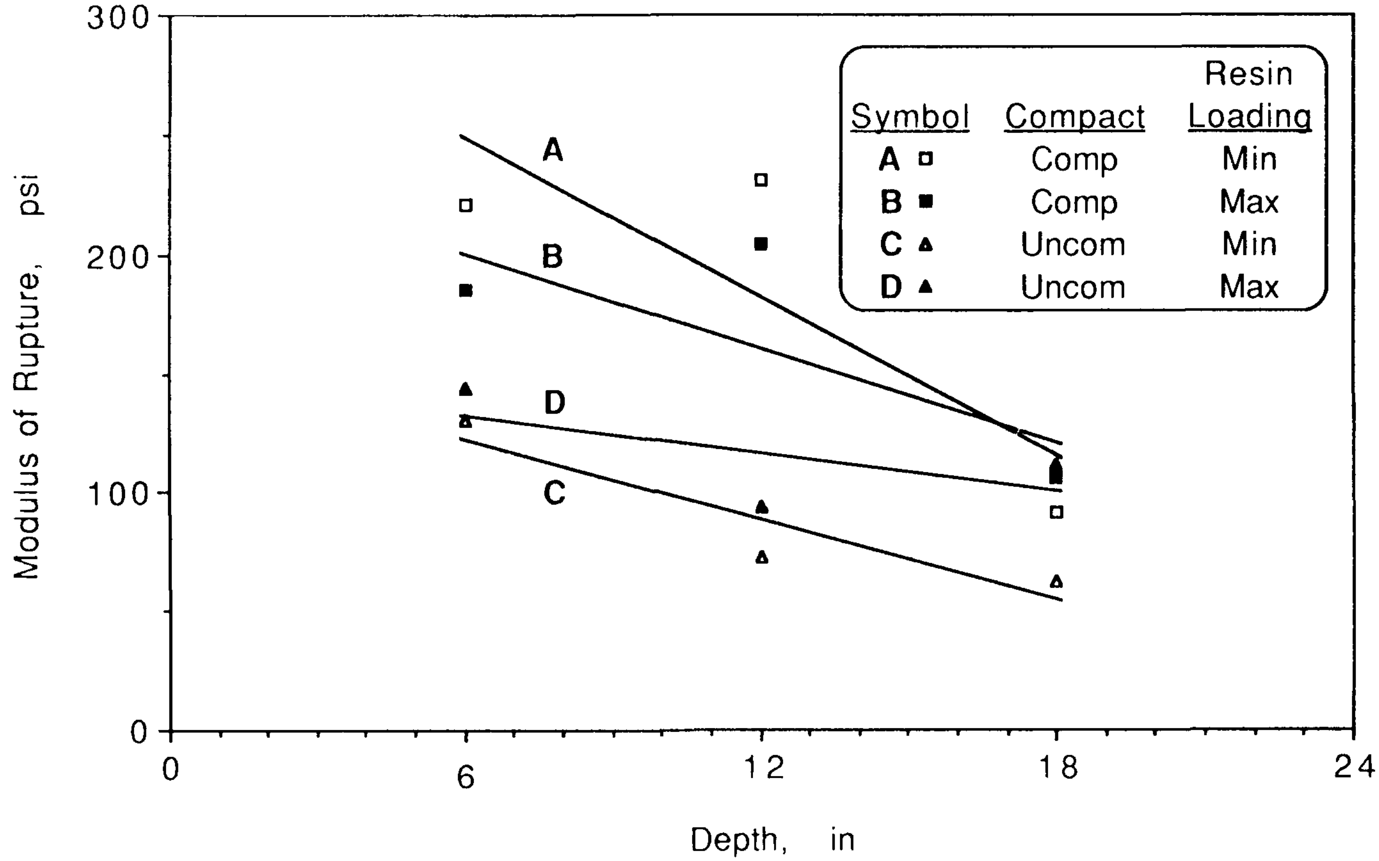


Figure 6.3 Flexural Strength of Siliceous Gravel PMA as a Function of the Depth of the Specimen.

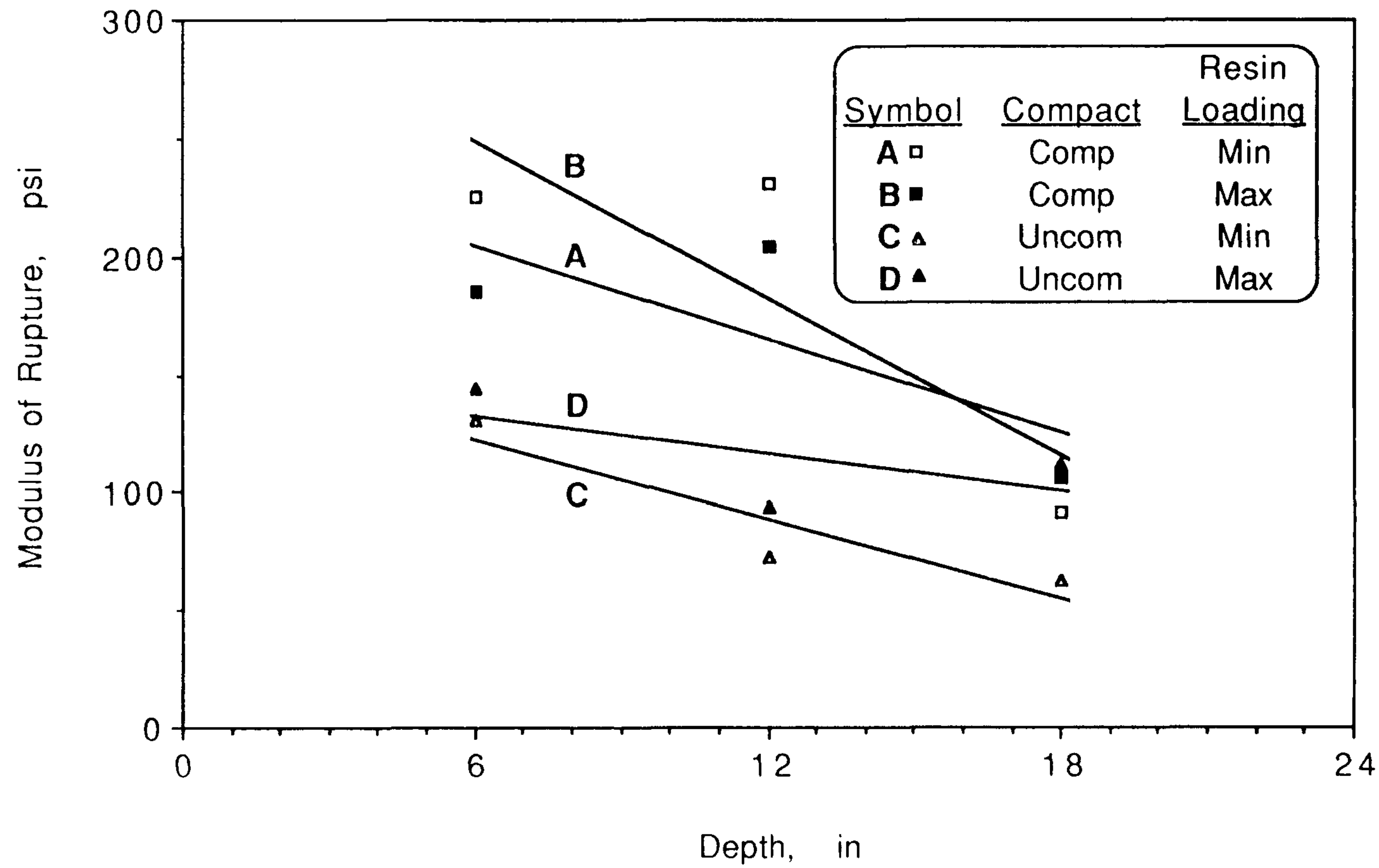


Figure 6.4 Flexural Strength of Crushed Limestone PMA as a Function of the Depth of the Specimen.

6.3 Resin Loading

Figs. 6.5 and 6.6 show the affect of resin loading on flexural strength for siliceous gravel PMA under compacted and uncompacted conditions. Under compacted conditions, Fig. 6.5, the flexural strength decreased by 8 percent at the 6-in. and 12-in. depths as the resin loading increased 50 percent. Under uncompacted conditions, Fig. 6.6, the flexural strength increased by 14 percent as the resin loading increased at all three depths.

Figs. 6.7 and 6.8 presents the affect of resin loading on flexural strength for crushed limestone PMA under compacted and uncompacted conditions. At all three depths in Fig. 6.7, the flexural strength significantly increased by 35 percent as the resin loading increased under compacted conditions. Also at all three depths in Fig. 6.8, the flexural strength increased by 13 percent as the resin loading increased under uncompacted conditions.

Besides increased strength, maximum resin loading conditions provided sufficient resin to percolate through the top 12 in. of aggregate and form PMA material at 18-in. and greater than 18-in. depths. Table A in the Appendix shows that under maximum resin loading conditions, enough resin percolated to the 18-in. depth to

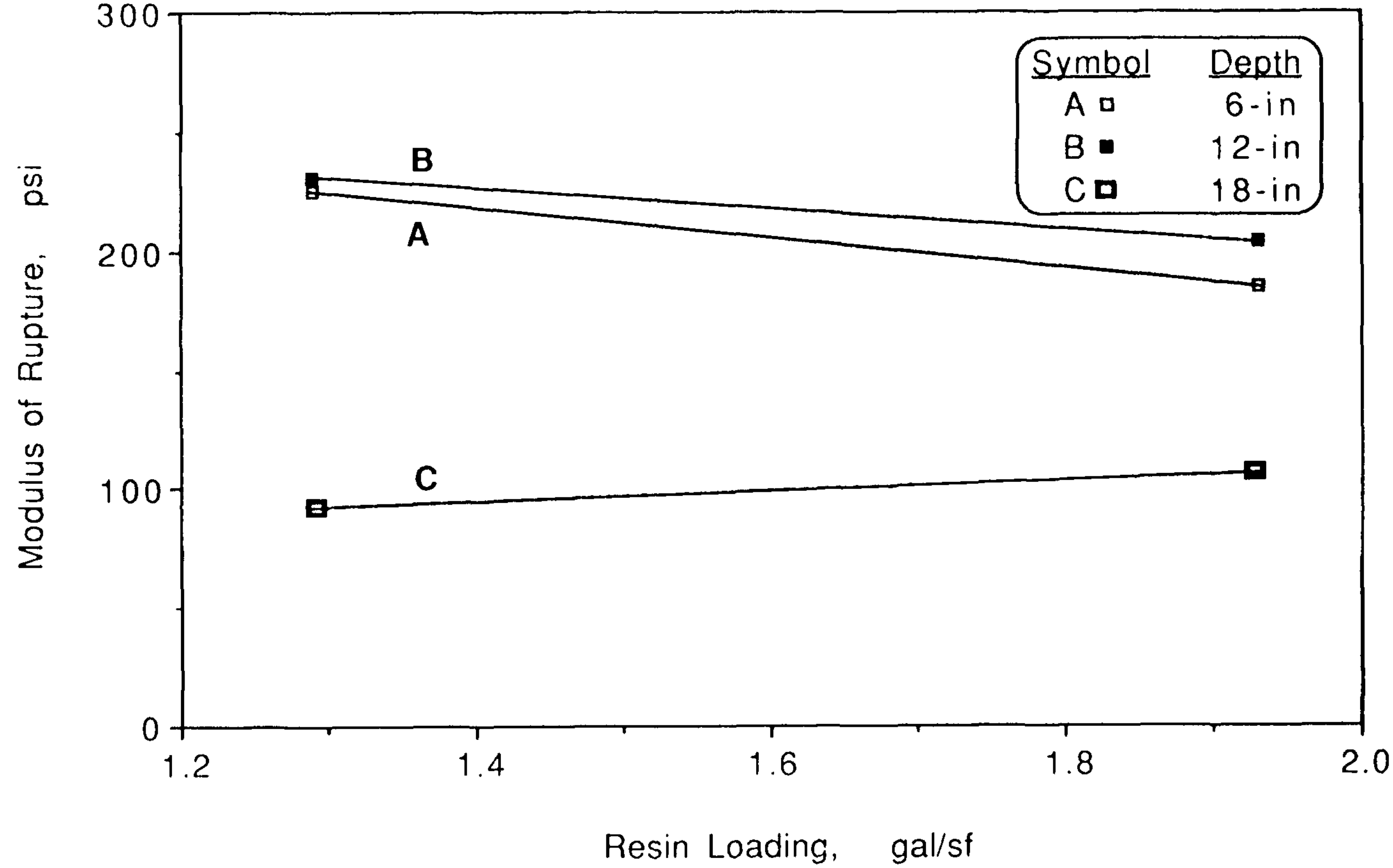


Figure 6.5 Flexural Strength of Siliceous Gravel PMA as a Function of Maximum and Minimum Resin Loadings Under Compacted Conditions.

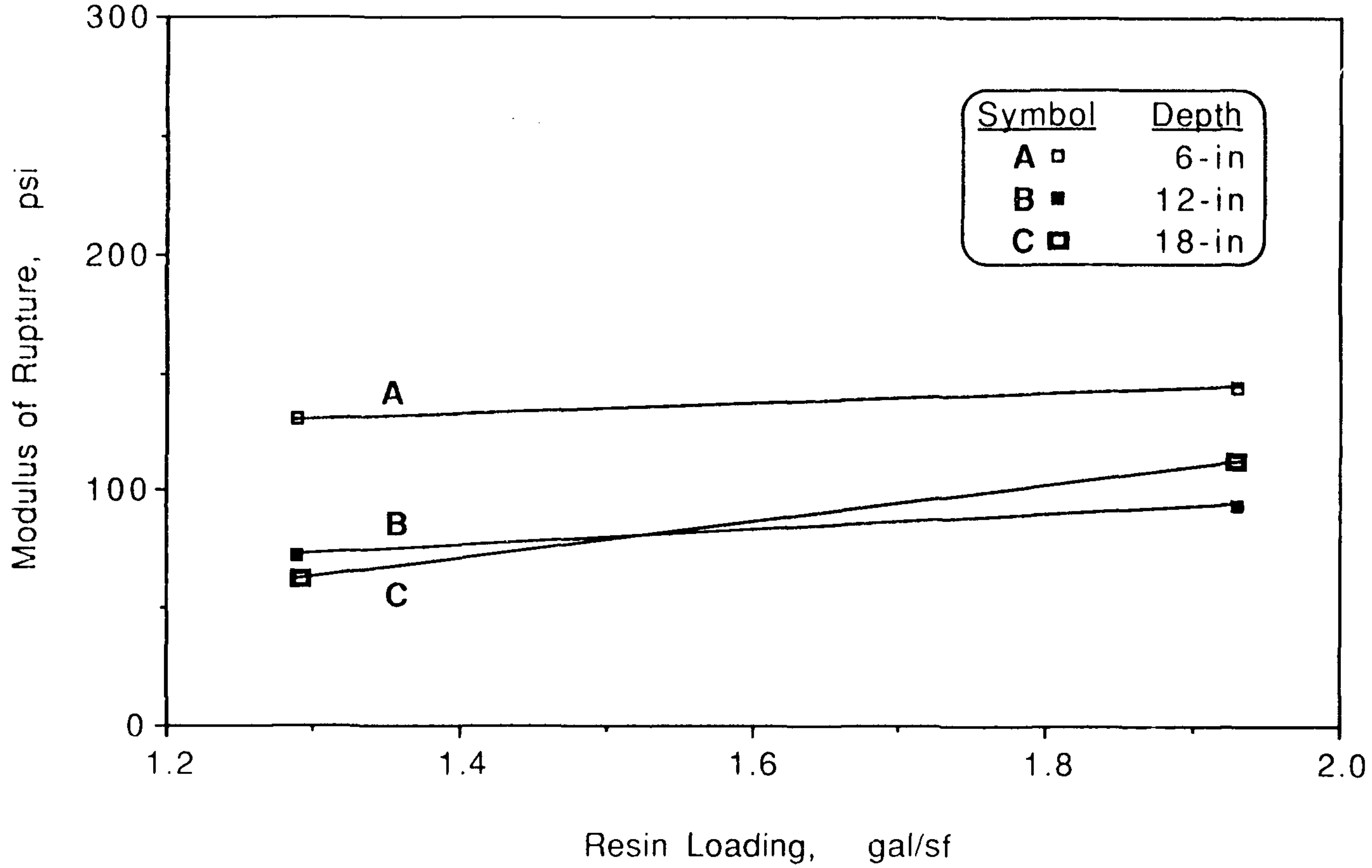


Figure 6.6 Flexural Strength of Siliceous Gravel PMA as a Function of Maximum and Minimum Resin Loadings Under Uncompacted Conditions.

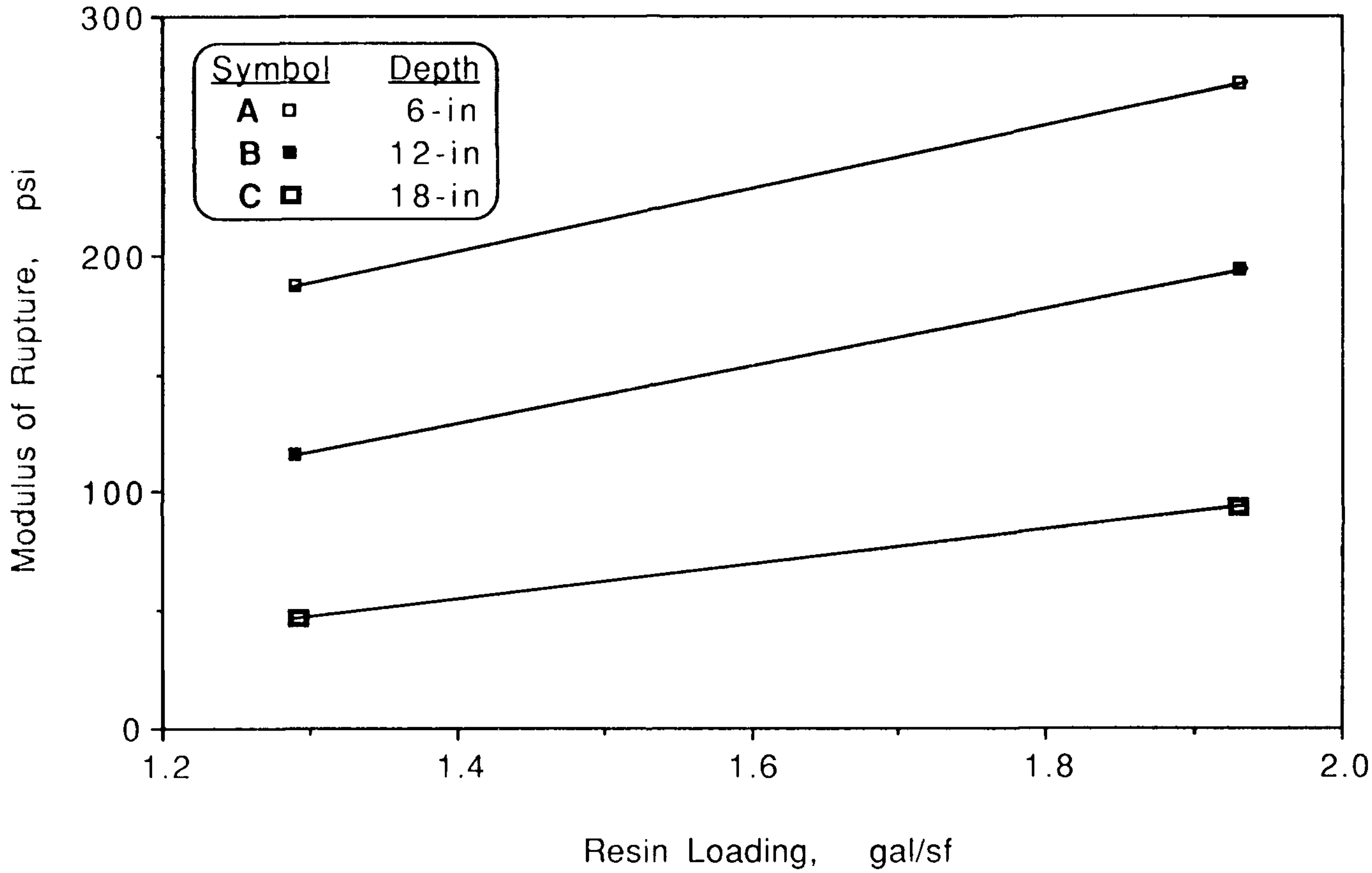


Figure 6.7 Flexural Strength of Crushed Limestone PMA as a Function of Maximum and Minimum Resin Loadings Under Compacted Conditions.

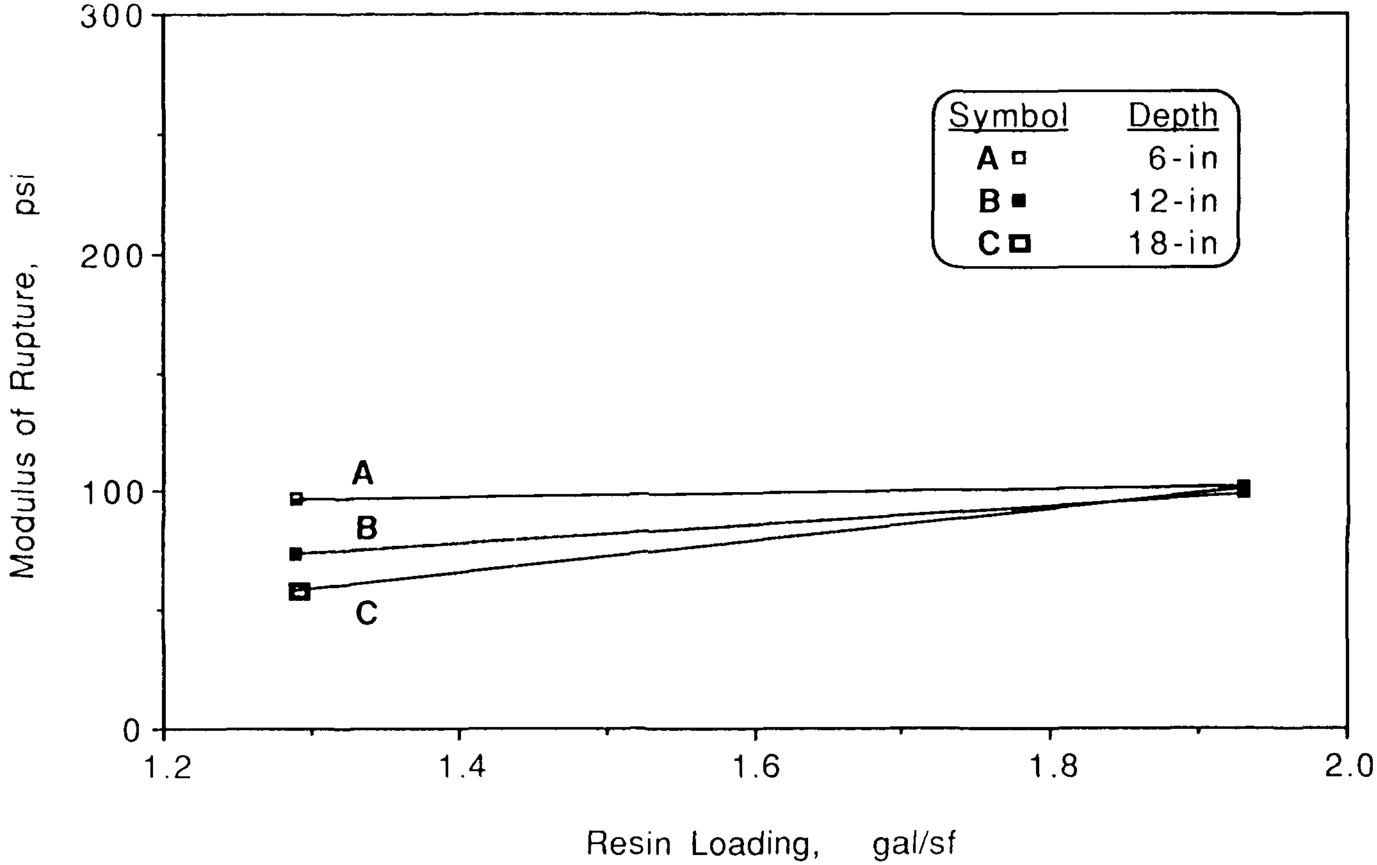


Figure 6.8 Flexural Strength of Crushed Limestone PMA as a Function of Maximum and Minimum Resin Loadings Under Uncompacted Conditions.

form a testable PMA specimen 14 out of 15 times, and the resin had an approximate 23-in. depth overall. Also, enough resin percolated and filled the bottom of the mold to form a 4.5 in. solid polymer beam in six mold sections (see Chapter 6.5). Under minimum resin loading conditions, sufficient resin percolated to the 18-in. depth and formed testable specimens 9 out of 14 times, and the resin had an approximate 20-in. depth overall.

In summary, a 50-percent increase in the resin loading increased the flexural strength of the PMA at all depths by an average of 14 percent; and more importantly, an increase in the resin loading provided sufficient resin to percolate through the top 12 in. of aggregate and form specimens of PMA at 18-in. depths. As a result of percolating to depths of at least 18 in., the overall stiffness of the PMA repair material is increased. So if there is not enough time to compact the aggregate in a crater or not enough equipment, increasing the resin loading will provide additional strength to the PMA repair material.

6.4 Density and Fercent Voids

Figs. 6.9 and 6.10 show how compactive effort affected the flexural strength of a PMA specimen. In Fig. 6.9 with siliceous gravel PMA, the flexural strength increased 67 percent from 103 psi. to 172 psi. when the density of the specimen was increased 9 percent. With crushed limestone PMA, the strength increased 72 percent from 89 psi. to 152 psi. when the density was increased 13 percent.

Likewise in Fig. 6.10, the flexural strength of siliceous gravel PMA increased 67 percent when the percent voids decreased 17 percent from 42 percent to 35 percent. And with crushed limestone PMA, the strength increased 72 percent when the percent voids decreased 17 percent from 44 percent to 37 percent. Therefore, the flexural strengths of compacted PMA specimens were much higher than for uncompacted specimens.

However, the flexural strength for uncompacted PMA was noteworthy. In an uncompacted condition, siliceous gravel PMA had an average strength of 100 psi. and crushed limestone PMA had an average of 90 psi. The strengths were averaged over all three depths and both resin loadings. In other words, PMA had measureable flexural strength under uncompacted conditions. Therefore, if time

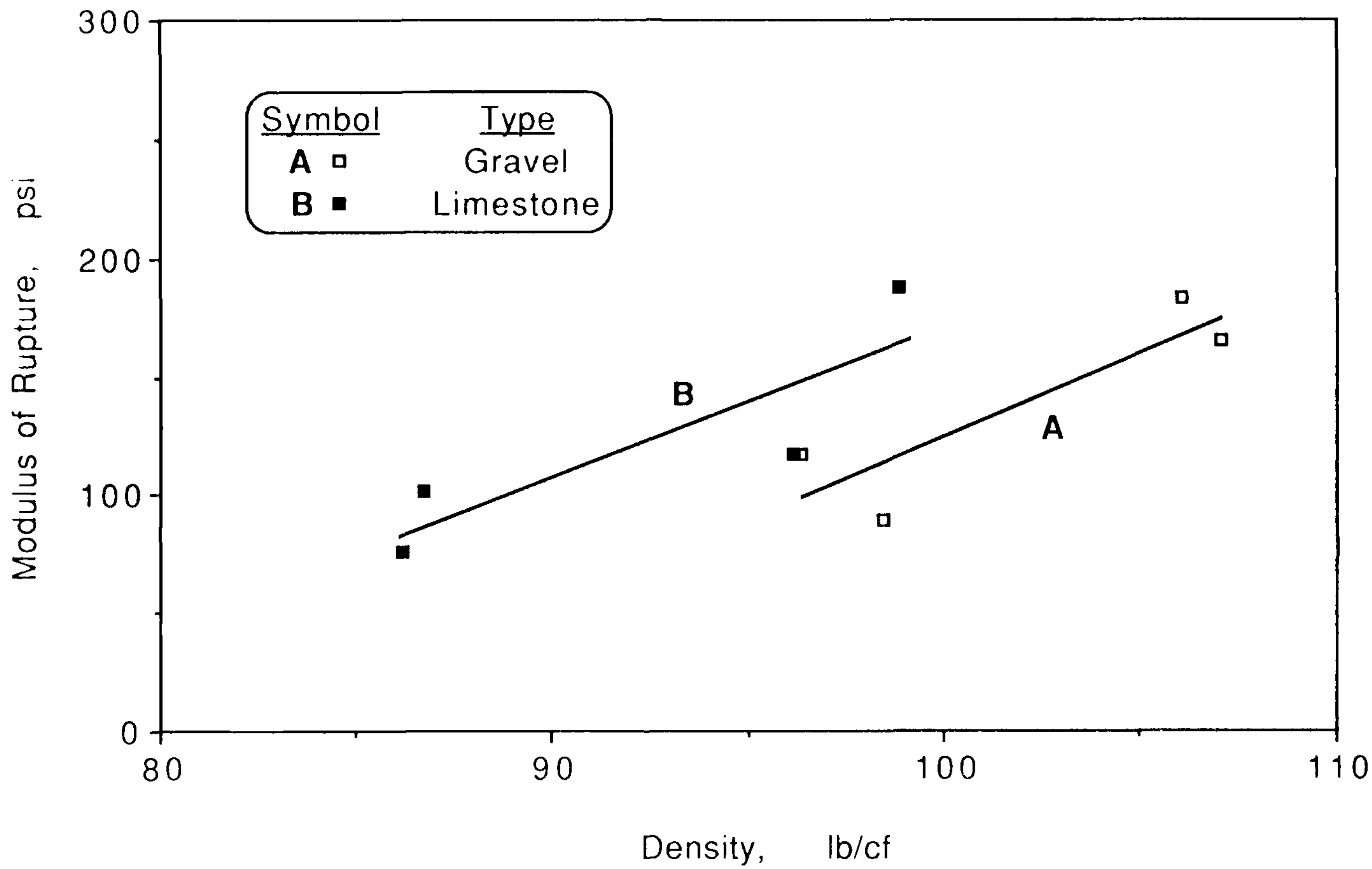


Figure 6.9 Flexural Strength of PMA as a Function of the Density of the Aggregate Matrix.

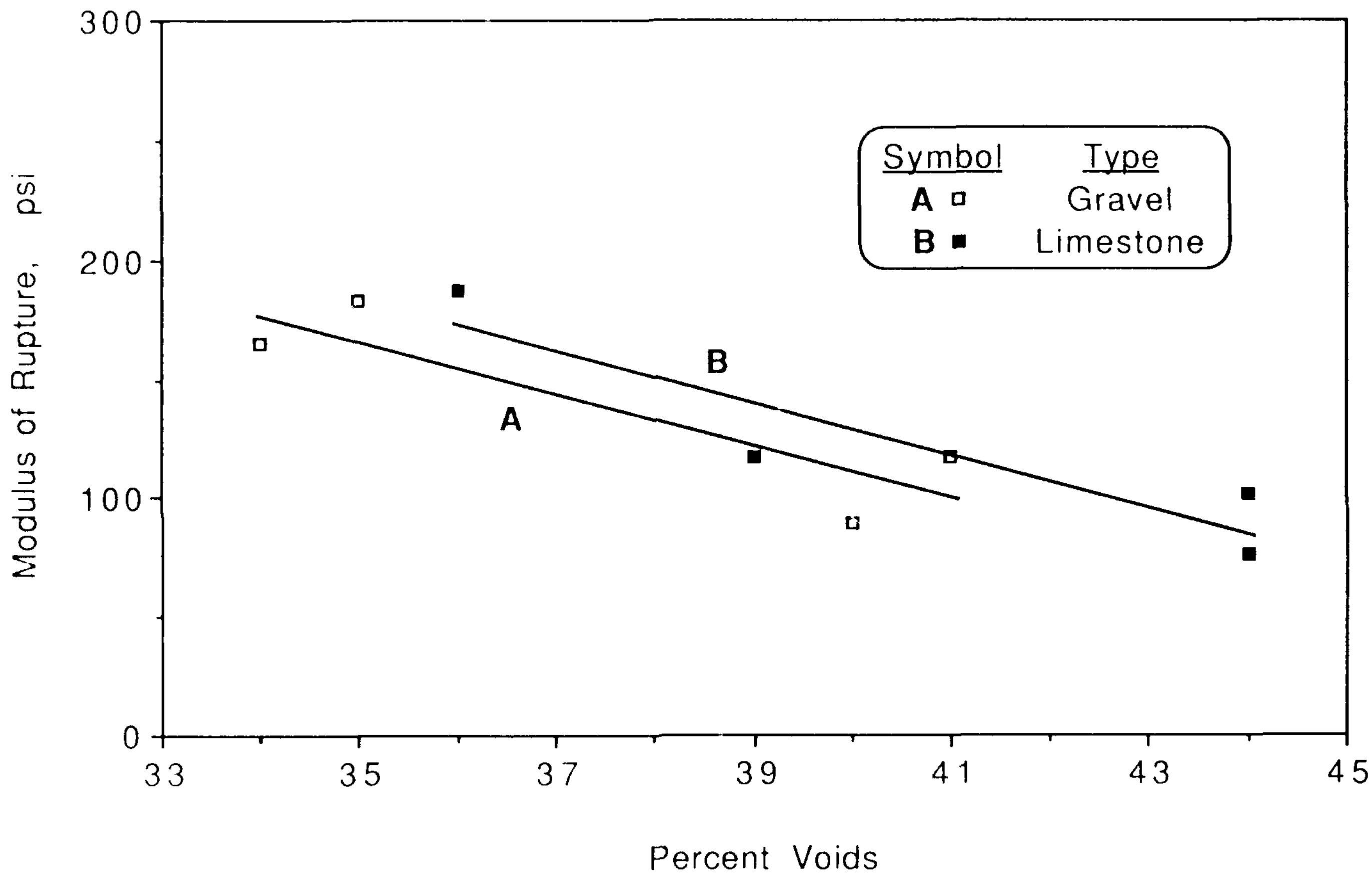


Figure 6.10 Flexural Strength of PMA as a Function of the Percent Voids in the Aggregate Matrix.

did not permit compaction during RRR operations, select aggregate could be quickly thrown into the crater, resin applied, and the uncompacted PMA would still achieve an average flexural strength of about 100 psi.

Also, other figures show how compaction resulted in higher flexural strengths. In Figs. 6.3 and 6.4, the compacted specimens averaged 172 percent increase in flexural strength from 18-in. to 6-in. depth while the uncompacted specimens increased only 50 percent. In other words, the amount of compaction affected the PMA strength more than resin loading.

The highest strength from any PMA specimen came from siliceous gravel PMA under compacted and maximum resin loading conditions at an 18-in. depth. One specimen, No. 112.43, had a flexural strength of 913 psi. and another, No. 112.63, had a strength of 625 psi. The extra strength could be attributed to the compactive effort which resulted in a large amount of retained resin, 50 percent and 56 percent, respectively. These two specimens were included in Appendix C but not in the graphs.

In summary, compactive effort affected the strength of PMA more than any other variable. Compaction increased the particle interfaces in the aggregate matrix. As a result of compaction, the resin formed a stronger bond with the aggregate matrix at all depths tested.

6.5 Percent Retained and Percent Weight

Fig. 6.11 presents the relationship between flexural strength and percent retained, and Fig. 6.12 presents the relationship between flexural strength and percent weight.

In Fig. 6.11, the flexural strength of siliceous gravel PMA increased 100 percent when the percent retained increased 27 percent. The strength of crushed limestone PMA increased 44 percent as the percent retained increased 36 percent.

In Fig. 6.12, the flexural strength of siliceous gravel PMA increased 45 percent when the percent weight increased 7 percent, and the strength of crushed limestone PMA increased 21 percent as the percent weight increased 8 percent.

Uncompacted and maximum resin loading conditions retained less resin on the aggregate matrix than compacted and maximum resin loading conditions. As a result, any resin not retained by the aggregate collected on the bottom of the mold and formed a solid slab (i.e., the voids were completely filled, see Chapter 6.3). Six of these

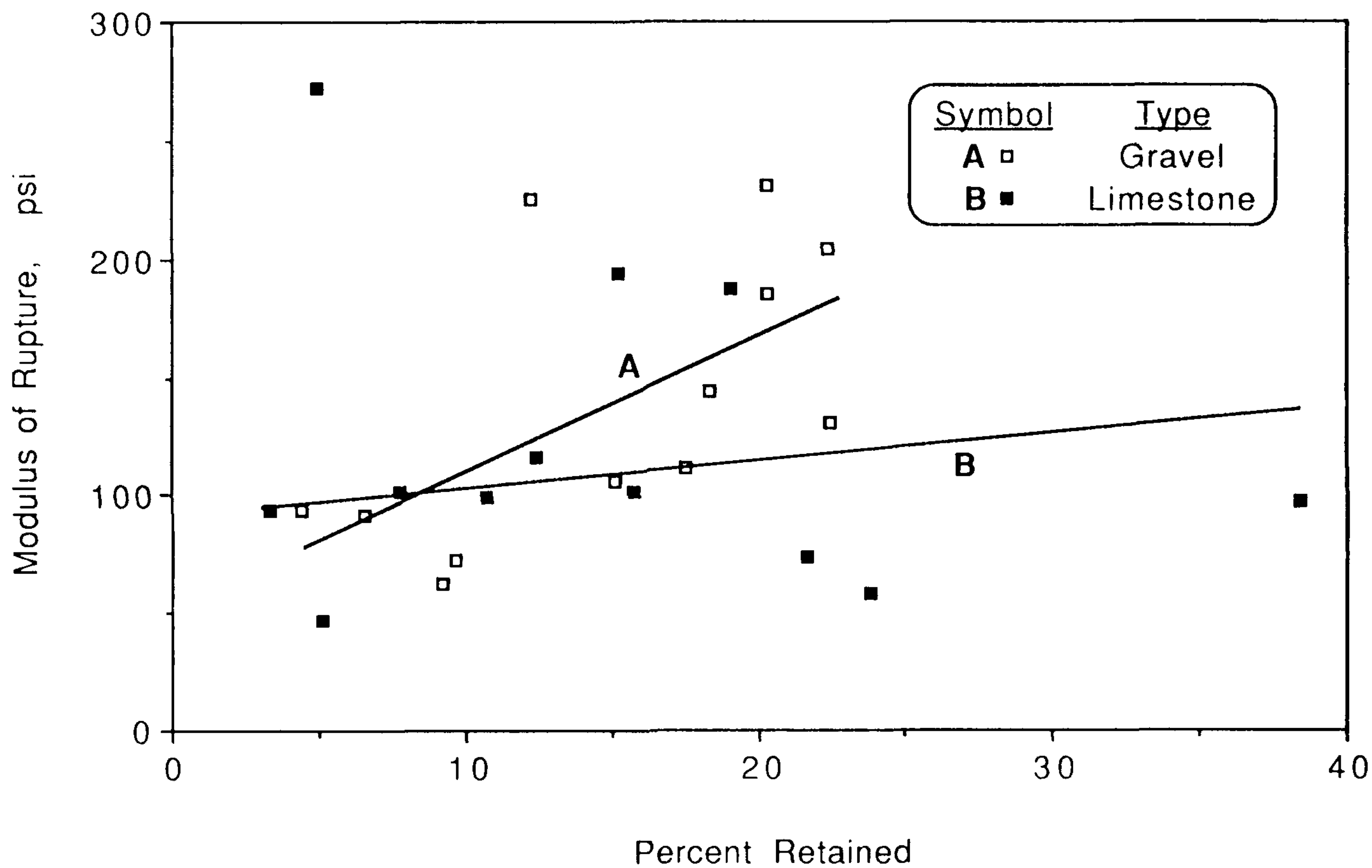


Figure 6.11 Flexural Strength of PMA as a Function of the Percent Retained of Resin in the Aggregate Matrix.

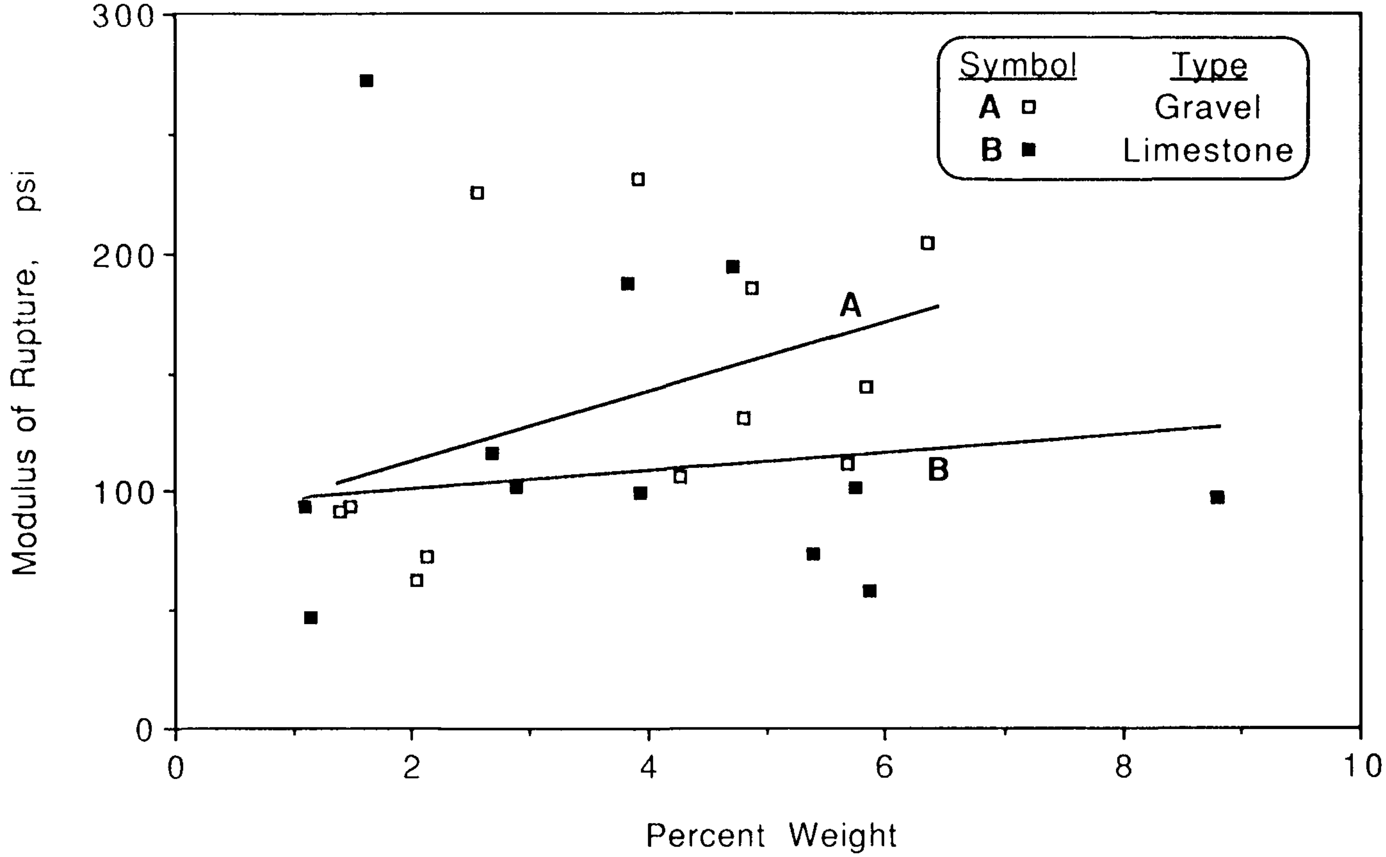


Figure 6.12 Flexural Strength of PMA as a Function of the Percent Weight of Resin in the Aggregate Matrix.

slabs were thick enough to be tested (No. 122.14, 122.24, 122.34, 222.14, 222.24, 222.34). The siliceous gravel specimens had an average flexural strength of 1205 psi., and the crushed limestone specimens had an average strength of 1010 psi. These specimens were included in Appendix C but not in the graphs.

6.6 Percent Resin Volume/Void Volume

Fig. 6.13 shows how flexural strength of PMA varied with the amount of resin that filled the voids in the PMA material. The percent strength was calculated by dividing the specimen's flexural strength by the flexural strength of a solid polymer specimen. As discussed in Chapter 6.5, the flexural strength of a solid specimen was 1205 psi. for siliceous gravel PMA and 1010 psi. for crushed limestone PMA.

Siliceous gravel PMA averaged 11 percent of the flexural strength of a solid specimen when approximately 1/6 of the voids were filled with resin. Crushed limestone PMA averaged 12 percent of a solid specimen when approximately 1/8 of the voids were filled with resin. Crushed limestone PMA specimen No. 212.21 achieved a maximum flexural strength of 27 percent of a solid specimen when

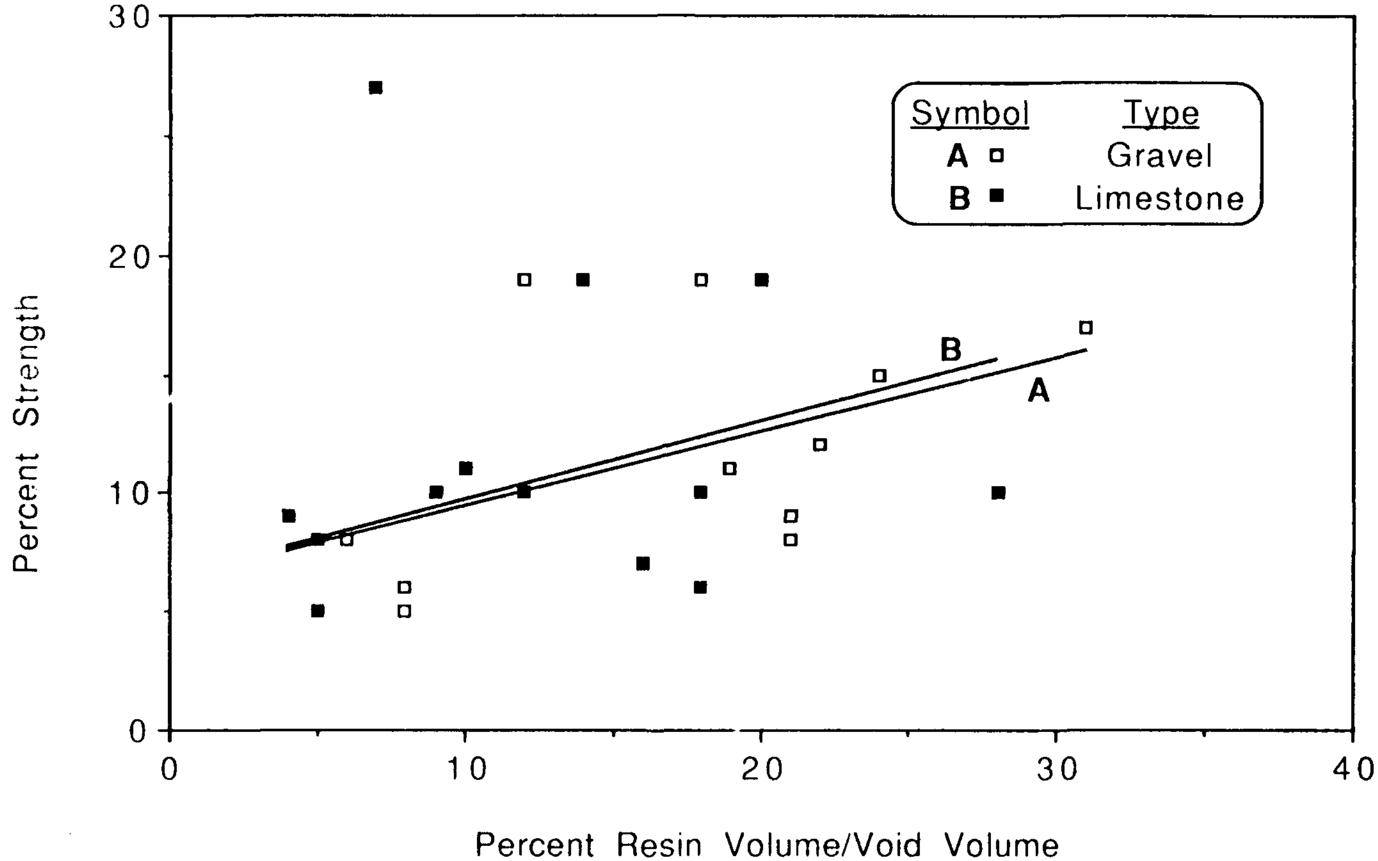


Figure 6.13 Percent Flexural Strength as a Function of Percent Resin Volume/Void Volume.

approximately 1/11 of the voids were filled with resin.

6.7 Miscellaneous Results

During this research, it was noted that the surface of the PMA material was rough from protruding aggregates. These aggregates may fragment and cause FOD damage to an aircraft, or they may puncture a tire. To alleviate this problem, a thin, strong cap was made efficiently and economically by pouring a small amount of resin over a thin bed of sand. Fig. 6.14 shows that a layer of polymer-sand provided a smooth and slip-resistant protective cap over the PMA material. This concept was tried on specimens No. 111.31, 112.11, 112.31, and 211.41. An average of 0.2 gal/sf. of resin and 3 lb/sf. of sand was used to make the polymer-sand cap.

Also, the cost of the resin (i.e., Parts A, B, and C mixed together) was about $1.05 per pound of resin. PMAspecimens at the 6 in. depth had an average flexural strength of 170 psi., retained 2.0 lb. of resin, and cost $2.10. PMA specimens had an overall average flexural strength of 130 psi., retained 1.9 lb. of resin, and cost $2.00. In other words, PMA repair material would require 10 lb of resin and cost $12.60 per square foot for an 18-in. repair depth.

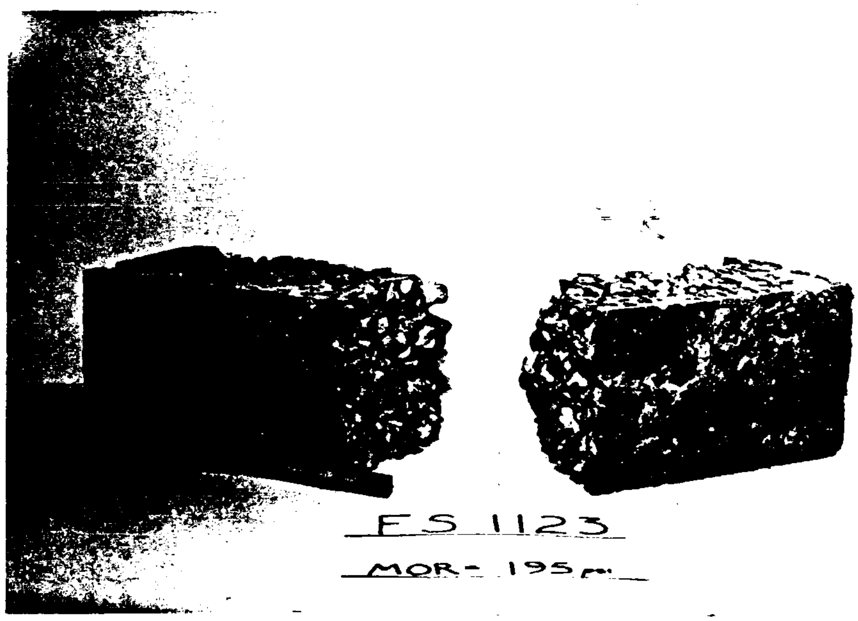


Figure 6.14 Siliceous Gravel PMA Specimen (No. 112.31) with Polymer-Sand Cap. Polymer-Sand Cap Economically Provides a Slip-Resistant FOD Cover Over a Repair Surface.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

This research describes an investigation of the use of polymer-modified aggregate (PMA) as a bomb damage repair material. PMA, an open-graded aggregate partially bonded with polymer at the particle interfaces, could be an economical repair material and provide a strong subgrade for repaired airfield surfaces. A PMA repair material would consist of a 6 to 18 in. layer of partially bonded, porous aggregate over push-back debris or over a layer of ballast stone base material. The select fill, an open-graded aggregate, would provide the primary load bearing capacity. Adding polymer would provide tensile strength to the aggregate matrix, which, in its unbonded state, would not exhibit any tensile strength. A PMA repair material would also provide FOD protection.

7.2 Conclusions

a. The mold and test method provided a satisfactory procedure for constructing polymer-modified aggregate

(PMA) under simulated field conditions.

b. PMA achieved an average flexural strength of 170 psi. at a 6-in. depth and an overall average of 130 psi.

c. Compactive effort affected the strength of PMA more than any other variable. Compaction increased the particle interfaces in the aggregate matrix. As a result, the resin formed a stronger bond with the aggregate matrix at all depths tested.

d. The flexural strength of PMA increased 67 percent for siliceous gravel and 73 percent for crushed limestone when the density of the preplaced aggregate in the specimen was increased 9 percent and 13 percent, respectively.

e. Siliceous gravel PMA obtained the highest flexural strength (915 psi.) under compacted and maximum resin loading conditions.

f. The flexural strength for uncompacted PMA averaged 95 psi.

g. A 50-percent increase in the resin loading increased the flexural strength of the PMA at all depths by an average of

14 percent.

h. An increase in the resin loading provided sufficient resin to percolate through the top 12 in. of aggregate and form specimens of PMA at 18-in. depths. As a result, the overall stiffness of the PMA repair material was increased.

i. The flexural strength of PMA increased an average of 133 percent as the depth from the surface decreased from 18 to 6 in.

j. The flexural strength of siliceous gravel PMA increased 100 percent when the percent retained of resin increased 27 percent, and the strength of crushed limestone PMA increased 44 percent when the percent retained increased 36 percent.

k. Crushed limestone PMA achieved a maximum flexural strength of 27 percent of a solid polymer specimen with very little resin--only 1/11 of the voids were filled with resin.

l. A polymer-sand cap provided an efficient and economical protective cap over the PMA material.

7.3 Recommendations

a. Conduct further research on the affects of the aggregate matrix on the flexural strength of PMA.

b. Investigate the affects of resin set time on flexural strength of PMA's, strength development of PMA, and resin penetation through PMA.

c. Investigate the affects of various moisture and temperature conditions on the flexural strength of PMA.

d. Measure the flexural strength of PMA after specimens have polymerized for 30 minutes.

e. Investigate the life cycle cost of PMA as a repair material for bomb damaged airfield surfaces.

f. Conduct research of PMA under field conditions. Develop correlation between PMA stress limit under field conditions and PMA flexural strength in laboratory tests.

g. Measure efficiency and effectivness of PMA as a repair material and chart clock times for PMA repair activities.

h. Encourage the US chemical industry to develop a resin which is environmentally safe and is effective under wet weather conditions.

APPENDIX A

Casting and Testing Data

Table A.1 Casting Data for Compacted Siliceous Gravel.

Specimen Number	Aggregate Weight (lb)	Int Resin Weight *(gm)	Part C ** (wt %)	Loss in Beakers ***(gm)	Loss in Container ****(gm)	Loss fm stick& spill(gm)	Set Time (m.s)	Cast Date	Air Temp (°F)	Cast Notes
111.11	169.75	4395	3.0	39	26	2	1.45	4/27/88	[illegible]0	
111.12										
111.21	172.00	4395	3.0	39	26	4	2.25	4/27/88	80	
111.22										
111.31	169.90	4395	3.0	35	26	3	2.15	4/27/88	80	f
111.32										
111.33										
112.11	171.25	6593	3.0	0	2593	0	2.10	5/7/88	76	a,b,f
112.21	176.50	6593	3.0	44	52	13	1.52	5/7/88	76	
112.22										
112.23										
112.31	171.75	6593	3.0	47	780	23	2.01	5/7/88	76	a,f
112.32										
112.33										
112.41	170.00	6587	2.9	55	51	2	1.52	5/14/88	84	
112.42										
112.43										
112.51	170.00	6587	2.9	48	49	5	2.00	5/14/88	84	
112.52										
112.53										
112.61	170.00	65[illegible]	2.9	57	54	4	1.55	5/14/88	84	
112.62										
112.63										

* Intial weight was sum of Part A, B & C.

** Part C was measured as a wt % of Part B.

*** Weight sum of Part A, B & C left in beakers.

**** Weight of resin left in mixing container.

Table A.2 Testing Data for Compacted Siliceous Gravel.

Specimen Number	Depth (in)	Depth (in)	Depth (in)	Width (in)	Width (in)	Width (in)	Length (in)	Weight Beam (lb)	Voids * (blk)	MOR ** (psi)	Load (lbf)	Test Notes
111.11	6.19	6.31	5.88	6.00	5.88	6.06	20.06	45.80		250		g
111.12	6.67	6.31	6.44	6.00	6.06	6.06	20.00	49.25	1		3560	h
111.21	5.75	5.88	6.06	6.00	5.94	6.00	20.00	45.55		205		g
111.22	6.44	6.31	6.25	6.00	6.00	6.00	20.06	47.00	2		3530	g
111.31	6.19	6.31	5.88	6.00	5.88	6.06	20.06	45.80		220		g
111.32	6.56	6.44	6.31	6.06	6.06	6.00	20.06	48.00	2		2440	h
111.33	6.00	5.88	5.81	6.25	6.25	6.00	20.00	37.25	9		1095	g
112.11	6.13	6.06	5.94	6.00	6.19	6.13	19.94	49.30		240		g
112.21	6.00	6.19	6.06	5.94	6.00	5.94	19.94	46.00		260		g
112.22	6.16	6.00	6.00	6.25	6.25	6.06	20.00	49.75	1	100		g,i
112.23	6.00	5.94	6.00	6.06	6.13	6.06	20.06	42.25	5		350	h
112.31	5.94	6.13	6.31	6.06	6.00	6.00	19.94	47.60		195		g,i
112.32	5.94	5.88	6.06	6.00	6.00	5.75	20.06	42.50	5		2735	h
112.33	5.81	5.88	5.75	5.75	6.00	5.75	20.06	36.50	8		1850	h
112.41	6.00	6.00	6.25	6.00	6.25	6.13	20.00	46.50			1650	g
112.42	6.13	6.00	6.00	6.13	6.25	6.25	20.25	48.00			2970	h
112.43	5.94	6.00	6.06	6.06	6.13	6.19	20.13	52.50			11185	h
112.51	6.00	6.13	6.25	6.00	6.00	6.00	20.13	52.50			2360	g
112.52	6.00	5.94	5.94	6.00	6.13	6.13	20.25	48.50	1		3140	g
112.53	6.25	6.25	6.38	6.00	6.06	6.06	20.06	47.00	5		1130	h
112.61	6.25	6.25	6.31	6.25	6.31	6.19	20.13	47.25	2		1340	g
112.62	6.00	6.06	6.06	6.06	6.19	6.13	20.19	48.51	1		2270	g
112.63	6.06	6.00	6.06	6.06	6.19	6.00	20.19	50.75	3		7700	h

* blk = block of wood, 3 in. x 2.5 in. x 2.5 in.

** MOR obtained from the Rainhart Testing Machine.

Table A.3 Testing Data for Compacted Siliceous Gravel and Notes.

Specimen Number	Test Date	Resin Depth **(In)
111.11	5/23.88	13.25to
111.12	6/22/88	20.50
111.21	5/23/88	4.00to
111.22	6/22/88	20.00
111.31	5/23/88	9.00to
111.32	6/22/88	20.00
111.33	6/22/88	
112.11	5/23/88	17.00to*
112.21	5/23/88	16.00to
112.22	6/22/88	23.13
112.23	6/22/88	
112.31	5/23/88	18.00to
112.32	6/22/88	23.13
112.33	6/22/88	
112.41	6/22/88	11.50to
112.42	6/22/88	21.50
112.43	6/22/88	
112.51	6/22/88	15.25to
112.52	6/22/88	20.50
112.53	6/22/88	
112.61	6/24/88	16.50to
112.62	6/24/88	20.75
112.63	6/24/88	

Cast and Test Notes

a. Weight of resin left in mixing container is an estimate. The lid did not have enough holes in it which slowed the pouring. The resin began to set in the container and some spilled.
b. Quick set.
c. Not enough aggregate to fill the mold. So, filled the mold to a depth of 20.13-in (i.e., 3-in down from the top of the mold). Since the volume was less than the others, the calculation for the specimen's density was adjusted.
d. An error was made in measuring the resins.
e. The resin thickened quickly due to the high ambient temperature and became difficult to pour between 1.00 and 1.30 (min.sec). The pour was completed by removing the lid.
f. The specimen was capped with a sand and resin mixture.
g. The specimen was tested with the side in tension.
h. The specimen was tested with the sawcut side in tension.
i. The Rainhart Testing Machine does not accurately measure a specimen's MOR under 200 psi.
j. The fracture line was less than 5% outside the middle one-third section.

* 23.13

** Resin depth approximated. A depth of 23.13+1.00 means 1.00-in of resin filled the bottom of the mold.

Table A.4 Casting Data for Uncompacted Siliceous Gravel.

Specimen Number	Aggregate Weight (lb)	Int Resin Weight *(gm)	Part C ** (wt %)	Loss in Beakers ***(gm)	Loss in Container ****(gm)	Loss fm stick& spill(gm)	Set Time (m.s)	Cast Date	Air Temp (°F)	Cast Notes
121.11	158.00	4377	2.1	39	35	5	1.46	6/24/88	99	e
121.12										
121.13										
121.21	160.00	4367	1.7	41	35	11	2.08	6/24/88	100	e
121.22										
121.23										
121.31	156.50	4357	1.2	39	32	15	2.51	6/24/88	102	e
121.32										
121.33										
122.11	157.50	6536	1.2	63	32	20	3.03	6/24/88	102	e
122.12										
122.13										
122.14										
122.21	151.00	6536	1.2	61	36	25	2.55	6/24/88	101	e
122.22										
122.23										
122.24										
122.31	155.50	6536	1.2	61	35	25	2.43	6/24/88	101	e
122.32										
122.33										
122.34										

* Intial weight was sum of Part A, B & C.

** Part C was measured as a wt % of Part B.

*** Weight sum of Part A, B & C left in beakers.

**** Weight of resin left in mixing container.

Table A.5 Testing Data for Uncompacted Siliceous Gravel.

Specimen Number	Depth (in)	Depth (in)	Depth (in)	Width (in)	Width (in)	Width (in)	Length (in)	Weight Beam (lb)	Voids * (blk)	MOR ** (psi)	Load (lbf)	Test Notes
121.11	6.00	6.00	6.13	6.00	6.00	6.00	20.00	43.50			1730	h
121.12	6.13	6.00	6.00	6.00	6.13	6.00	20.00	41.25	2		850	h
121.13	6.00	6.00	6.00	6.00	5.75	6.00	20.00	35.00	7		520	h
121.21	6.00	6.00	6.00	6.13	6.13	6.25	20.00	43.00	2		1750	h
121.22	6.00	6.00	6.00	6.00	6.13	6.00	20.00	39.50	4		970	h
121.23	6.13	6.00	6.13	6.06	6.06	6.06	20.00	40.00	4		865	h
121.31	6.00	6.25	6.25	6.00	6.25	6.00	20.00	43.50	1		1350	g
121.32	6.00	6.25	6.06	6.25	6.19	6.25	20.00	39.50	4		900	h
121.33	6.06	6.00	6.00	6.06	6.13	6.13	20.00	38.00	5		885	h
122.11	6.25	6.25	6.25	6.06	6.06	6.06	20.00	43.00			2000	g
122.12	6.25	6.25	6.25	6.00	6.06	6.00	20.00	41.50	2		1510	h
122.13	6.00	6.00	6.00	6.00	6.00	6.00	20.00	39.75	3		1240	h
122.14	4.50	4.50	4.44	6.13	6.13	6.13	20.00	37.50			7700	h
122.21	6.13	6.00	6.00	6.00	6.00	6.00	20.00	43.00	1		1850	g
122.22	6.25	6.19	6.06	6.13	6.00	6.13	20.00	41.00	1		1020	h
122.23	6.00	6.00	6.06	6.06	6.06	6.06	20.00	42.25	1		1420	h
122.24	4.56	4.56	4.50	6.13	6.13	6.13	20.00	37.50			8400	h
122.31	6.25	6.25	6.25	6.00	6.00	6.00	20.00	44.50	1		1660	h
122.32	6.25	6.50	6.25	6.13	6.19	6.00	20.00	42.75	1		1170	g
122.33	6.13	6.13	6.13	6.19	6.25	6.13	20.00	41.50	4		1520	g
122.34	4.13	4.06	4.06	6.13	6.19	6.13	20.00	34.00			7320	h

* blk = block of wood, 3 in. x 2.5 in. x 2.5 in.

** MOR obtained from the Rainhart Testing Machine.

Table A.6 Testing Data for Uncompacted Siliceous Gravel and Notes.

Specimen Number	Test Date	Resin Depth *(in)
121.11	6/29/88	23.13+
121.12	6/29/88	1.00
121.13	6/29/88	
121.21	6/29/88	23.13+
121.22	6/29/88	2.50
121.23	6/29/88	
121.31	6/29/88	23.13+
121.32	6/29/88	2.50
121.33	6/29/88	
122.11	6/29/88	23.13+
122.12	6/29/88	4.50
122.13	6/29/88	
122.14	6/29/88	
122.21	6/29/88	23.13+
122.22	6/29/88	4.50
122.23	6/29/88	
122.24	6/29/88	
122.31	6/29/88	23.13+
122.32	6/29/88	4.00
122.33	6/29/88	
122.34	6/29/88	

Cast and Test Notes

a. Weight of resin left in mixing container is an estimate. The lid did not have enough holes in it which slowed the pouring. The resin began to set in the container and some spilled.
b. Quick set.
c. Not enough aggregate to fill the mold. So, filled the mold to a depth of 20.13-in (i.e., 3-in down from the top of the mold). Since the volume was less than the others, the calculation for the specimen's density was adjusted.
d. An error was made in measuring the resins.
e. The resin thickened quickly due to the high ambient temperature and became difficult to pour between 1.00 and 1.30 (min.sec). The pour was completed by removing the lid.
f. The specimen was capped with a sand and resin mixture.
g. The specimen was tested with the side in tension.
h. The specimen was tested with the sawcut side in tension.
i. The Rainhart Testing Machine does not accurately measure a specimen's MOR under 200 psi.
j. The fracture line was less than 5% outside the middle one-third section.

* Resin depth approximated. A depth of 23.13+1.00 means 1.00-in of resin filled the bottom of the mold.

Table A.7 Casting Data for Compacted Crushed Limestone.

Specimen Number	Aggregate Weight (lb)	Int Resin Weight *(gm)	Part C ** (wt %)	Loss in Beakers ***(gm)	Loss in Container ****(gm)	Loss fm stick& spill(gm)	Set Time (m.s)	Cast Date	Air Temp (°F)	Cast Notes
211.21	148.50	4395	3.0	42	151	2	1.15	5/6/88	89	a,b
211.22										
211.31	148.50	4395	3.0	43	148	2	1.25	5/6/88	89	a,b
211.32										
211.41	130.00	3110	4.3	33	45	22	1.05	5/14/88	94	b,c,d,f
211.42										
211.51	137.25	4392	2.9	31	40	12	1.55	5/14/88	94	b,c
211.52										
211.53										
211.61	138.50	4392	2.9	30	40	7	1.39	5/14/88	94	c,j
211.62										
211.63										
212.11	160.50	6593	3.0	44	60	2	2.10	5/7/88	76	
212.12										
212.13										
212.21	158.50	6593	3.0	71	65	2	2.15	5/7/88	76	
212.22										
212.23										
212.31	157.25	6593	3.0	61	70	2	2.18	5/7/88	76	
212.32										
212.33										

* Intial weight was sum of Part A, B & C.

** Part C was measured as a wt % of Part B.

*** Weight sum of Part A, B & C left in beakers.

**** Weight of resin left in mixing container.

Table A.8 Testing Data for Compacted Crushed Limestone.

Specimen Number	Depth (in)	Depth (in)	Depth (in)	Width (in)	Width (in)	Width (in)	Length (in)	Weight Beam (lb)	Voids * (blk)	MOR ** (psi)	Load (lbf)	Test Notes
211.21	6.00	5.88	5.94	6.06	6.06	6.13	19.94	41.20		215		g
211.22	5.94	6.00	6.25	6.00	6.06	6.06	20.25	41.25	2		1380	h
211.31	5.94	6.19	5.81	6.06	6.19	6.00	20.06	41.45		195		g
211.32	6.25	6.19	6.44	6.00	6.00	6.06	20.13	39.25	3		1315	h
211.41	6.00	6.25	6.25	6.25	6.19	6.19	20.00	43.25			2485	h
211.42	6.06	6.06	6.06	5.94	6.00	6.00	20.25	31.00	10		150	g
211.51	5.88	6.00	6.00	6.06	6.13	6.00	20.00	40.50	1		2245	g
211.52	5.94	6.06	5.94	6.06	6.06	6.00	20.25	41.25	1		1745	h
211.53	6.13	5.88	6.13	6.00	6.06	6.13	20.13	33.00	11		190	h
211.61	6.50	6.38	6.25	6.00	6.13	5.94	20.19	42.50	3		2225	g,j
211.62	6.00	5.94	6.00	6.13	6.06	6.13	20.13	40.00	3		2555	h
211.63	6.00	6.00	6.00	6.00	6.00	5.75	20.25	34.50	8		915	h
212.11	5.94	6.06	6.13	5.88	6.13	5.88	20.13	42.80		315		g
212.12	6.25	6.25	6.19	6.06	6.25	6.25	20.13	42.00	4		2420	h
212.13	6.00	6.06	6.06	6.13	6.25	6.13	20.31	43.00	1		2290	h
212.21	6.00	6.13	6.00	6.06	6.19	6.13	20.06	43.35		270		g
212.22	6.13	6.25	6.50	5.94	6.19	6.00	20.25	45.50			2000	h
212.23	6.13	6.19	6.13	6.13	6.13	6.00	20.25	41.50	3		140	h
212.31	6.25	6.13	6.19	6.19	6.25	6.19	20.00	43.00	1	230		g
212.32	5.88	6.00	5.94	6.25	6.19	6.00	20.25	44.50	2		3020	h
212.33	5.94	6.06	5.88	6.00	6.25	5.75	20.50	35.00	8		1010	h

* blk = block of wood, 3 in. x 2.5 in. x 2.5 in.

** MOR obtained from the Rainhart Testing Machine.

Table A.9 Testing Data for Compacted Crushed Limestone and Notes.

Specimen Number	Test Date	Resin Depth *(In)
211.21	5/23/88	14.00to
211.22	6/22/88	23.13
211.31	5/23/88	17.75to
211.32	6/22/88	23.13
211.41	6/22/88	20.75to
211.42	6/22/88	20.75
211.51	6/24/88	16.00to
211.52	6/24/88	20.75
211.53	6/24/88	
211.61	6/24/88	20.75to
211.62	6/24/88	23.13
211.63	6/24/88	
212.11	5/23/88	22.75to
212.12	6/24/88	23.13
212.13	6/24/88	
212.21	5/23/88	22.75to
212.22	6/22/88	23.13
212.23	6/22/88	
212.31	5/23/88	16.75to
212.32	6/22/88	23.13
212.33	6/22/88	

Cast and Test Notes

a. Weight of resin left in mixing container is an estimate. The lid did not have enough holes in it which slowed the pouring. The resin began to set in the container and some spilled.

b. Quick set.

c. Not enough aggregate to fill the mold. So, filled the mold to a depth of 20.13-in (i.e., 3-in down from the top of the mold). Since the volume was less than the others, the calculation for the specimen's density was adjusted.

d. An error was made in measuring the resins.

e. The resin thickened quickly due to the high ambient temperature and became difficult to pour between 1.00 and 1.30 (min.sec). The pour was completed by removing the lid.

f. The specimen was capped with a sand and resin mixture.

g. The specimen was tested with the side in tension.

h. The specimen was tested with the sawcut side in tension.

i. The Rainhart Testing Machine does not accurately measure a specimen's MOR under 200 psi.

j. The fracture line was less than 5% outside the middle one-third section.

* Resin depth approximated. A depth of 23.13+1.00 means 1.00-in of resin filled the bottom of the mold.

Table A.10 Casting Data for Uncompacted Crushed Limestone.

Specimen Number	Aggregate Weight (lb)	Int Resin Weight *(gm)	Part C ** (wt %)	Loss in Beakers ***(gm)	Loss in Container ****(gm)	Loss fm stick& spill(gm)	Set Time (m.s)	Cast Date	Air Temp (°F)	Cast Notes
221.11	140.50	4357	1.2	42	32	20	3.24	6/27/88	94	e
221.12										
221.13										
221.21	137.40	4357	1.2	42	38	10	3.14	6/27/88	94	e
221.22										
221.23										
221.31	137.25	4357	1.2	43	37	11	3.20	6/27/88	94	e
221.32										
221.33										
222.11	139.25	6536	1.2	72	42	25	3.24	6/27/88	94	e
222.12										
222.13										
222.14										
222.21	140.00	6536	1.2	74	38	40	3.22	6/27/88	94	e
222.22										
222.23										
222.24										
222.31	138.75	6536	1.2	74	38	20	3.20	6/27/88	95	e
222.32										
222.33										
222.34										

* Intial weight was sum of Part A, B & C.

** Part C was measured as a wt % of Part B.

*** Weight sum of Part A, B & C left in beakers.

**** Weight of resin left in mixing container.

Table A.11 Testing Data for Uncompacted Crushed Limestone.

Specimen Number	Depth (in)	Depth (in)	Depth (in)	Width (in)	Width (in)	Width (in)	Length (in)	Weight Beam (lb)	Voids * (blk)	MOR ** (psi)	Load (lbf)	Test Notes
221.11	6.13	6.25	6.25	6.00	6.00	6.06	20.00	41.50	1		1240	h
221.12	6.00	6.00	6.13	6.00	5.75	6.13	20.00	35.00	3		900	h
221.13	6.13	6.00	6.13	6.13	6.13	5.75	20.00	34.50	6		715	h
221.21	6.25	6.25	6.25	6.00	5.94	5.94	20.00	39.50	1		1000	h
221.22	6.00	5.94	5.94	5.94	6.13	6.00	20.00	36.50	2		895	h
221.23	5.94	5.94	6.00	6.00	6.00	6.13	20.00	32.00	6		710	h
221.31	6.38	6.38	6.25	6.00	5.75	5.88	20.00	38.75	1		1530	g
221.32	6.00	6.00	6.13	6.00	5.75	5.88	20.00	36.50	1		850	h
221.33	6.00	5.88	6.00	5.88	5.75	6.00	20.00	33.50	4		610	h
222.11	6.38	6.25	6.25	5.88	6.00	6.00	20.00	38.25	1		1330	h
222.12	6.00	6.00	6.00	6.00	6.13	6.06	20.00	37.75	1		1475	h
222.13	6.00	6.00	6.00	6.00	6.06	6.00	20.00	38.25	1		1100	h
222.14	4.75	4.75	4.75	6.00	5.88	6.00	20.00	34.50			6880	h
222.21	6.00	6.00	6.00	6.00	6.06	5.94	20.00	37.50			1460	h
222.22	6.25	6.25	6.13	6.00	6.00	6.00	20.00	37.75	1		1300	h
222.23	6.06	5.88	6.00	6.13	6.06	6.13	20.00	37.50	1		1100	h
222.24	4.75	4.81	4.67	6.06	6.25	6.13	20.00	36.50			8540	h
222.31	6.00	6.25	6.25	5.88	6.00	6.00	20.00	36.50	1		1060	g
222.32	6.25	6.25	6.19	6.00	5.75	6.00	20.00	38.25			940	h
222.33	6.00	6.00	6.13	5.88	6.00	6.00	20.00	36.50	2		1450	h
222.34	4.50	4.63	4.63	6.06	6.13	6.06	20.00	35.50			7040	h

* blk = block of wood, 3 in. x 2.5 in. x 2.5 in.

** MOR obtained from the Rainhart Testing Machine.

Table A.12 Testing Data for Uncompacted Crushed Limestone and Notes.

Specimen Number	Test Date	Resin Depth *(In)
221.11	6/29/88	23.13+
221.12	6/29/88	2.00
221.13	6/29/88	
221.21	6/29/88	23.13+
221.22	6/29/88	2.00
221.23	6/29/88	
221.31	6/29/88	23.13+
221.32	6/29/88	2.50
221.33	6/29/88	
222.11	6/29/88	23.13+
222.12	6/29/88	4.50
222.13	6/29/88	
222.14	6/29/88	
222.21	6/29/88	23.13+
222.22	6/29/88	5.00
222.23	6/29/88	
222.24	6/29/88	
222.31	6/29/88	23.13+
222.32	6/29/88	5.00
222.33	5/29/88	
222.34	6/29/88	

Cast and Test Notes

a. Weight of resin left in mixing container is an estimate. The lid did not have enough holes in it which slowed the pouring. The resin began to set in the container and some spilled.

b. Quick set.

c. Not enough aggregate to fill the mold. So, filled the mold to a depth of 20.13-in (i.e., 3-in down from the top of the mold). Since the volume was less than the others, the calculation for the specimen's density was adjusted.

d. An error was made in measuring the resins.

e. The resin thickened quickly due to the high ambient temperature and became difficult to pour between 1.00 and 1.30 (min.sec). The pour was completed by removing the lid.

f. The specimen was capped with a sand and resin mixture.

g. The specimen was tested with the side in tension.

h. The specimen was tested with the sawcut side in tension.

i. The Rainhart Testing Machine does not accurately measure a specimen's MOR under 200 psi.

j. The fracture line was less than 5% outside the middle one-third section.

* Resin depth approximated. A depth of 23.13+1.00 means 1.00-in of resin filled the bottom of the mold.

APPENDIX B

Aggregate Gradations

Figure B.1 Aggregate Gradation of Siliceous Gravel.

Sieve Size	Percent Retained
1&1/2 in.	0.0
1 in.	5.0
3/4 in.	31.0
1/2 in.	71.5
No. 4	98.0

Figure B.2 Aggregate Gradation of Crushed Limestone.

Sieve Size	Percent Retained
1&1/2 in.	0.0
1 in.	3.0
3/4 in.	29.0
1/2 in.	68.5
No. 4	97.0

APPENDIX C

Calculation Results

Table C.1 Calculation Results of Modulus of Rupture, Density and Percent Voids for Compacted Siliceous Gravel.

Specimen Number	Average Depth (in)	Average Width (in)	Length (in)	Specimen Volume (cf)	MOR (psi)	Density (lb/cf)	Percent Voids
111.11	6.13	5.98	20.06	0.4253	250	105.68	35
111.12	6.47	6.04	20.00	0.4525	253		
111.21	5.90	5.98	20.00	0.4081	205	107.08	34
111.22	6.33	6.00	20.06	0.4411	264		
111.31	6.13	5.98	20.06	0.4253	220	105.77	35
111.32	6.44	6.04	20.06	0.4514	175		
111.33	5.90	6.17	20.00	0.4207	92		
112.11	6.04	6.11	19.94	0.4259	240	106.61	35
112.21	6.08	5.96	19.94	0.4184	260	109.88	33
112.22	6.05	6.19	20.00	0.4334	100		
112.23	5.98	6.08	20.06	0.4223	29		
112.31	6.13	6.02	19.94	0.4256	195	106.93	34
112.32	5.96	5.92	20.06	0.4094	234		
112.33	5.81	5.83	20.06	0.3937	169		
112.41	6.08	6.13	20.00	0.4314	131	105.84	35
112.42	6.04	6.21	20.25	0.4398	236		
112.43	6.00	6.13	20.13	0.4282	913		
112.51	6.13	6.00	20.13	0.4282	189	105.84	35
112.52	5.96	6.09	20.25	0.4251	261		
112.53	6.29	6.04	20.06	0.4413	85		
112.61	6.27	6.25	20.13	0.4565	98	105.84	35
112.62	6.04	6.13	20.19	0.4324	183		
112.63	6.04	6.08	20.19	0.4293	625		

Table C.2 Calculation Results of Percent Retained of Resin and Percent Weight of Resin for Compacted Siliceous Gravel.

Specimen Number	Initial Specimen Wgt (lb)	Tested Specimen Wgt (lb)	Voids (blk)*	Final Specimen Wgt (lb)	Resin Wgt in Specimen (lb)**	Percent Retained Resin	Final* Resin** Wgt(gm)	Final Resin Wgt(lb)	Percent Weight Resin
111.11	44.95	45.80		45.80	0.85	9	4328	9.54	2
111.12	47.82	49.25	1	50.13	2.30	24			5
111.21	43.70	45.55		45.55	1.85	19	4326	9.54	4
111.22	47.24	47.00	2	48.75	1.51	16			3
111.31	44.99	45.80		45.80	0.81	9	4331	9.55	2
111.32	47.75	48.00	2	49.75	2.00	21			4
111.33	44.50	37.25	9	45.13	0.62	7			1
112.11	45.40	49.30		49.30	3.90	44	4000	8.82	8
112.21	45.97	46.00		46.00	0.03	0	6484	14.29	0
112.22	47.63	49.75	1	50.63	3.00	21			6
112.23	46.40	42.25	5	46.63	0.22	2			0
112.31	45.51	47.60		47.60	2.09	17	5743	12.66	4
112.32	43.77	42.50	5	46.88	3.10	25			7
112.33	42.09	36.50	8	43.50	1.41	11			3
112.41	45.65	46.50		46.50	0.85	6	6479	14.28	2
112.42	46.55	48.00		48.00	1.45	10			3
112.43	45.32	52.50		52.50	7.18	50			14
112.51	45.32	52.50		52.50	7.18	50	6485	14.30	14
112.52	44.99	48.50	1	49.38	4.38	31			9
112.53	46.70	47.00	5	51.38	4.67	33			9
112.61	48.32	47.25	2	49.00	0.68	5	6472	14.27	1
112.62	45.76	48.51	1	49.39	3.62	25			7
112.63	45.44	50.75	3	53.38	7.94	56			15

* blk = block of wood ** Resin Wgt in Specimen = Wf - Wi. ***Wgt = Intial Resin Wgt - Resin Losses.

Table C.3 Calculation Results of Percent Resin Volume per Void Volume and Percent Strength for Compacted Siliceous Gravel.

Specimen Number	Resin Volume (cf)	Void Volume (cf)	Percent Voids with Resin	Percent Resin Vol/ Void Vol	Percent Strength
111.11	0.0126	0.1493	32	8	21
111.12	0.0340	0.1589	28	21	21
111.21	0.0273	0.1398	28	20	17
111.22	0.0224	0.1511	29	15	22
111.31	0.0120	0.1491	32	8	18
111.32	0.0296	0.1582	28	19	15
111.33	0.0092	0.1475	33	6	8
112.11	0.0576	0.1471	21	39	20
112.21	0.0004	0.1361	32	0	22
112.22	0.0443	0.1410	22	31	8
112.23	0.0033	0.1374	32	2	2
112.31	0.0309	0.1462	27	21	16
112.32	0.0459	0.1406	23	33	19
112.33	0.0208	0.1352	29	15	14
112.41	0.0125	0.1510	32	8	11
112.42	0.0215	0.1540	30	14	20
112.43	0.1062	0.1499	10	71	76
112.51	0.1062	0.1499	10	71	16
112.52	0.0648	0.1489	20	44	22
112.53	0.0691	0.1545	19	45	7
112.61	0.0101	0.1598	33	6	8
112.62	0.0536	0.1514	23	35	15
112.63	0.1174	0.1503	8	78	52

Table C.4 Calculation Results of Modulus of Rupture, Density and Percent Voids for Uncompacted Siliceous Gravel.

Specimen Number	Average Depth (in)	Average Width (in)	Length (in)	Specimen Volume (cf)	MOR (psi)	Density (lb/cf)	Percent Voids
121.11	6.04	6.00	20.00	0.4197	142	98.37	40
121.12	6.04	6.04	20.00	0.4227	69		
121.13	6.00	5.92	20.00	0.4109	44		
121.21	6.00	6.17	20.00	0.4285	142	99.61	39
121.22	6.00	6.04	20.00	0.4197	80		
121.23	6.09	6.06	20.00	0.4269	69		
121.31	6.17	6.08	20.00	0.4342	105	97.43	40
121.32	6.10	6.23	20.00	0.4401	70		
121.33	6.02	6.11	20.00	0.4255	72		
122.11	6.25	6.06	20.00	0.4384	152	98.05	40
122.12	6.25	6.02	20.00	0.4355	116		
122.13	6.00	6.00	20.00	0.4167	103		
122.14	4.48	6.13	20.00	0.3179	1127		
122.21	6.04	6.00	20.00	0.4197	152	94.01	42
122.22	6.17	6.09	20.00	0.4344	79		
122.23	6.02	6.06	20.00	0.4222	116		
122.24	4.54	6.13	20.00	0.3221	1197		
122.31	6.25	6.00	20.00	0.4340	127	96.81	41
122.32	6.33	6.11	20.00	0.4476	86		
122.33	6.13	6.19	20.00	0.4392	118		
122.34	4.08	6.15	20.00	0.2907	1285		

Table C.5 Calculation Results of Percent Retained of Resin and Percent Weight of Resin for Uncompacted Siliceous Gravel.

Specimen Number	Initial Specimen Wgt (lb)	Tested Specimen Wgt (lb)	Voids (blk)*	Final Specimen Wgt (lb)	Resin Wgt In Specimen (lb)**	Percent Retained Resin	Final* Resin** Wgt (gm)	Final Resin Wgt (lb)	Percent Weight Resin
121.11	41.28	43.50		43.50	2.22	23	4298	9.48	5
121.12	41.58	41.25	2	43.00	1.42	15			3
121.13	40.42	35.00	7	41.13	0.71	7			2
121.21	42.68	43.00	2	44.75	2.07	22	4280	9.44	5
121.22	41.80	39.50	4	43.00	1.20	13			3
121.23	42.53	40.00	4	43.50	0.97	10			2
121.31	42.30	43.50	1	44.38	2.07	22	4272	9.42	5
121.32	42.88	39.50	4	43.00	0.12	1			0
121.33	41.46	38.00	5	42.38	0.92	10			2
122.11	42.98	43.00		43.00	0.02	0	6421	14.16	0
122.12	42.70	41.50	2	43.25	0.55	4			1
122.13	40.86	39.75	3	42.38	1.52	11			4
122.14	31.17	37.50		37.50	6.33	45			17
122.21	39.45	43.00	1	43.88	4.42	31	6414	14.14	10
122.22	40.84	41.00	1	41.88	1.04	7			2
122.23	39.69	42.25	1	43.13	3.43	24			8
122.24	30.28	37.50		37.50	7.22	51			19
122.31	42.02	44.50	1	45.38	3.36	24	6415	14.14	7
122.32	43.34	42.75	1	43.63	0.29	2			1
122.33	42.52	41.50	4	45.00	2.48	18			6
122.34	28.14	34.00		34.00	5.86	41			17

* blk = block of wood ** Resin Wgt in Specimen = Wf - Wi. ***Wgt = Intial Resin Wgt - Resin Losses.

Table C.6 Calculation Results of Percent Resin Volume per Void Volume and Percent Strength for Uncompacted Siliceous Gravel.

Specimen Number	Resin Volume (cf)	Void Volume (cf)	Percent Voids with Resin	Percent Resin Vol/ Void Vol	Percent Strength
121.11	0.0328	0.1662	32	20	12
121.12	0.0210	0.1674	35	13	6
121.13	0.0105	0.1627	37	6	4
121.21	0.0306	0.1664	32	18	12
121.22	0.0177	0.1630	35	11	7
121.23	0.0144	0.1658	35	9	6
121.31	0.0306	0.1744	33	18	9
121.32	0.0018	0.1768	40	1	6
121.33	0.0136	0.1709	37	8	6
122.11	0.0002	0.1744	40	0	13
122.12	0.0081	0.1733	38	5	10
122.13	0.0225	0.1658	34	14	9
122.14	0.0937	0.1265	10*	74**	94
122.21	0.0654	0.1774	27	37	13
122.22	0.0153	0.1837	39	8	7
122.23	0.0508	0.1785	30	28	10
122.24	0.1068	0.1362	9*	78**	99
122.31	0.0496	0.1760	29	28	11
122.32	0.0043	0.1816	40	2	7
122.33	0.0367	0.1781	32	21	10
122.34	0.0867	0.1179	11*	74**	107

* Percent voids with resin should be 0 percent since beam was a solid specimen.

** *Percent resin volume/void volume should be 100 percent since beam was a solid specimen.*

Table C.7 Calculation Results of Modulus of Rupture, Density and Percent Voids for Compacted Crushed Limestone.

Specimen Number	Average Depth (in)	Average Width (in)	Length (in)	Specimen Volume (cf)	MOR (psi)	Density (lb/cf)	Percent Voids
211.21	5.94	6.08	19.94	0.4170	215	92.45	40
211.22	6.06	6.04	20.25	0.4292	112		
211.31	5.98	6.08	20.06	0.4223	195	92.45	40
211.32	6.29	6.02	20.13	0.4413	99		
211.41	6.17	6.21	20.00	0.4432	189	93.00	40
211.42	6.06	5.98	20.25	0.4247	12		
211.51	5.96	6.06	20.00	0.4183	188	98.18	37
211.52	5.98	6.04	20.25	0.4233	145		
211.53	6.05	6.06	20.13	0.4271	15		
211.61	6.38	6.02	20.19	0.4488	150	99.08	36
211.62	5.98	6.11	20.13	0.4254	211		
211.63	6.00	5.92	20.25	0.4160	77		
212.11	6.04	5.96	20.13	0.4198	315	99.92	35
212.12	6.23	6.19	20.13	0.4490	181		
212.13	6.04	6.17	20.31	0.4380	183		
212.21	6.04	6.13	20.06	0.4298	270	98.68	36
212.22	6.29	6.04	20.25	0.4457	150		
212.23	6.15	6.09	20.25	0.4387	11		
212.31	6.19	6.21	20.00	0.4449	230	97.90	37
212.32	5.94	6.15	20.25	0.4279	251		
212.33	5.96	6.00	20.50	0.4242	85		

Table C.8 Calculation Results cf Percent Retained of Resin and Percent Weight of Resin for Compacted Crushed Limestone.

Specimen Number	Initial Specimen Wgt (lb)	Tested Specimen Wgt (lb)	Voids (blk)*	Final Specimen Wgt (lb)	Resin Wgt In Specimen (lb)**	Percent Retained Resin	Final* Resin** Wgt (gm)	Final Resin Wgt (lb)	Percent Weight Resin
211.21	38.55	41.20		41.20	2.65	29	4200	9.26	6
211.22	39.68	41.25	2	43.00	3.32	36			8
211.31	39.04	41.45		41.45	2.41	26	4202	9.26	6
211.32	40.80	39.25	3	41.88	1.07	12			3
211.41	41.22	43.25		43.25	2.03	31	3010	6.64	5
211.42	39.49	31.00	10	39.75	0.26	4			1
211.51	41.07	40.50	1	41.38	0.31	3	4309	9.50	1
211.52	41.56	41.25	1	42.13	0.57	6			1
211.53	41.93	33.00	11	42.63	0.69	7			2
211.61	44.46	42.50	3	45.13	0.66	7	4315	9.51	1
211.62	42.15	40.00	3	42.63	0.48	5			1
211.63	41.22	34.50	8	41.50	0.28	3			1
212.11	41.95	42.80		42.80	0.85	6	6487	14.30	2
212.12	44.86	42.00	4	45.50	0.64	4			1
212.13	43.77	43.00	1	43.88	0.11	1			0
212.21	42.41	43.35		43.35	0.94	7	6455	14.23	2
212.22	43.98	45.50		45.50	1.52	11			3
212.23	43.29	41.50	3	44.13	0.84	6			2
212.31	43.56	43.00	1	43.88	0.32	2	6460	14.24	1
212.32	41.89	44.50	2	46.25	4.36	31			9
212.33	41.53	35.00	8	42.00	0.47	3			1

* blk = block of wood ** Resin Wgt in Specimen = Wf - Wi. ***Wgt = Intial Resin Wgt - Resin Losses.

Table C.9 Calculation Results of Percent Resin Volume per Void Volume and Percent Strength for Compacted Crushed Limestone.

Specimen Number	Resin Volume (cf)	Void Volume (cf)	Percent Voids with Resin	Percent Resin Vol/ Void Vol	Percent Strength
211.21	0.0392	0.1679	31	23	21
211.22	0.0491	0.1728	29	28	11
211.31	0.0356	0.1700	32	21	19
211.32	0.0159	0.1777	37	9	10
211.41	0.0300	0.1769	33	17	19
211.42	0.0038	0.1695	39	2	1
211.51	0.0046	0.1529	35	3	19
211.52	0.0084	0.1547	35	5	14
211.53	0.0102	0.1561	34	7	2
211.61	0.0098	0.1615	34	6	15
211.62	0.0071	0.1531	34	5	21
211.63	0.0042	0.1497	35	3	8
212.11	0.0126	0.1487	32	8	31
212.12	0.0094	0.1591	33	6	18
212.13	0.0016	0.1552	35	1	18
212.21	0.0139	0.1557	33	9	27
212.22	0.0225	0.1615	31	14	15
212.23	0.0124	0.1590	33	8	1
212.31	0.0047	0.1635	36	3	23
212.32	0.0645	0.1572	22	41	25
212.33	0.0069	0.1559	35	4	8

Table C.10 Calculation Results of Modulus of Rupture, Density and Percent Voids for Uncompacted Crushed Limestone.

Specimen Number	Average Depth (in)	Average Width (in)	Length (in)	Specimen Volume (cf)	MOR (psi)	Density (lb/cf)	Percent Voids
221.11	6.21	6.02	20.00	0.4327	96	87.47	43
221.12	6.04	5.96	20.00	0.4169	74		
221.13	6.09	6.00	20.00	0.4229	58		
221.21	6.25	5.96	20.00	0.4311	77	85.54	45
221.22	5.96	6.02	20.00	0.4155	75		
221.23	5.96	6.04	20.00	0.4169	60		
221.31	6.34	5.88	20.00	0.4310	117	85.45	45
221.32	6.04	5.88	20.00	0.4110	71		
221.33	5.96	5.88	20.00	0.4054	53		
222.11	6.29	5.96	20.00	0.4341	101	86.69	44
222.12	6.00	6.06	20.00	0.4211	122		
222.13	6.00	6.02	20.00	0.4181	91		
222.14	4.75	5.96	20.00	0.3277	921		
222.21	6.00	6.00	20.00	0.4167	122	87.16	44
222.22	6.21	6.00	20.00	0.4313	101		
222.23	5.98	6.11	20.00	0.4227	91		
222.24	4.74	6.15	20.00	0.3375	1112		
222.31	6.17	5.96	20.00	0.4254	84	86.38	44
222.32	6.23	5.92	20.00	0.4266	74		
222.33	6.04	5.96	20.00	0.4169	120		
222.34	4.59	6.08	20.00	0.3229	990		

Table C.11 Calculation Results of Percent Retained of Resin and Percent Weight of Resin for Uncompacted Crushed Limestone.

Specimen Number	Initial Specimen Wgt (lb)	Tested Specimen Wgt (lb)	Voids (blk)*	Final Specimen Wgt (lb)	Resin Wgt in Specimen (lb)**	Percent Retained Resin	Final* Resin** Wgt (gm)	Final Resin Wgt (lb)	Percent Weight Resin
221.11	37.85	41.50	1	42.38	4.53	48	4263	9.40	11
221.12	36.46	35.00	3	37.63	1.16	12			3
221.13	36.99	34.50	6	39.75	2.76	29			7
221.21	36.88	39.50	1	40.38	3.50	37	4267	9.41	9
221.22	35.54	36.50	2	38.25	2.71	29			7
221.23	35.66	32.00	6	37.25	1.59	17			4
221.31	36.83	38.75	1	39.63	2.80	30	4266	9.40	7
221.32	35.12	36.50	1	37.38	2.25	24			6
221.33	34.64	33.50	4	37.00	2.36	25			6
222.11	37.64	38.25	1	39.13	1.49	11	6397	14.10	4
222.12	36.50	37.75	1	38.63	2.12	15			5
222.13	36.24	38.25	1	39.13	2.88	20			7
222.14	28.41	34.50		34.50	6.09	43			18
222.21	36.32	37.50		37.50	1.18	8	6384	14.07	3
222.22	37.59	37.75	1	38.63	1.04	7			3
222.23	36.84	37.50	1	38.38	1.54	11			4
222.24	29.41	36.50		36.50	7.09	50			19
222.31	36.75	36.50	1	37.38	0.63	4	6404	14.12	2
222.32	36.85	38.25		38.25	1.40	10			4
222.33	36.01	36.50	2	38.25	2.24	16			6
222.34	27.90	35.50		35.50	7.60	54			21

* blk = block of wood ** Resin Wgt in Specimen = Wf - Wi. ***Wgt = Intial Resin Wgt - Resin Losses.

Table C.12 Calculation Results of Percent Resin Volume per Void Volume and Percent Strength for Uncompacted Crushed Limestone.

Specimen Number	Resin Volume (cf)	Void Volume (cf)	Percent Voids with Resin	Percent Resin Vol/ Void Vol	Percent Strength
221.11	0.0670	0.1881	28	36	10
221.12	0.0172	0.1812	39	9	7
221.13	0.0408	0.1839	34	22	6
221.21	0.0517	0.1928	33	27	8
221.22	0.0400	0.1858	35	22	7
221.23	0.0235	0.1864	39	13	6
221.31	0.0414	0.1930	35	21	12
221.32	0.0333	0.1841	37	18	7
221.33	0.0349	0.1815	36	19	5
222.11	0.0220	0.1909	39	12	10
222.12	0.0314	0.1852	37	17	12
222.13	0.0426	0.1839	34	23	9
222.14	0.0901	0.1441	16*	63**	91
222.21	0.0175	0.1820	39	10	12
222.22	0.0153	0.1884	40	8	10
222.23	0.0227	0.1846	38	12	9
222.24	0.1048	0.1474	13*	71**	110
222.31	0.0093	0.1879	42	5	8
222.32	0.0207	0.1885	39	11	7
222.33	0.0331	0.1842	36	18	12
222.34	0.1125	0.1427	9*	79**	98

* Percent voids with resin should be 0 percent since beam was a solid specimen.

** Percent resin volume/void volume should be 100 percent since beam was a solid specimen.

APPENDIX D

Data Points for Graphs

Table D.1 Data Points for Figure 6.1.

Curve	Specimen Depth (in)	MOR (psi)	Specimen Number
A	6	185	112.01
	12	204	112.02
	18	106	112.03
B	6	144	122.01
	12	94	122.02
	18	112	122.03
C	6	272	212.01
	12	194	212.02
	18	94	212.03
D	6	102	222.01
	12	99	222.02
	18	101	222.03

Table D.2 Data Points for Figure 6.2.

Curve	Specimen Depth (in)	MOR (psi)	Specimen Number
A	6	225	111.01
	12	231	111.02
	18	92	111.03
B	6	130	121.01
	12	73	121.02
	18	63	121.03
C	6	187	211.01
	12	116	211.02
	18	47	211.03
D	6	97	221.01
	12	74	221.02
	18	58	221.03

Table D.3 Data Points for Figure 6.3.

Curve	Specimen Depth (in)	MOR (psi)	Specimen Number
A	6	225	111.01
	12	231	111.02
	18	92	111.03
B	6	185	112.01
	12	204	112.02
	18	106	112.03
C	6	130	121.01
	12	73	121.02
	18	63	121.03
D	6	144	122.01
	12	94	122.02
	18	112	122.03

Table D.4 Data Points for Figure 6.4.

Curve	Specimen Depth (in)	MOR (psi)	Specimen Number
A	6	187	211.01
	12	116	211.02
	18	47	211.03
B	6	272	212.01
	12	194	212.02
	18	94	212.03
C	6	97	221.01
	12	74	221.02
	18	58	221.03
D	6	102	222.01
	12	99	222.02
	18	101	222.03

Table D.5 Data Points for Figure 6.5.

Curve	Resin Loading (gal/sf)	MOR (psi)	Specimen Depth (in)	Specimen Number
A	1.29	225	6	111.01
	1.93	185	6	112.01
B	1.29	231	12	111.02
	1.93	204	12	112.02
C	1.29	92	18	111.03
	1.93	106	18	112.03

Table D.6 Data Points for Figure 6.6.

Curve	Resin Loading (gal/sf)	MOR (psi)	Specimen Depth (in)	Specimen Number
A	1.29	130	6	121.01
	1.93	144	6	122.01
B	1.29	73	12	121.02
	1.93	94	12	122.02
C	1.29	63	18	121.03
	1.93	112	18	122.03

Table D.7 Data Points for Figure 6.7.

Curve	Resin Loading (gal/sf)	MOR (psi)	Specimen Depth (in)	Specimen Number
A	1.29	187	6	211.01
	1.93	272	6	212.01
B	1.29	116	12	211.02
	1.93	194	12	212.02
C	1.29	47	18	211.03
	1.93	94	18	212.03

Table D.8 Data Points for Figure 6.8.

Curve	Resin Loading (gal/sf)	MOR (psi)	Specimen Depth (in)	Specimen Number
A	1.29	97	6	221.01
	1.93	102	6	222.01
B	1.29	74	12	221.02
	1.93	99	12	222.02
C	1.29	58	18	221.03
	1.93	101	18	222.03

Table D.9 Data Points for Figure 6.9.

Curve	Density (lb/cf)	MOR (psi)	Specimen Number
A	96.29	117	122.00
	98.47	89	121.00
	106.04	183	111.00
	107.08	165	112.00
B	86.15	76	221.00
	86.74	101	222.00
	96.23	117	211.00
	98.83	187	212.00

Table D.10 Data Points for Figure 6.10.

Curve	Percent Voids	MOR (psi)	Specimen Number
A	34	161	112.00
	35	183	111.00
	40	89	121.00
	41	117	122.00
B	36	187	212.00
	39	117	211.00
	44	76	221.00
	44	101	222.00

Table D 11 Data Points for Figure 6.11.

Curve	Percent Retained Resin	MOR (psi)	Specimen Number	Curve	Percent Retained Resin	MOR (psi)	Specimen Number
A	4	94	122.02	B	3	94	212.03
	7	92	111.03		5	47	211.03
	9	63	121.03		5*	272	212.01
	10	73	121.02		8	102	222.01
	12	225	111.01		11	99	222.02
	15	106	112.03		12	116	211.02
	18	112	122.03		15	194	212.02
	18	144	122.01		16	101	222.03
	20	185	112.01		19	187	211.01
	20	231	111.02		22	74	221.02
	22	130	121.01		24	58	221.03
	22	204	112.02		38*	97	221.01

* Data point not included in calculation of "best-fit" linear curve.

Table D.12 Data Points for Figure 6.12.

Curve	Percent Weight Resin	MOR (psi)	Specimen Number	Curve	Percent Weight Resin	MOR (psi)	Specimen Number
A	1	92	111.03	B	1	47	211.03
	1	94	122.02		1	94	212.03
	2	63	121.03		2*	272	212.01
	2	73	121.02		3	102	222.01
	3	225	111.01		3	116	211.02
	4	106	112.03		4	99	222.02
	4	231	111.02		4	187	211.01
	5	130	121.01		5	74	221.02
	5	185	112.01		5	194	212.02
	6	112	122.03		6	58	221.03
	6	144	122.01		6	101	222.03
	6	204	112.02		9*	97	221.01

* Data point not included in calculation of "best-fit" linear curve.

Table D.13 Data Points for Figure 6.13.

Curve	Percent Resin Vol/ Void Vol	Percent Strength	Specimen Number	Curve	Percent Resin Vol/ Void Vol	Percent Strength	Specimen Number
A	5	8	122.02	B	4	9	212.03
	6	8	111.03		5	5	211.03
	8	5	121.03		7*	27	212.01
	8	6	121.02		9	10	222.01
	12	19	111.01		10	11	211.02
	18	19	111.02		12	10	222.02
	19	11	121.01		14	19	211.01
	21	8	112.03		16	7	221.02
	21	9	122.03		20	19	212.02
	22	12	122.01		18	6	221.03
	24	15	112.01		18	10	222.03
	31	17	112.02		28*	10	221.01

* Data point not included in calculation of "best-fit" linear curve.

APPENDIX E

Linear Equations for Graphs

The calucation of fitted curves produced an equation along with a correlation coefficient. The equation used to fit the linear regression curve is as follows: $Y_i = aX_i + b + error$. The correlation coefficient was designated by R^2 (R squared). The closer R^2 was to 1.00, then the more reliable was the curve fit equation generated.

E.1. Figure 6.1 Flexural Strength of PMA as a Function of the Depth of the Specimen Under Maximum Resin Loading Conditions.

a. y = 252.00 - 7.5833x ; R^2 = 0.599

b. y = 148.67 - 2.6667x ; R^2 = 0.399

c. y = 364.67 - 14.833x ; R^2 = 0.995

d. y = 101.67 - 8.3e - 2x ; R^2 = 0.107

E.2. Figure 6.2 Flexural Strength of PMA as a Function of the Depth of the Specimen Under Minimum Resin Loading Conditions.

a. y = 315.67 - 11.083x ; R^2 = 0.716

b. y = 155.67 - 5.5833x ; R^2 = 0.859

c. y = 256.67 - 11.667x ; R^2 = 1.000

d. $y = 115.33 - 3.2500x$; $R^2 = 0.989$

E.3. Figure 6.3 Flexural Strength of Siliceous Gravel PMA as a Function of the Depth of the Specimen.

a. $y = 315.67 - 11.083x$; $R^2 = 0.716$

b. $y = 252.00 - 7.5833x$; $R^2 = 0.599$

c. $y = 155.67 - 5.5833x$; $R^2 = 0.859$

d. $y = 148.67 - 2.6667x$; $R^2 = 0.399$

E.4. Figure 6.4 Flexural Strength of Crushed Limestone PMA as a Function of the Depth of the Specimen.

a. $y = 256.67 - 11.667x$; $R^2 = 1.000$

b. $y = 364.67 - 14.833x$; $R^2 = 0.995$

c. $y = 115.33 - 3.2500x$; $R^2 = 0.989$

d. $y = 101.67 - 8.3e - 2x$; $R^2 = 0.107$

E.5. Figure 6.5 Flexural Strength of Siliceous Gravel PMA as a Function of Maximum and Minimum Resin Loadings Under Compacted Conditions.

a. $y = 305.62 - 62.500x$; $R^2 = 1.000$

b. $y = 285.42 - 42.188x$; $R^2 = 1.000$

c. $y = 87.969 + 3.1250x$; $R^2 = 1.000$

E.6. Figure 6.6 Flexural Strength of Siliceous Gravel PMA as a Function of Maximum and Minimum Resin Loadings Under Uncompacted Conditions.

a. $y = 101.78 + 21.875x$; $R^2 = 1.000$

b. $y = 30.672 + 32.813x$; $R^2 = 1.000$

c. $y = -35.766 + 76.563x$; $R^2 = 1.000$

E.7. Figure 6.7 Flexural Strength of Crushed Limestone PMA as a Function of Maximum and Minimum Resin Loadings Under Compacted Conditions.

a. $y = 15.672 + 132.81x$; $R^2 = 1.000$

b. $y = -41.219 + 121.88x$; $R^2 = 1.000$

c. $y = -47.734 + 73.438x$; $R^2 = 1.000$

E.8. Figure 6.8 Flexural Strength of Crushed Limestone PMA as a Function of Maximum and Minimum Resin Loadings Under Uncompacted Conditions.

a. $y = 86.922 + 7.8125x$; $R^2 = 1.000$

b. $y = 23.609 + 39.063x$; $R^2 = 1.000$

c. $y = -28.672 + 67.188x$; $R^2 = 1.000$

E.9. Figure 6.9 Flexural Strength of PMA as a Function of the Density of the Aggregate Matrix.

a. $y = -565.90 + 6.9001x$; $R^2 = 0.757$

b. $y = -463.46 + 6.3455x$; $R^2 = 0.749$

E.10. Figure 6.10 Flexural Strength of PMA as a Function of the Percent Voids in the Aggregate Matrix.

a. $y = 531.76 - 10.514x$; $R^2 = 0.758$

b. $y = 571.55 - 11.075x$; $R^2 = 0.844$

E.11. Figure 6.11 Flexural Strength of PMA as a Function of the Percent Retained of Resin in the Aggregate Matrix.

a. $y = 52.484 + 5.7674x$; $R^2 = 0.378$

b. $y = 91.771 + 1.1425x$; $R^2 = 0.026$

E.12. Figure 6.12 Flexural Strength of PMA as a Function of the

Percent Weight of Resin in the Aggregate Matrix.

a. $y = 83.132 + 14.598x$; $R^2 = 0.196$

b. $y = 93.164 + 3.7640x$; $R^2 = 0.018$

E.13. Figure 6.13 Percent Flexural Strength as a Function of Percent Resin Volume/Void Volume.

a. $y = 6.3024 + 0.31472x$; $R^2 = 0.275$

b. $y = 6.4634 + 0.32830x$; $R^2 = 0.143$

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