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# Marshall properties of asphaltic concrete containing glass-rich fractions

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# MARSHALL PROPERTIES OF ASPHALTIC CONCRETE

# CONTAINING GLASS-RICH FRACTIONS

BY

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# ABSTRACT

The use of crushed waste glass as an aggregate in asphaltic concrete has been suggested as a means for re-using glass separated from municipal refuse. Laboratory studies and field installations have generally utilized clean glass obtained by hand sorting bottles from the other refuse and crushing them to produce a desired gradation. For this type of asphalt to be economical though, the glass fraction must be separated mechanically. For mechanically separated materials, the glass-rich fraction also contains such items as metal, bone, rubber and other non-glass materials.

The objective of the study was to determine the effects upon Marshall properties of laboratory compacted conventional asphaltic paving mixtures when clean glass aggregates and glass-rich fractions were substituted for varying proportions of the conventional aggregates.

Five glass-rich fractions with varying gradation and composition were substituted for conventional aggregates in an asphaltic concrete at 10, 30 and 50 percent replacement levels on selected sieve sizes. Similar substitutions were made using clean glass at the same replacement levels and control specimens containing no glass were made for comparison with the specimens containing glass. Marshall properties of all specimens were determined and a statistical analysis was used to determine the relationship between glass addition level and changes in Marshall properties.

The results showed that glass-rich fractions and clean glass materials of selected sieve sizes can be substituted for conventional aggregates in asphaltic concrete without causing flow, stability or

voids in the mineral aggregate to fall outside limits specified by The Asphalt Institute. In some cases, air void limits were exceeded when increasing amounts of glass-rich fractions were added. Additions of fine incinerator residues caused air voids to increase to a greater degree than was caused by clean glass additions. Since air voids can be adjusted by modifying gradation and/or asphalt content it was concluded that glass-rich fractions can replace portions of the conventional aggregate in an asphaltic concrete with the resulting mixture satisfying Marshall design criteria.

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# I. INTRODUCTION

## A. Statement of the Problem

The use of crushed waste glass as an aggregate in asphaltic concrete has been suggested as a means for reusing glass separated from municipal refuse. Laboratory studies and field installations have generally utilized clean glass obtained by hand sorting bottles from the other refuse and crushing them to produce a desired gradation (1,2,3). However, the economic feasibility of this concept depends upon using glass separated by large-scale mechanical processes. Several mechanical separation systems produce a glass-rich fraction in particle sizes ranging from 1/2-inch to minus 200 material and of varying gradation. These mechanically separated glass-rich fractions contain other materials such as metals, bone and rubber (4).

To minimize the costs cf using waste glass in paving, it would be desirable to use the glass-rich fraction without further processing to remove the non-glass components or alter the gradation. If this material can be blended with conventional aggregates without appreciably affecting the properties of an asphaltic concrete, this would be an economical way of disposing of this waste product. The degree to which properties of asphaltic concrete are affected by the addition of glass-rich fractions, however, is unknown.

The objective of this study was to determine the effect upon Marshall properties of laboratory compacted conventional asphalt paving mixtures when clean glass aggregates and glass-rich fractions were substituted for varying proportions of the conventional aggregates.

The specific objectives were to:

1. Compare the Marshall properties of asphaltic mixtures containing conventional aggregates with the properties of similar mixtures in which clean glass and glass-rich fractions had been substituted for varying proportions of the conventional aggregates.
2. Determine the relationship between Marshall properties and the amount of clean glass or glass-rich fractions added to an asphaltic mixture.

## II. REVIEW OF LITERATURE

Work was initiated at the University of Missouri-Rolla in 1969 to investigate whether clean waste glass could be utilized as a substitute for conventional aggregate in asphaltic concrete mixtures. The raw refuse from cities and towns has been found to contain 6 to 10 percent glass by weight (5). If, after separating the refuse into component parts, a use could be found for the glass fraction, the expense of disposing of the glass portion could be eliminated and the savings in the cost of conventional aggregates could be used to partially offset the costs of separating the refuse.

Foster (6) determined that mixtures meeting Marshall requirements could be designed using aggregates composed entirely of clean crushed container glass. The water resistance of these mixtures, however, was poor since severe stripping or loss in adhesion between the asphalt and glass occurred when specimens were subjected to a standard water immersion procedure. Additions of commercial anti-stripping agents, hydrated lime and limestone dust were used to control stripping and it was found that hydrated lime was the most effective material for this purpose. The addition of 1 percent hydrated lime by weight of the glass aggregate resulted in retained strengths of 100 percent; i.e., specimens tested wet had the same strength as dry specimens.

Studies of the glass aggregates utilized in initial studies showed that most of the coarse particles present were flat and elongated. A study was undertaken by Doyle (7) to determine the effects of gradation, shape and angularity of glass particles on Marshall properties. The shape of the coarse aggregate had little effect upon Marshall properties since mixtures containing nearly equidimensional particles had the same Marshall properties as mixtures containing flat and elongated pieces. Substitution of spherical glass particles for more angular crushed container glass resulted in very low stabilities, indicating that particle angularity contributes significantly to the mixture strength. Altering the gradation to produce denser mixes increased stability somewhat but reduced voids to unacceptably low values.

Field installations showed that asphaltic mixtures containing clean glass blended with conventional aggregates in varying amounts could be mixed and placed with standard equipment. Marshall properties were adequate in most cases and the performance of glasphalt pavements was satisfactory with respect to skid resistance and resistance to rutting and shoving. Raveling was noted on pavements exposed to studded tire traffic and chains, but pavements not exposed to this type of traffic experienced little surface deterioration (8).

To be economically practical, glass separated from waste material and containing other materials would have to be utilized to minimize processing costs. Keith (4) undertook a study to determine the effects upon Marshall properties when using glass-rich fractions rather than clean glass. He found that acceptable mixtures could be designed utilizing these fractions but that no glass-rich fraction examined had a gradation which permitted the total substitution for conventional aggregate, so an addition of conventional aggregate was always needed. Non-glass materials were found to affect the mix properties. Increasing amounts of non-glass components, without altering the gradation or asphalt content, increased voids and flow while causing a decrease in stability. Mixtures using up to 77 percent waste glass by weight were designed to meet Marshall requirements.

## III. CHARACTERISTICS OF GLASS-RICH FRACTIONS SEPARATED FROM MUNICIPAL REFUSE

Systems for separating raw refuse as well as incinerator residue have been devised and are in varying stages of development. In each system the separated components include a glass-rich fraction. Glass-rich fractions used in this investigation were obtained from a raw refuse separation system developed by the Black Clawson Company and an incinerator residue separation system developed by the U.S. Bureau of Mines. These systems are described briefly below.

### A. Separation Systems

#### 1. Black Clawson

The Black Clawson Company utilizes a wet separation system called Hydrasposal Fibreclaim (9). A conveyor feeds mixed refuse into a wet pulping machine which is fitted with a non-destructible rotor designed to cut rags, plastic, rubber hose and wire, etc.; disintegrate food waste and paper; break bottles; and chop aluminum. Non-pulpable items such as tin cans, massive iron, stones and the like are ejected through an opening in the bottom of the hydropulper and are removed continuously by a junk remover. The disintegrated and pulped materials are removed in a water slurry having 3 to 4 percent solids through a perforated extraction plate beneath the pulper rotor. The slurry is passed through a liquid cyclone to remove essentially all of the remaining inorganic materials such as sand, glass, aluminum, ceramics, etc. This inorganic matter rejected by the liquid cyclone consists primarily of glass. The slurry is further treated to separate useful long paper-making fibers and the organic rejects are then burned in a fluid bed reactor.

About 95 percent of the Black Clawson Glass-rich fraction ranges in size from plus 30 mesh to minus 1/2-inch mesh. Non-glass components which can be hand separated from the coarse fraction plus magnetic material from all size fractions comprises about 17 percent by weight of the material examined. Results of a sieve analysis and component separation conducted by Keith (4) are shown in Tables I and II.

2. Bureau of Mines

The U.S. Bureau of Mines has developed a continuous processing plant using wet mechanical methods for recovering and separating low temperature incinerator residues into fractions that can be further treated to produce materials suitable for recycling (10). A conveyor feeds the residue to a punched plated trommel screen having 1 1/4-inch holes and fitted with internal lifters to achieve a tumbling action. During screening the residues are sprayed continuously with water. The minus 1 1/4-inch material is screened and washed on a circular vibrating screen equipped with both No. 4 and 20-mesh screens and most of the plus 1 1/4-inch material is then blended with the plus 4-mesh fraction and shredded in a hammermill. The minus 4-plus 20-mesh fraction from screening is joined with the shredded material where it is washed and screened on both 4 and 20-mesh screens. The oversize material is passed through a magnetic separator and the nonmagnetic fraction is fed to a hammermill which breaks the glass and other non-metals. The discharge is screened on 4 and 20-mesh screens with the plus 4-mesh material being recovered as a nonferrous metal concentrate.

The minus 4 plus 20-mesh fraction is treated in a magnetic separator to produce a magnetic fraction and the non-magnetic product, which contains an appreciable quantity of nonferrous metal mixed with glass, is dewatered in a spiral-type classifier. The pulp is ground in a peripheral discharge rod mill and screening is used to recover a nonferrous metal oversize product. The minus 20-mesh material is further processed by flotation and in magnetic separators of various field strengths to produce a product that is primarily colorless glass containing small amounts of light amber glass and carbon as well as magnetic or colored glass concentrate.

Four products obtained from the U.S. Bureau of Mines were utilized in the present work. They include coarse and fine glass-rich fractions, jig heavies and matrix magnetic products.

a. Coarse Incinerator Residue

The coarse incinerator residue was taken out of the process just after passing the circular vibrating screen, but before arriving at the hammermill. The gradation and composition of this material are shown in Tables I and III.

b. Fine Incinerator Residue

The fine incinerator residue was removed from the system after passing through the peripheral discharge rod mill. The gradation of this material is shown in Table I.

c. Jig Heavies

The jig heavies product was removed from the system at the drum magnetic separator. The nonmagnetic product was removed from the conventional circuit and fed to a Harz-type jig. A heavy cup product with a light overflow product of glass and refractory materials with a minor amount of magnetic slag was obtained. The heavy cup product (jig heavies) is mostly iron bearing slag with a small amount of glass and traces of heavy nonferrous metals such as copper, brass, and zinc. Total iron in typical samples of this material was between 40 and 45 percent. The gradation is shown in Table I.

d. Matrix Magnetic Product

The matrix magnetic product was obtained from the overflow of the Harz-type jig that was used in the jig heavies process. The material is returned to the conventional circuit by feeding it to the rod mill. The discharge of the rod mill is screened to remove plus 20-mesh nonferrous metals and the minus 20-mesh product goes to the matrix-type wet magnetic separators. The gradation of this material is shown in Table I.

# IV. MATERIALS AND TEST PROCEDURES

## A. Materials

### 1. Glass-Rich Fractions

Glass-rich fractions from the raw refuse and incinerator residue described previously were sieved into size fractions ranging from material passing the 1/2-inch sieve and retained on the 3/8-inch sieve to material passing the No. 200 sieve.

### 2. Clean Glass Aggregates

Clean glass aggregates were produced by crushing waste glass consisting primarily of non-returnable beverage bottles. The bottles were initially soaked in a hot water bath where labels and all other foreign materials were removed. After drying, the bottles were crushed in a hammermill for a coarse glass aggregate. Some of this glass was crushed further in a ball mill to obtain the smaller sieve sizes. The crushed glass was then sieved into size fractions ranging from material passing the 1/2-inch sieve and retained on the 3/8-inch sieve to material passing the No. 200 sieve.

### 3. Asphalt

The asphalt used was an 85-100 penetration asphalt cement produced from a west Texas crude oil. The properties of this asphalt cement are listed in Table IV.

### 4. Calcium Hydroxide

Reagent grade calcium hydroxide was used as an anti-stripping additive in all mixes containing glass or glass-rich fractions.

5. Conventional Aggregates

Coarse aggregate (material retained on a No. 8 sieve) was a crushed limestone locally available in the Rolla area. It was sieved into three size fractions which were recombined to obtain the desired gradation. Fine aggregate (material passing a No. 8 sieve) was a Meramec River sand which had been sieved into six size fractions and was then recombined to yield the desired gradation.

B. Test Procedures

1. Sieve Analyses

Sieve analyses of glass-rich fractions were conducted in accordance with ASTM C 136.

2. Bulk Specific Gravity Calculations

For coarse glass-rich fractions a representative sample of the material to be tested was obtained. If the material was porous it was soaked in water for 24 hours. The sample was surface dried, weighed and weight A was placed in a 2000 ml flask. For non-porous materials, weight A was a dry weight. The material was covered with water, and a vacuum was applied for 15 minutes to aid in removing the air from the sample. The vacuum was removed, the flask filled with water, and weight C obtained. Weight B was the weight of the flask filled with water only. The porous materials were oven dried to obtain weight D. The bulk specific gravity (BSG) was then calculated from the expression $BSG = \frac{D}{A+B-C}$.

For fine material a sample was soaked in water for 24 hours. The sample was brought to a saturated surface dry condition and 500 gm were placed in a 500 ml flask and weighed to determine weight B. After filling the flask with sufficient water to immerse the sample, it was left standing for 24 hours to permit entrapped air to escape. The flask was then filled with water to the 500 ml mark and weighed to determine weight C. The sample was then oven dried to obtain weight A. The bulk specific gravity (BSG) was then calculated from the expression

$$BSG = \frac{A}{500-(C-B)} .$$

Values for the bulk specific gravities of the glass-fractions utilized are given in Table V.

3. Marshall Test Procedures

The Marshall tests were conducted according to procedures specified by ASTM D 1559 with the following exceptions:

a. Immediately after mixing for two minutes in a Hobart Model N-50 mixer, the bituminous mixture was placed in compaction molds. The molds were then placid in an oven at 275 F for 30 minutes to insure a uniform temperature for all specimens at compaction. After removing the molds from the oven, the mixtures were spaded and compacted according to specifications.

b. A mechanical compaction hammer was used for compaction.

c. For testing purposes an automatic recording test press, Model 750, Pine Instrument Company, was used in place of the specified loading jack, proving ring assembly, and flow meter.

4. Asphalt Absorption by Aggregate

The amount of asphalt absorbed by the aggregates used in this investigation was determined by Rices Method so that the air voids present in the compacted asphaltic concretes could be calculated. The asphaltic concrete mixture was prepared using the standard Marshall test mixing procedure, but instead of compacting it the mixture was placed in a pan where it was broken into lumps smaller than 0.25 in. A quantity of the sample was weighed and the weight of a 2000 ml flask filled with water was determined. The sample was placed in the flask and immersed in water, then subjected to a vacuum to extract the air present. The flask plus sample was then filled with water and weighed again. The volume of the sample was found by adding the weight of the flask filled with water to the dry sample weight and subtracting the weight of the flask containing the sample and filled with water. Assuming no absorption, the volume of the sample was determined by dividing the weights of asphalt and aggregate present in the sample by their respective unit weights and summing these values. The volume of asphalt absorbed was found by subtracting the volume determined in the test from the volume assuming no absorption. The weight of this volume of asphalt was then determined and expressed as a percentage of the dry aggregate weight. Absorption values for the glass-rich fractions utilized are given in Table VI.

## V. DESIGN OF CONTROL MIXTURE

An asphaltic concrete consisting of conventional crushed stone and sand aggregates combined with an asphalt cement was designed using the standard Marshall method of mix design with 50 blow compaction. The aggregate gradation used is shown in Table VII, and the mixture properties at total asphalt contents ranging from 4.5 to 7.0 percent are shown in Figure 1. The aggregate absorption was determined to be 0.667 pounds per hundred pounds of aggregate using Rice's method. The optimum asphalt content, at which stability, flow, air voids, and voids in the mineral aggregate were within acceptable limits specified by The Asphalt Institute as shown in Table VIII was 6 percent. This corresponds to an effective asphalt content of 5.4 percent when absorption of asphalt by the aggregate is taken into account. Marshall properties of the control mixture at an effective asphalt content of 5.4 percent are given in Table IX. This mixture was used for comparison with mixes containing varying proportions of clean glass and glass-rich fractions.

## VI. SUBSTITUTION OF CLEAN GLASS AND GLASS-RICH FRACTION IN THE CONTROL MIXTURE

The predominant size fractions present in each glass-rich fraction were determined from the sieve analysis. For the Black Clawson product, the major size fractions were retained on the No. 4, 8, and 16 sieves. Using the same gradation employed in the control batch, mixtures were made in which 10, 30, and 50 percent by volume of the conventional aggregates retained on the No. 4, 8, and 16 sieves were replaced by clean glass and the Black Clawson glass-rich fraction. For each sieve size on which conventional aggregate was replaced by a clean glass material or the Black Clawson product, the volume of the conventional aggregate on that sieve size was found by dividing its weight by its unit weight. The volume of the Black Clawson product or clean glass material to be added was determined by multiplying the volume of the conventional aggregate on that sieve by the appropriate percent replacement level. This value was subtracted from the original volume of conventional aggregate to obtain the volume of conventional aggregate required. Each of these volumes was then multiplied by its unit weight to obtain the weights used. For example, the conventional aggregate retained on the No. 4 sieve weighed 290 g. and dividing this by its unit weight, 2.615 g/cc, yielded a volume of 111 cc. At a 10 percent replacement level, 11 cc of Black Clawson material was required and 100 cc of conventional aggregates. Multiplying these values by the unit weights yielded weights of 28 and 261 g. for the Black Clawson and conventional aggregates respectively. The volume of asphalt in each mixture was kept constant and since the Black Clawson material absorbed more asphalt than the conventional aggregate this meant that more asphalt was added to these mixtures. Three specimens were made for each addition level and type of glass employed plus three control specimens for a total of 21 specimens, using standard Marshall methods for compaction. The unit weight, stability, and flow were then measured and the air voids and voids in the mineral aggregate were calculated.

A similar procedure was used for each of the other four glass-rich fractions used in the investigation. The particle sizes substituted for each glass-rich fraction are given in Table X.

Since the size fractions on which replacements were made varied for each glass-rich fraction investigated, the glass replacement expressed as a percent of the total aggregate also varied. For instance, at the 50 percent addition level in the Black Clawson series, the total aggregate was 25.1 percent glass while at the 50 percent addition level in the matrix magnetic series the total aggregate was 13.6 percent glass.

## VII. EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS TECHNIQUES

The same experimental design was used for each of the five glass-rich fractions studied in the investigation. Using the Black Clawson fraction, for example, seven specimens were molded each day for three days, with each set of seven including a control specimen containing only conventional aggregate and specimens containing clean glass or glass-rich fractions at the 0, 10, 30, and 50 percent addition levels. A randomized complete block design was used with three blocks representing each of the three days on which specimens were made. This permitted a separation of block effects and treatment effects in the analysis of variance procedure used to analyze the data.

After the Marshall properties had been determined for the 21 specimens, an analysis of variance was conducted to determine whether there were any statistically significant differences in stability, flow, air voids, and voids in the mineral aggregate for the clean glass or glass-rich fractions at a 0.05 significance level. A sample calculation for this procedure is given in Appendix C. If a statistically significant difference was found, the data were further analyzed for linear, quadratic, or cubic regression trends. The purpose of this analysis was to determine if there were any predictable mathematical relationships that could be formulated between the increasing amounts of glass or glass-rich materials added and the changes in individual Marshall properties. The regression relation between percent glass and the Marshall properties was determined by orthogonal polynomials, with the orthogonal coefficients being calculated for the unequally spaced treatments using a method described by Grandage (11). Orthogonal coefficients were calculated as described in Appendix D and these coefficients were then used to determine the presence or absence of a linear, quadratic or cubic trend in the data. A sample calculation for this procedure is given in Appendix E (12).

The data were plotted and where statistically significant trends were indicated by the statistical analysis, a curve was fitted using the orthogonal polynomial analysis. If no statistically significant differences were noted, no curves were drawn.

## VIII. EXPERIMENTAL RESULT AND DISCUSSION

Marshall test data for the five glass-rich fractions tested are given in Tables XI through XV and the results of statistical analyses are given in Table XVI. The results are shown graphically in Figures 2 through 6.

In the test series utilizing Black Clawson glass-rich fractions and clean glass, Figure 2, increasing amounts of Black Clawson material resulted in lower air voids, and voids in the mineral aggregate (VMA), higher flow and a substantially lower stability. This is expected since the smoother surface texture of glass as compared to the crushed limestone it replaces would decrease the internal friction in the mixture. However, the stability at 50 percent replacement still exceeded the minimum requirements established by The Asphalt Institute (13).

The clean glass replacement in the same test series resulted in a similar decrease in stability but there was no statistically significant change in flow. The air voids and VMA both decreased initially with increasing additions of glass but then increased with higher additions. The changes were of the same magnitude as those produced by the glass-rich fraction.

In the test series using Bureau of Mines coarse residue, Figure 3, there was no statistically significant change in the stability, air voids, VMA, or flow when increasing amounts of the residue were added to the control mixture. Figure 3 shows an apparent trend toward decreasing stability with increasing amounts of residue up to 50 percent replacement, but the analysis of variance revealed no statistically significant differences. The clean glass replacement in the same test series indicated no statistically significant changes in air voids, VMA, or flow but there was a linear decrease in stability with increasing additions of clean glass which was similar to the trend noted in the Black Clawson series. There was little difference in the effects of clean glass and the Bureau of Mines residue on voids or flow.

There was no statistically significant effect upon stability when increasing amounts of the Bureau of Mines fine incinerator residue, Figure 4, were added to the control mixture. Flow, air voids, and voids in the mineral aggregate all showed upward linear trends with increasing additions of the residue. The clean glass replacement in the same series caused no statistically significant effect upon flow or stability. Air voids and VMA showed upward linear trends similar to the fine residue trends.

In the tests utilizing the matrix magnetic product, Figure 5, flow was not significantly affected when the amount of the product substituted was increased. Both air voids and VMA increased linearly with increasing additions while stability followed a falling quadratic trend. The clean glass replacement in the same series caused no statistically significant changes in any of the properties when increasing amounts of clean glass were substituted for conventional aggregates.

In the tests using the jig heavy product, Figure 6, there was no statistically significant effect upon stability or flow with increasing additions of the product to the control mixture. For air voids and VMA, an upward linear trend with increasing addition level was noted. The clean glass replacement in the same series showed no statistically significant effect upon flow or voids. Stability decreased linearly with increasing glass substitution.

These tests show that in one case, the Bureau of Mines coarse series, there is no statistically significant change in Marshall properties when a glass-rich fraction is substituted for up to 50 percent of the conventional aggregate in selected size ranges. In most cases, however, there was a statistically significant increase or decrease in at least one of the Marshall properties when glass was added.

The practical significance of these variations can be evaluated by determining whether the addition levels studied caused Marshall properties to fall outside allowable limits specified by The Asphalt Institute (13). These limits are shown in Table VIII. None of the additions of clean glass or glass-rich fractions which resulted in statistically significant changes in Marshall properties caused stability, flow or voids in the mineral aggregate to fall outside the allowable limits of 500 pounds minimum stability, 8 to 18 flow units and 15 percent minimum voids in the mineral aggregate. In two of the five test series, air voids were outside allowable limits. At additions greater than 30 percent in the Black Clawson tests, air voids fell below the lower limit of 3 percent and in the jig heavies tests, additions in excess of 30 percent caused air voids to exceed the upper limits of 5 percent. In these two cases, it would be necessary to modify the mix design if more than a 30 percent addition of these materials was used. This could be accomplished by adjusting the aggregate gradation and/or asphalt content.

In several test series, the maximum addition of 50 percent glass increased the air voids to near the maximum permissible level of 5 percent. It might be argued that if the control batch had an air void content near the upper limits, only a small addition of glass-rich material would cause the limit to be exceeded. However, normal variations in asphalt content can also cause air voids to fluctuate and exceed the upper limit. The Missouri State Highway Department (14) permits the asphalt content to fluctuate from optimum by plus or minus 0.5 percent. Using the Marshall design curves for the control mixture shown in Figure 1, it can be seen that a decrease in asphalt content of 0.5 percent would cause air voids to increase from 3.2 percent at optimum to 4.4 percent or a 37.5 percent increase. In the Black Clawson, matrix magnetic and Bureau of Mines coarse series, additions of up to 50 percent glass caused no more change in air voids than the permissible fluctuations in asphalt content would produce. In the Bureau of Mines fine series, an addition of 30 percent glass-rich material caused an increase in air voids equivalent to that produced by decreasing the asphalt content 0.5 percent while in the jig heavies series a 15 percent addition increased air voids to the same level resulting from a 0.5 percent decrease in asphalt content. In these cases, the addition of glass-rich fractions at levels up to 15 or 30 percent for the jig heavies and Bureau of Mines fine series respectively would cause no greater variations in air content than those produced by permissible fluctuations in asphalt content. At higher additions, however, increased air voids might require modifications in the design.

A comparison of the effects of clean glass and glass-rich fractions in each test series shows that, in most cases, the presence of non-glass components had no harmful effects. In the Bureau of Mines coarse and jig heavies series, the clean glass replacement resulted in stability decreases while additions of glass-rich fractions had no effect upon stability. In the other three series, mixtures containing either clean glass or glass-rich fractions behaved almost identically.

For all three of the series in which fine incinerator residues were used, glass-rich fractions caused greater increases in voids than were caused by clean glass materials. This was probably due to the rougher surface texture of the slag-like residue which would increase the internal friction and compaction resistance.

In the series using coarse glass-rich fractions, changes in air voids caused by glass additions were of about the same magnitude regardless of whether clean glass or glass-rich fractions were added. Flow differences between mixtures containing clean glass and glass-rich fractions were very small in all series.

## IX. CONCLUSIONS AND RECOMMENDED RESEARCH

The present study has demonstrated that glass rich fractions and clean glass materials of selected sieve sizes can be substituted for conventional aggregates in asphaltic concrete without causing flow, stability or voids in the mineral aggregate to fall outside limits specified by the Asphalt Institute.

In some cases, air void limits were exceeded when increasing amounts of glass-rich fractions were added. Additions of fine incinerator residues caused air voids to increase to a greater degree than was caused by clean glass additions. Since air voids in a mixture can be adjusted by the relatively simple process of adjusting gradation or asphalt content, it is concluded that glass-rich fractions can replace portions of the conventional aggregate in an asphaltic concrete with the resulting mixture satisfying Marshall design criteria specified by The Asphalt Institute. In general, it is concluded that the presence of non-glass components in the glass had no particularly harmful effect upon Marshall properties.

Two potential areas for further research are indicated. First, it is recommended that additional studies be performed to determine the effects of substituting glass-rich fractions for coarse gravel aggregate or fine crushed aggregate. Second, a study is needed to determine the daily or seasonal variations in gradation and composition of glass-rich fractions to assess the effects that such fluctuations might have on the properties of asphaltic mixtures containing the fractions.

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# VITA

James Joseph Schneider was born on September 30, 1948, in St. Charles, Missouri. He received his primary and secondary education in the Francis Howell School district in St. Charles County, Missouri. In September, 1966, he entered the University of Missouri-Rolla where he obtained a Bachelor of Science degree in Civil Engineering in May, 1970. He then began his graduate work towards a Master of Science degree in Civil Engineering in September, 1970.

# APPENDICES

# APPENDIX A

## Tables

TABLE I

GRADATION OF GLASS-RICH FRACTIONS

| Sieve | Percent Passing | | | | |
|---|---|---|---|---|---|
| | Black Clawson | Coarse Residue | Fine Residue | Matrix Magnetic | Jig Heavies |
| 1-in. | 100.0 | 99.0 | 100.0 | 100.0 | 100.0 |
| 3/4-in. | 100.0 | 97.0 | 100.0 | 100.0 | 100.0 |
| 1/2-in. | 100.0 | 85.0 | 100.0 | 100.0 | 100.0 |
| 3/8-in. | 97.0 | 72.0 | 100.0 | 100.0 | 100.0 |
| No. 4 | 70.0 | 31.0 | 100.0 | 100.0 | 100.0 |
| No. 8 | 29.0 | 6.0 | 100.0 | 100.0 | 73.0 |
| No. 16 | 16.0 | 1.0 | 100.0 | 99.6 | 44.0 |
| No. 30 | 5.0 | 0.0 | 99.5 | 37.3 | 10.0 |
| No. 50 | 2.0 | 0.0 | 94.0 | 10.3 | 2.0 |
| No. 100 | 0.4 | 0.0 | 54.5 | 2.3 | 0.5 |
| No. 200 | 0.1 | 0.0 | 20.1 | 0.5 | 0.3 |

TABLE II

COMPOSITION OF BLACK CLAWSON GLASS-RICH FRACTION

| Size Fraction | | Percent by Weight of Components Indicated | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Passing | Retained | Glass | Ferrous Metal | Non-Ferrous Metal | Bone | Rubber & Plastic | Stone | Misc. |
| 1/2-in. | 3/8-in. | 47.5 | 7.6 | 6.2 | 1.5 | 21.1 | 9.6 | 6.5 |
| 3/8-in. | No. 4 | 72.5 | 3.3 | 2.3 | 1.8 | 6.3 | 9.4 | 4.4 |
| No. 4 | No. 8 | 81.1 | 2.4 | 1.1 | 1.6 | 1.0 | 9.1 | 3.7 |
| No. 8 | No. 16 | 97.7* | 2.3 | -- | -- | -- | -- | -- |
| No. 16 | No. 30 | 96.2 | 3.8 | -- | -- | -- | -- | -- |
| No. 30 | No. 50 | 94.0 | 6.0 | -- | -- | -- | -- | -- |
| No. 50 | No. 100 | 90.9 | 9.1 | -- | -- | -- | -- | -- |
| No. 100 | No. 200 | 86.4 | 13.6 | -- | -- | -- | -- | -- |
| No. 200 | Pan | 100.0 | 0.0 | -- | -- | -- | -- | -- |
| TOTAL | | 83.0 | 3.1 | 1.2 | 1.1 | 2.8 | 6.0 | 2.8 |

*Magnetic and visual classification used on all sizes larger than a No. 8 sieve. Entire non-magnetic fraction smaller than No. 8 sieve assumed to be glass.

TABLE III

COMPOSITION OF BUREAU OF MINES
COARSE INCINERATOR RESIDUE

| Size Fraction | | Percent by Weight of Components Indicated | | | | | |
|---|---|---|---|---|---|---|---|
| Passing | Retained | Glass | Ferrous Metal | Non-Ferrous Metal | Slag | Stone | Misc. |
| 1 1/2-in | 1-in. | 100 | 0 | 0 | 0 | 0 | 0 |
| 1-in. | 3/4-in. | 37.7 | 0 | 2.7 | 42.8 | 10.0 | 6.8 |
| 3/4-in. | 1/2-in. | 64.5 | 7.9 | 3.2 | 15.4 | 4.8 | 4.2 |
| 1/2-in. | 3/8-in. | 71.1 | 8.2 | 1.6 | 14.5 | 1.6 | 3.0 |
| 3/8-in. | No. 4 | 72.0 | 6.3 | 3.7 | 13.1 | 3.1 | 1.8 |
| No. 4 | No. 8 | 61.9 | 11.3 | 3.7 | 14.1 | 5.7 | 3.3 |
| No. 8 | No. 16 | 89.8* | 10.2 | | | | |
| TOTAL | | 68.0 | 7.2 | 2.9 | 15.3 | 3.6 | 3.0 |

*Magnetic and visual classification used on all sizes larger than No. 8 sieve. Entire non-magnetic fraction smaller than No. 8 sieve assumed to be glass.

TABLE IV

PROPERTIES OF ASPHALT*

| | |
|---|---|
| Specific Gravity @ 60 F | 1.01 |
| Penetration @ 77 F | 93 |
| Flash, Cleveland Open Cup, F | 620 |
| Solubility in $CCL_4$, % | 99.93 |
| Ductility @ 77 F, cm. | 150+ |

*Furnished through courtesy of Shell Oil Company.

TABLE V

BULK SPECIFIC GRAVITY OF GLASS-RICH FRACTIONS

| Series | Size Fraction | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 3/8 | No. 4 | No. 8 | No. 16 | No. 30 | No. 50 | No. 100 | No. 200 | -200 |
| Black Clawson | | 2.227 | 2.349 | 2.348 | | | | | |
| Coarse Residue | 2.467 | 2.458 | 2.413 | | | | | | |
| Fine Residue | | | | | | 2.807 | 2.807 | 2.807 | 2.807 |
| Matrix Magnetic | | | 2.582 | 2.582 | 2.582 | | | | |
| Jig Heavies | | | 3.959 | 3.959 | 3.959 | 3.959 | | | |

TABLE VI

ASPHALT ABSORPTION
OF GLASS-RICH FRACTIONS

| Fraction | Absorption* |
|---|---|
| Black Clawson | 2.0 |
| Coarse Residue | 2.2 |
| Fine Residue | 0.0 |
| Matrix Magnetic | 0.0 |
| Jig Heavies | 0.0 |

*Grams of asphalt per 100 grams of glass-rich fraction.

TABLE VII

GRADATION OF CONVENTIONAL AGGREGATE BLEND USED IN CONTROL SPECIMENS

| Sieve | Percent Passing |
|---|---|
| 1/2-in. | 100 |
| 3/8-in. | 90 |
| No. 4 | 65 |
| No. 8 | 48 |
| No. 16 | 35 |
| No. 30 | 23 |
| No. 50 | 14 |
| No. 100 | 8 |
| No. 200 | 4 |

TABLE VIII

MARSHALL DESIGN CRITERIA*

| Test Property | Min | Max |
|---|---|---|
| Stability, lbs | 500 | -- |
| Flow, .01-in. | 8 | 18 |
| Air Voids, % (Surfacing) | 3 | 5 |
| Voids in Mineral Aggregate, % (1/2" max size) | 15 | -- |

*Recommended by the Asphalt Institute for medium traffic (50 blow compaction).

TABLE IX

CONTROL MIXTURE MARSHALL PROPERTIES
AT OPTIMUM ASPHALT CONTENT*

| Test Property | Value |
|---|---|
| Stability, lbs. | 1810 |
| Flow, .01-in. | 8.2 |
| Air Voids, % | 3.28 |
| Voids in Mineral Aggregate, % | 15.64 |

*Values from smoothed curves in Figure 1. Each point in Figure 1 is the average of 3 tests.

TABLE X

*SIZE FRACTIONS SUBSTITUTED IN TEST SERIES**

| Series | Sieve Size | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 3/8 | No. 4 | No. 8 | No. 16 | No. 30 | No. 50 | No. 100 | No. 200 | -200 |
| Black Clawson | | X | X | X | | | | | |
| Coarse Residue | X | X | X | | | | | | |
| Fine Residue | | | | | | X | X | X | X |
| Matrix Magnetic | | | | | X | X | X | | |
| Jig Heavies | | | X | X | X | X | | | |

*An X denotes a sieve size on which a glass-rich fraction or clean glass was substituted for conventional aggregate.

TABLE XI

MARSHALL PROPERTIES FOR
BLACK CLAWSON SERIES

| Marshall Property | Addition Level | | | | | | |
|---|---|---|---|---|---|---|---|
| | Control | Clean Glass Addition | | | Black Clawson Addition | | |
| | 0% | 10% | 30% | 50% | 10% | 30% | 50% |
| Stability, lbs. | 1990 | 1750 | 1620 | 1200 | 1870 | 1320 | 1360 |
| | 1740 | 1815 | 1595 | 1365 | 1920 | 1525 | 1540 |
| | 1860 | 1835 | 1675 | 1450 | 1840 | 1600 | 1340 |
| Flow, .01-in. | 8.5 | 8.8 | 8.2 | 8.0 | 8.8 | 8.8 | 9.5 |
| | 9.0 | 9.2 | 9.5 | 8.5 | 9.0 | 9.8 | 11.0 |
| | 8.5 | 8.2 | 8.2 | 8.0 | 8.8 | 8.8 | 9.5 |
| Unit Wt., pcf. | 144.5 | 145.1 | 144.5 | 143.3 | 144.2 | 142.4 | 141.7 |
| | 144.0 | 144.0 | 144.2 | 143.1 | 144.6 | 143.6 | 142.2 |
| | 143.8 | 144.9 | 144.3 | 143.5 | 144.5 | 142.5 | 141.2 |
| Air Voids, % | 3.54 | 2.92 | 2.84 | 3.19 | 3.20 | 3.37 | 2.75 |
| | 3.90 | 3.66 | 3.06 | 3.37 | 2.97 | 2.55 | 2.41 |
| | 3.98 | 3.05 | 2.98 | 3.08 | 3.03 | 3.26 | 3.08 |
| VMA, % | 15.86 | 15.32 | 15.26 | 15.54 | 15.56 | 15.70 | 15.17 |
| | 16.18 | 15.97 | 15.44 | 15.70 | 15.36 | 14.99 | 14.87 |
| | 16.24 | 15.43 | 15.38 | 15.44 | 15.41 | 15.61 | 15.46 |

TABLE XII

MARSHALL PROPERTIES FOR
COARSE INCINERATOR RESIDUE SERIES

| Marshall Property | Addition Level | | | | | | |
|---|---|---|---|---|---|---|---|
| | Control | Clean Glass Addition | | | Residue Addition | | |
| | 0% | 10% | 30% | 50% | 10% | 30% | 50% |
| Stability, lbs. | 1940 | 1815 | 1625 | 1380 | 1920 | 1640 | 1560 |
| | 1760 | 1715 | 1650 | 1490 | 1930 | 1730 | 1895 |
| | 1970 | 1805 | 1555 | 1390 | 1875 | 1585 | 1665 |
| Flow, .01-in. | 9.5 | 8.0 | 7.8 | 8.5 | 9.0 | 8.8 | 8.5 |
| | 7.2 | 7.8 | 8.0 | 7.8 | 9.2 | 10.2 | 9.0 |
| | 8.5 | 8.8 | 7.8 | 8.8 | 8.0 | 8.0 | 8.8 |
| Unit Wt., pcf. | 145.2 | 144.7 | 143.5 | 142.8 | 144.1 | 143.2 | 142.2 |
| | 144.1 | 144.0 | 143.5 | 143.0 | 144.6 | 143.8 | 141.8 |
| | 144.4 | 144.7 | 144.1 | 143.2 | 144.8 | 143.4 | 141.9 |
| Air Voids, % | 3.10 | 3.18 | 3.48 | 3.47 | 3.56 | 3.71 | 3.84 |
| | 3.79 | 3.66 | 3.53 | 3.35 | 3.24 | 3.27 | 4.12 |
| | 3.61 | 3.19 | 3.12 | 3.24 | 3.08 | 3.54 | 4.09 |
| VMA, % | 15.48 | 15.53 | 15.79 | 15.80 | 15.88 | 16.00 | 16.12 |
| | 16.08 | 15.96 | 15.84 | 15.69 | 15.60 | 15.61 | 16.37 |
| | 15.92 | 15.55 | 15.48 | 15.60 | 15.46 | 15.85 | 16.34 |

TABLE XIII

MARSHALL PROPERTIES FOR
FINE INCINERATOR RESIDUE SERIES

| Marshall Property | Addition Level | | | | | | |
|---|---|---|---|---|---|---|---|
| | Control | Clean Glass Addition | | | Residue Addition | | |
| | 0% | 10% | 30% | 50% | 10% | 30% | 50% |
| Stability, lbs. | 1815 | 2125 | 1955 | 1815 | 2120 | 2025 | 1805 |
| | 1945 | 1970 | 1815 | 1860 | 1860 | 1850 | 1970 |
| | 1990 | 1920 | 1970 | 1885 | 2030 | 1905 | 1955 |
| Flow, .01-in. | 8.2 | 9.0 | 8.2 | 8.2 | 8.2 | 8.5 | 8.5 |
| | 7.8 | 8.0 | 7.8 | 8.2 | 7.8 | 8.5 | 8.5 |
| | 8.5 | 8.5 | 8.0 | 7.8 | 8.2 | 9.0 | 8.5 |
| Unit Wt., pcf. | 145.5 | 145.4 | 144.3 | 143.2 | 145.1 | 145.1 | 144.2 |
| | 144.4 | 145.0 | 143.9 | 143.3 | 145.6 | 143.7 | 143.5 |
| | 145.4 | 145.4 | 144.4 | 144.4 | 145.4 | 145.0 | 144.3 |
| Air Voids, % | 2.88 | 2.91 | 3.51 | 4.13 | 3.37 | 3.71 | 4.72 |
| | 3.64 | 3.18 | 3.80 | 4.06 | 3.04 | 4.67 | 5.15 |
| | 2.96 | 2.87 | 3.42 | 3.44 | 3.16 | 3.80 | 4.63 |
| VMA, % | 15.29 | 15.31 | 15.82 | 16.36 | 15.70 | 16.01 | 16.89 |
| | 15.94 | 15.55 | 16.07 | 16.30 | 15.41 | 16.84 | 17.26 |
| | 15.35 | 15.28 | 15.73 | 15.68 | 15.52 | 16.08 | 16.81 |

TABLE XIV

MARSHALL PROPERTIES FOR
MATRIX MAGNETIC SERIES

| Marshall Property | Addition Level | | | | | | |
|---|---|---|---|---|---|---|---|
| | Control | Clean Glass Addition | | | Matrix Magnetic Addition | | |
| | 0% | 10% | 30% | 50% | 10% | 30% | 50% |
| Stability, lbs. | 1750 | 1710 | 1800 | 1730 | 1990 | 1870 | 1745 |
| | 1770 | 1930 | 1970 | 1785 | 1870 | 1900 | 1660 |
| | 1845 | 1945 | 1760 | 1525 | 1850 | 1815 | 1650 |
| Flow, .01-in. | 8.8 | 8.0 | 8.6 | 7.8 | 9.5 | 8.0 | 8.2 |
| | 8.0 | 8.5 | 10.0 | 8.5 | 8.2 | 8.5 | 7.8 |
| | 8.0 | 8.0 | 8.0 | 8.2 | 8.0 | 7.8 | 8.0 |
| Unit Wt., pcf. | 143.8 | 144.1 | 143.1 | 143.2 | 144.4 | 143.2 | 142.7 |
| | 144.3 | 144.2 | 144.2 | 143.9 | 144.4 | 143.1 | 142.6 |
| | 143.9 | 143.2 | 142.6 | 142.7 | 143.5 | 143.1 | 141.8 |
| Air Voids, % | 4.01 | 3.74 | 4.05 | 4.06 | 3.62 | 4.45 | 4.81 |
| | 3.68 | 3.72 | 3.52 | 3.60 | 3.64 | 4.47 | 4.88 |
| | 3.96 | 4.35 | 4.62 | 4.43 | 4.21 | 4.50 | 5.40 |
| VMA, % | 16.27 | 16.02 | 16.30 | 16.29 | 15.93 | 16.64 | 16.96 |
| | 15.98 | 16.00 | 15.85 | 15.90 | 15.94 | 16.70 | 17.02 |
| | 16.23 | 16.55 | 16.79 | 16.62 | 16.44 | 16.68 | 17.48 |

TABLE XV

MARSHALL PROPERTIES FOR
JIG HEAVIES SERIES

| Marshall Property | Addition Level | | | | | | |
|---|---|---|---|---|---|---|---|
| | Control | Clean Glass Addition | | | Jig Heavies Addition | | |
| | 0% | 10% | 30% | 50% | 10% | 30% | 50% |
| Stability, lbs. | 1890 | 1775 | 1535 | 1270 | 1760 | 1780 | 1530 |
| | 1870 | 1705 | 1600 | 1440 | 1955 | 1860 | 1785 |
| | 1840 | 1790 | 1500 | 1330 | 1705 | 1620 | 1760 |
| Flow, .01-in. | 7.8 | 8.5 | 7.5 | 7.8 | 8.5 | 7.8 | 7.5 |
| | 7.8 | 8.0 | 7.5 | 7.0 | 7.5 | 7.5 | 8.5 |
| | 8.2 | 7.5 | 7.5 | 8.0 | 7.2 | 8.2 | 8.5 |
| Unit Wt., pcf. | 144.7 | 144.1 | 144.3 | 143.5 | 147.4 | 152.4 | 157.6 |
| | 144.7 | 143.7 | 143.8 | 143.4 | 147.0 | 152.4 | 157.9 |
| | 144.0 | 144.6 | 143.7 | 143.7 | 147.0 | 152.5 | 157.4 |
| Air Voids, % | 2.90 | 3.15 | 2.71 | 2.96 | 3.57 | 5.08 | 6.35 |
| | 2.92 | 3.42 | 3.10 | 3.04 | 3.87 | 5.10 | 6.16 |
| | 3.37 | 2.84 | 3.12 | 2.69 | 3.85 | 5.03 | 6.42 |
| VMA, % | 15.24 | 15.46 | 15.07 | 15.28 | 15.83 | 17.14 | 18.24 |
| | 15.26 | 15.70 | 15.41 | 15.35 | 16.10 | 17.16 | 18.07 |
| | 15.65 | 15.20 | 15.43 | 15.04 | 16.06 | 17.10 | 18.30 |

TABLE XVI

RESULTS OF ANALYSIS OF VARIANCE*

| Series | Material | Flow | Stability | Air Voids | VMA |
|---|---|---|---|---|---|
| Black | Product | yes | yes | yes | yes |
| Clawson | Glass+ | no | yes | yes | yes |
| Coarse | Product | no | no | no | no |
| Residue | Glass+ | no | yes | no | no |
| Fine | Product | yes | no | yes | yes |
| Residue | Glass+ | no | no | yes | yes |
| Matrix | Product | no | yes | yes | yes |
| Magnetic | Glass+ | no | no | no | no |
| Jig | Product | no | no | yes | yes |
| Heavies | Glass+ | no | yes | no | no |

*Yes denotes that a significant difference was found between treatment means.
+This material is crushed clean glass.

# APPENDIX B

## Figures

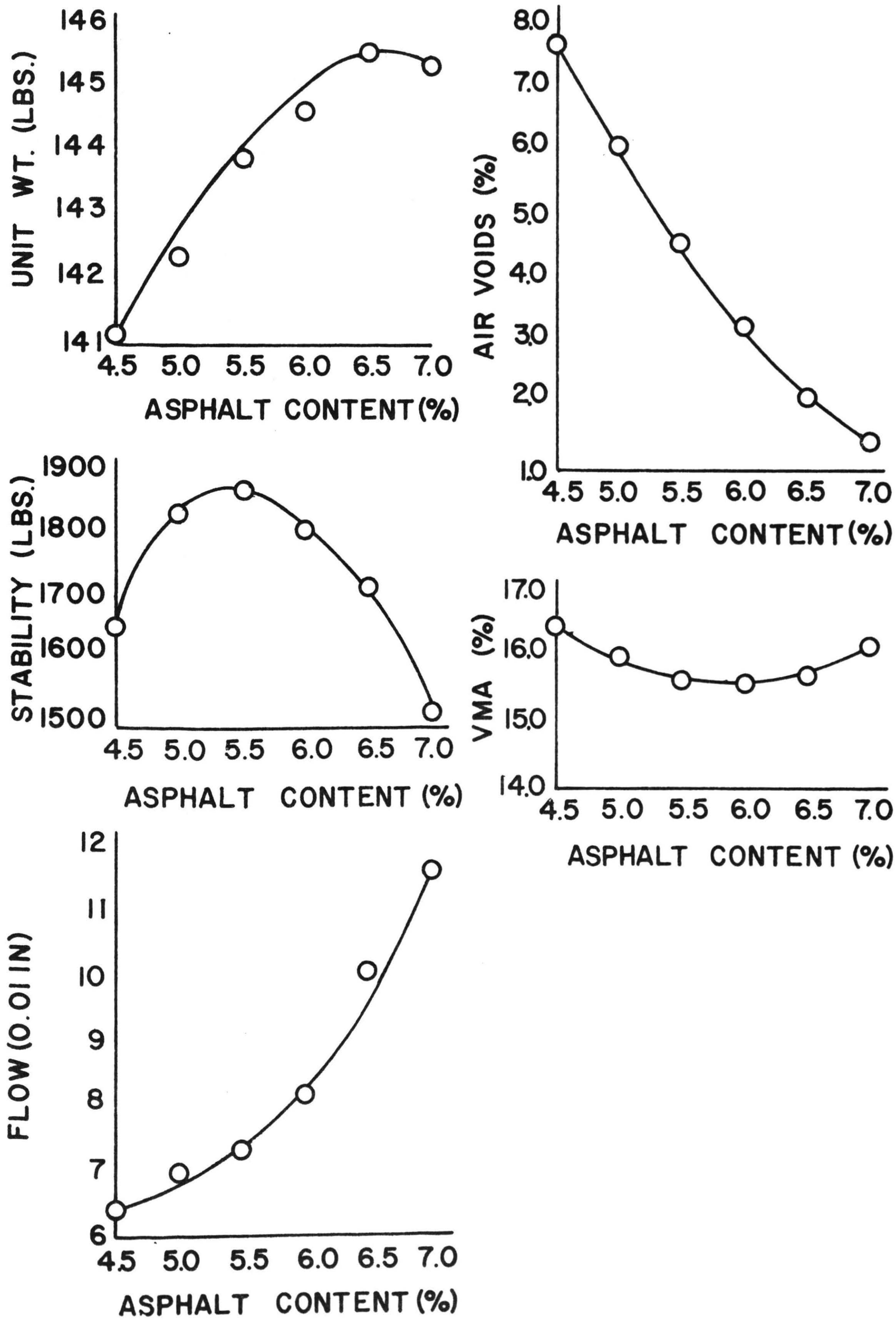


Figure 1. Marshall Design Curves for Control Mixture

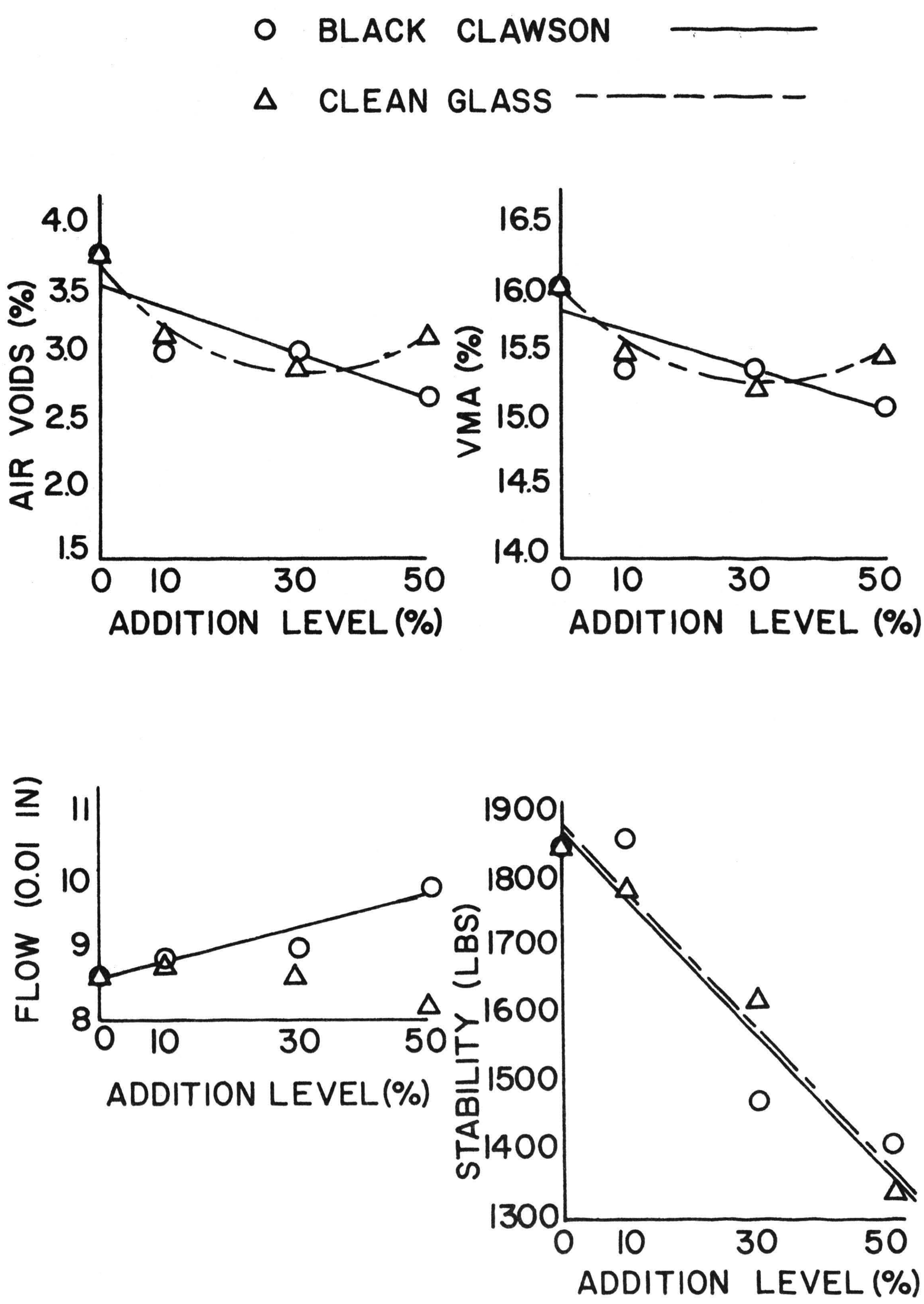


Figure 2. Marshall Properties for Varying Additions of Clean Glass and Black Clawson Glass-Rich Fractions

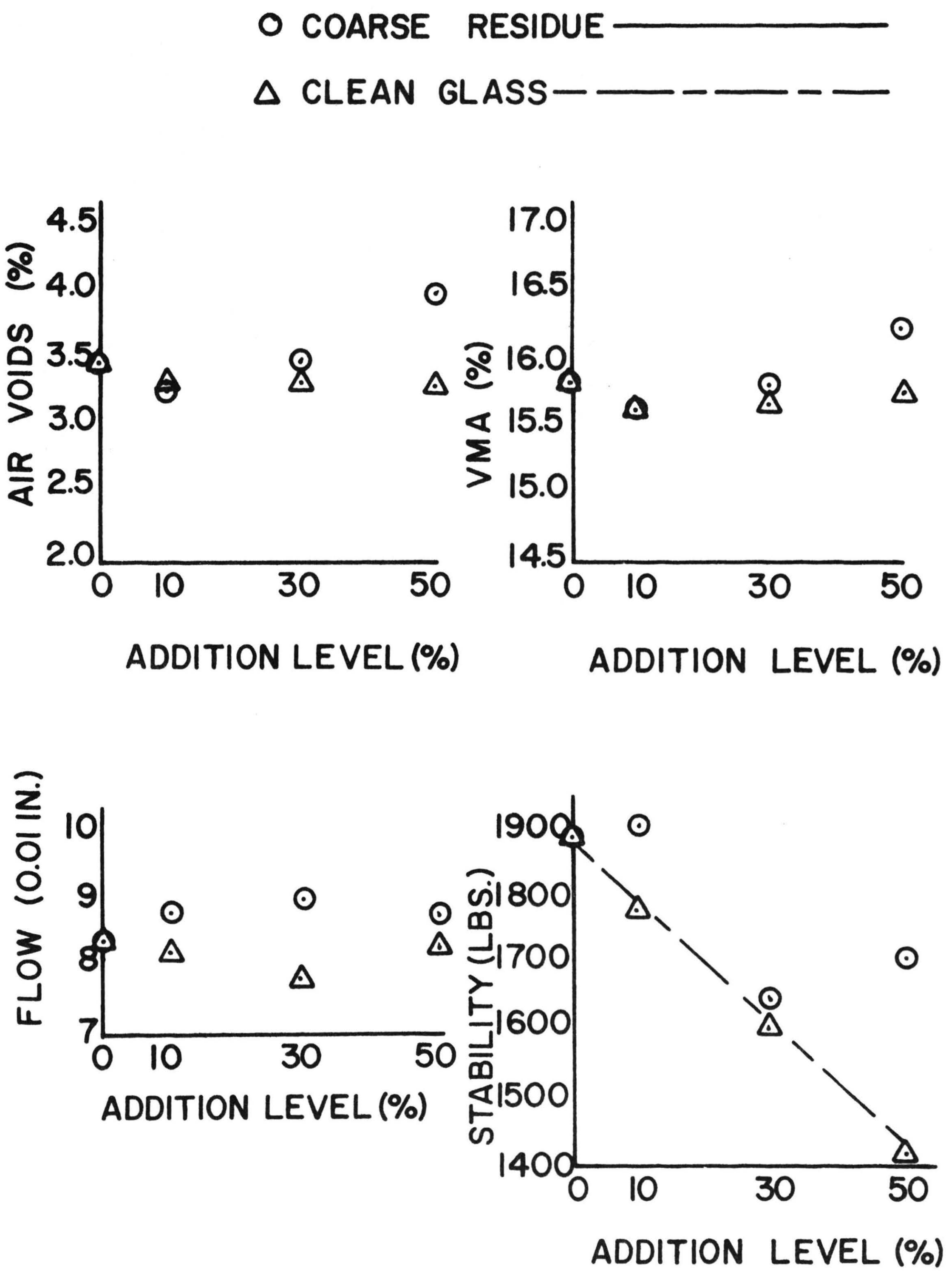


Figure 3. Marshall Properties for Varying Additions of Clean Glass and Bureau of Mines Coarse Glass-Rich Fractions

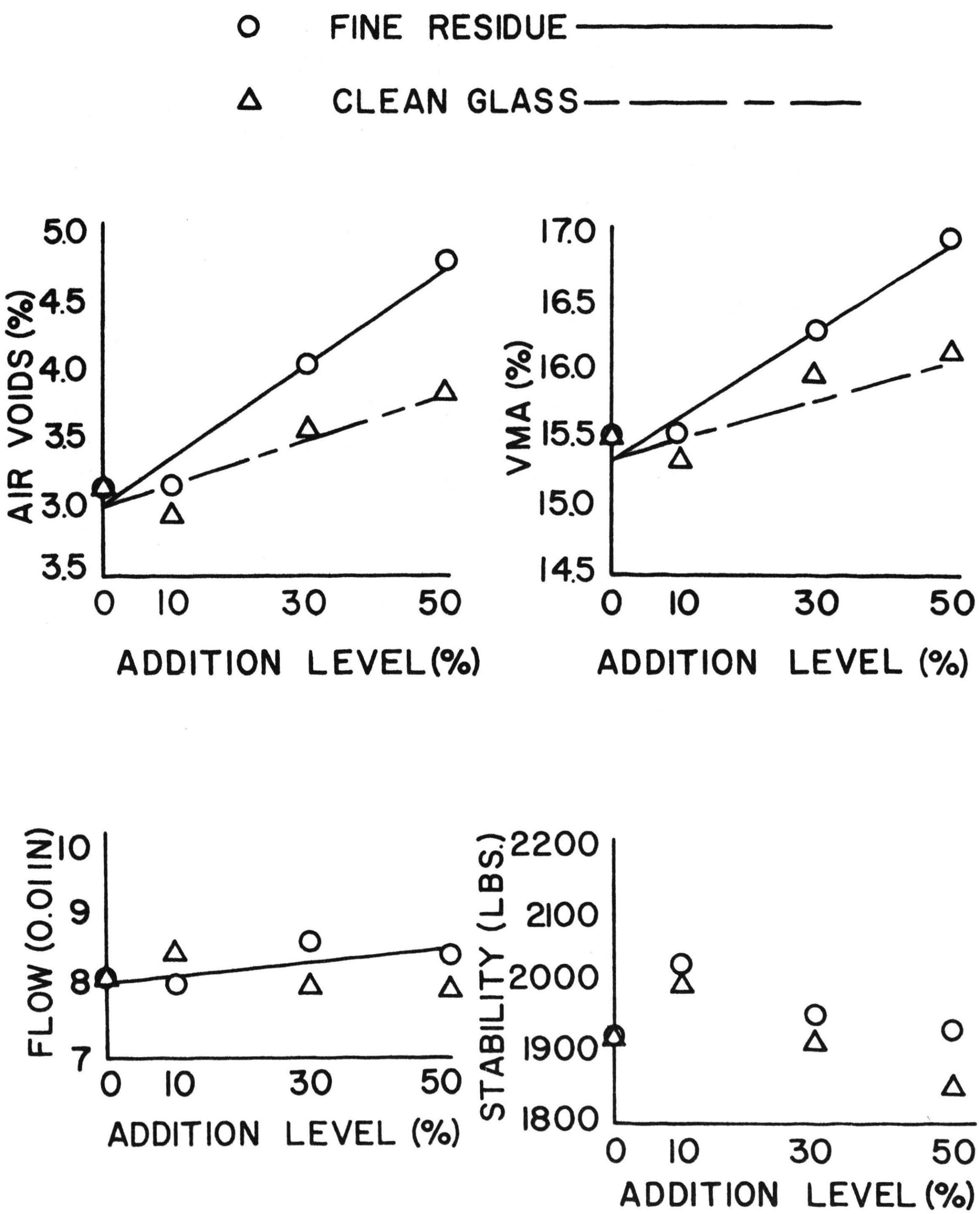


Figure 4. Marshall Properties for Varying Additions of Clean Glass and Bureau of Mines Fine Glass-Rich Fractions

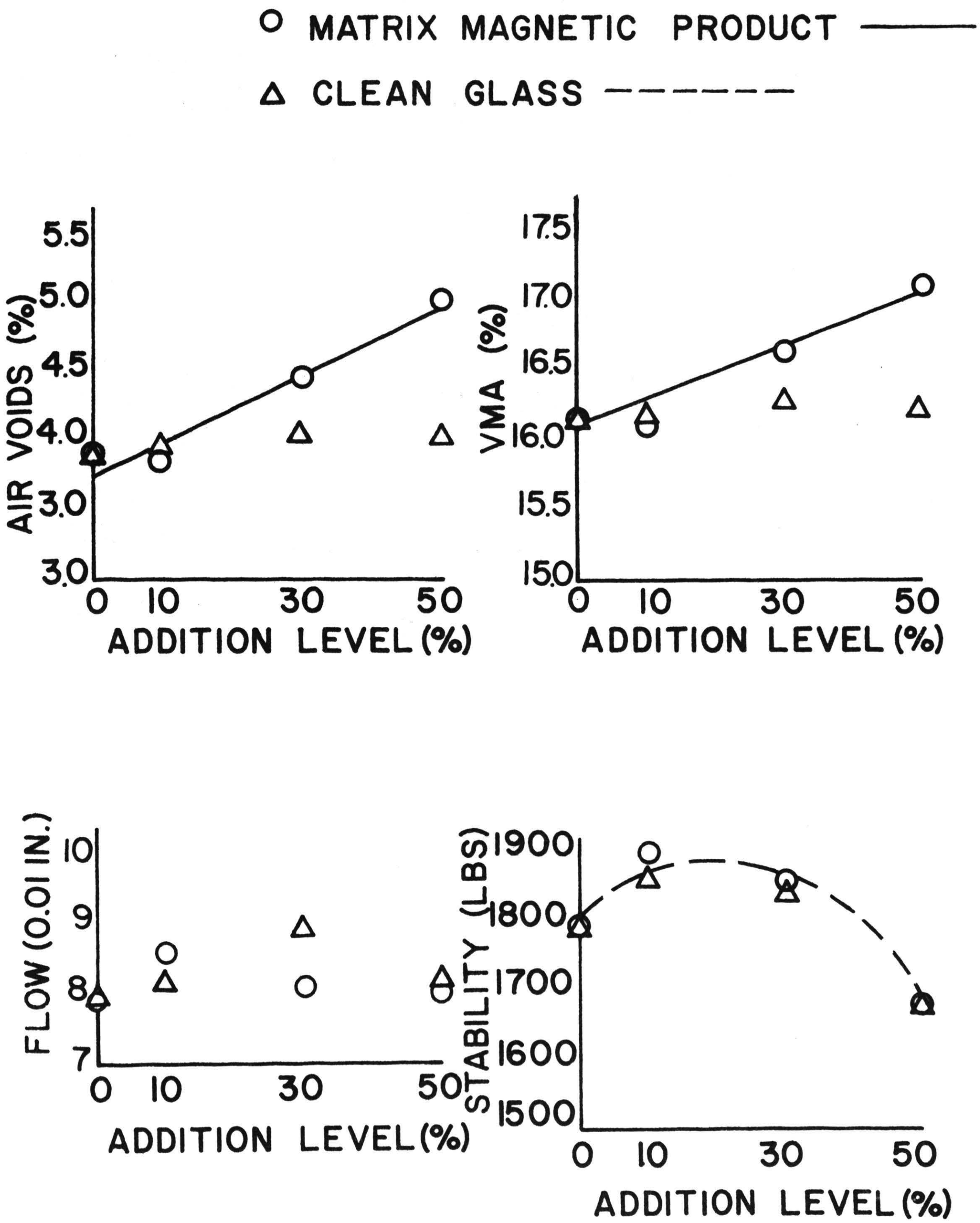


Figure 5. Marshall Properties for Varying Additions of Clean Glass and Matrix Magnetic Glass-Rich Fractions

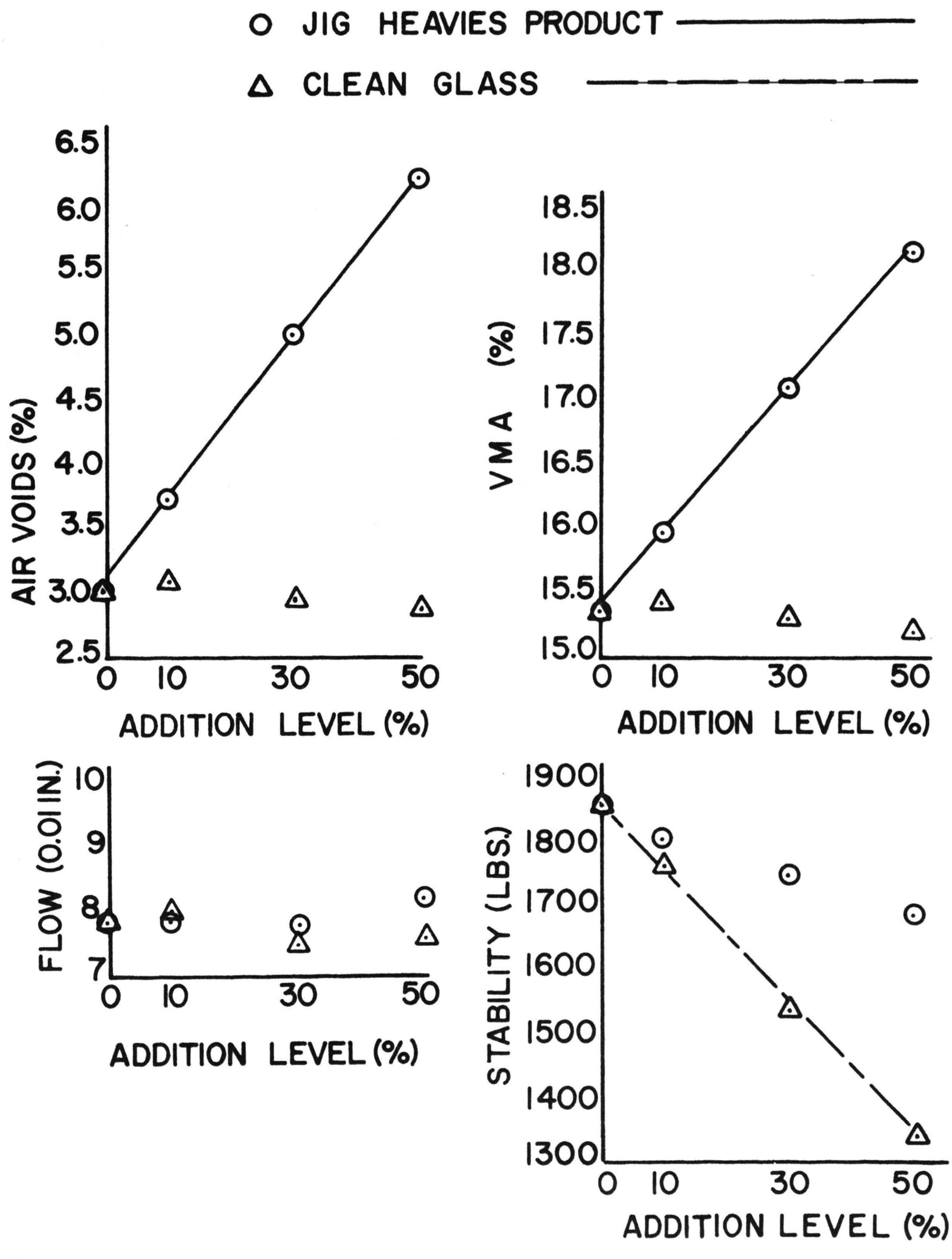


Figure 6. Marshall Properties for Varying Additions of Clean Glass and Jig Heavies Glass-Rich Fractions

# APPENDIX C

## Analysis of Variance

# APPENDIX C

## Analysis of Variance

To determine if there was a statistically significant difference among the means for Marshall properties measured on specimens containing varying amounts of clean glass or glass-rich fractions, an analysis of variance technique was used. This is a standard technique, but a brief example is given to demonstrate how the procedure was utilized.

In Table XVII, the air voids data for the Black Clawson series is given in the form utilized for analysis. The method by which the value for the correction term, total sum of squares, treatment sum of squares, replicate sum of squares, and error sum of squares were calculated is outlined.

After the values for the sums of squares were found, an analysis of variance table as shown in Table XVII was compiled. The mean squares for the treatment and error terms were calculated by dividing the respective sums of squares by the degrees of freedom. The ratio of the treatment mean square to the error mean square is the calculated F value which is compared with a tabulated F value at a 5 percent significance level. If the calculated F is larger than the tabulated F value, a significant difference among the means is indicated. If the calculated F is smaller than the tabulated F value, there is no significant difference among the means.

TABLE XVII

ANALYSIS OF VARIANCE FOR
BLACK CLAWSON SERIES AIR VOIDS

| Replicate | Addition Level | | | | Replicate Summation |
| --- | --- | --- | --- | --- | --- |
| | 0% | 10% | 30% | 50% | |
| 1 | 3.54 | 3.20 | 3.37 | 2.75 | 12.86 |
| 2 | 3.90 | 2.97 | 2.55 | 2.41 | 11.83 |
| 3 | 3.98 | 3.03 | 3.26 | 3.08 | 13.35 |
| Treatment Summation | 11.42 | 9.20 | 9.18 | 8.24 | |

Total Summation = 38.04

Correction Term

$$(38.04)^2/12=120.59$$

Total Sum of Squares

$$((3.54)^2+(3.90)^2+(3.98)^2+\ldots(3.08)^2)-120.59=2.58$$

Replicate Sum of Squares

$$((12.86)^2+(11.83)^2+(13.35)^2)/4-120.59=0.30$$

Treatment Sum of Squares

$$((11.42)^2+(9.20)^2+(9.18)^2+(8.24)^2)/3-120.59=1.82$$

Error Sum of Squares

$$2.58 - 0.30 - 1.82 = 0.46$$

TABLE XVII

ANALYSIS OF VARIANCE FOR
BLACK CLAWSON SERIES AIR VOIDS
(continued)

ANOVA TABLE

| Source | Degrees of freedom | Sum of Squares | Mean Square | F test |
|---|---|---|---|---|
| Replicate | 2 | 0.30 | 0.151 | |
| Treatment | 3 | 1.82 | 0.607 | $\frac{0.607}{0.076} = 7.96$ |
| Error | 6 | 0.46 | 0.076 | |
| Total | 11 | 2.58 | | |

F calculated 7.96 > F table 4.76 : Conclude A Significant Difference Exists Among Means

# APPENDIX D

## Calculation of Orthogonal Coefficients

# APPENDIX D

## Calculation of Orthogonal Coefficients

Once it had been established that a significant difference existed among treatment means for the property under consideration, the next item determined was whether the data followed a linear, quadratic, or cubic trend. A method described in "The Design and Analysis of Biological Experiments," by W.C. Jacob and R.D. Sief (12) was used to translate the trends found into usable equations.

Orthogonal coefficients are used in this method. Because the treatment levels were unevenly spaced, these coefficients had to be calculated. A brief description for the calculation of the linear coefficients follows. Calculations for the quadratic and cubic coefficients are similar, but with somewhat more mathematics involved. Table VIII shows a computational procedure for the linear coefficients.

Column one is the percent replacement levels for treatments divided by 10. Column two is the number of replications for each treatment level. Column three is an intermediate step in which a variable "a" is found. Column four is found by substituting the value of "a" back into column three. Column five is found by dividing column four by column two. Column six, the linear coefficients, is found by multiplying column five numbers by their largest common factor. Column seven is a check since it is necessary that the sum of the replications times the coefficients must be equal to zero.

Tables XIX and XX show the procedures for the quadratic and cubic coefficients respectively. Column headings show that the steps involved are similar to linear procedures.

All coefficients are given in Table XXI.

TABLE XVIII

OUTLINE OF COMPUTATIONAL PROCEDURES
FOR LINEAR COEFFICIENTS

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| $X_i$ | $r_i$ | $r_i L'_i = r_i(X_i + a_1)$ | $r_i L'_i$ | $L'_i$ | $L_i$ | $r_i L_i$ |
| 0 | 3 | $0+3a_1$ | -27/4 | -9/4 | -9 | -27 |
| 1 | 3 | $3+3a_1$ | -15/4 | -5/4 | -5 | -15 |
| 3 | 3 | $9+3a_1$ | 9/4 | 3/4 | 3 | 9 |
| 5 | 3 | $15+3a_1$ | 33/4 | 11/4 | 11 | 33 |
| TOTAL | | $27+12a_1=0$ | 0 | 0 | 0 | 0 |
| | | $a_1=-9/4$ | | | | |

TABLE XIX

OUTLINE FOR COMPUTATIONAL PROCEDURES FOR QUADRATIC COEFFICIENTS

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| $X_i$ | $r_i$ | $L_i$ | $r_iQ'_i=r_i(X^2_i+b_2X_i+a_2)$ | $(r_iQ'_i)L_i$ |
| 0 | 3 | -9 | $3a_2$ | $-27a_2$ |
| 1 | 3 | -5 | $3+3b_2+3a_2$ | $-15=15b_2-15a_2$ |
| 3 | 3 | 3 | $27+9b_2+3a_2$ | $81+27b_2+9a_2$ |
| 5 | 3 | 11 | $75+9b_2+3a_2$ | $825+165b_2+33a_2$ |
| | TOTAL | | $105+27b_2+12a_2=0$ | $891+177b_2=0$ |
| | | | $a=456/177$ | $b_2=-891/177$ |

TABLE XIX

OUTLINE FOR COMPUTATIONAL PROCEDURES FOR QUADRATIC COEFFICIENTS (continued)

| | 6 | 7 | 8 | 9 |
|---|---|---|---|---|
| | $r_i Q'_i$ | $Q_i$ | $r_i Q_i$ | $r_i Q_i L_i$ |
| | 1368/177 | 76 | 228 | -648 |
| | -744/177 | -43 | -129 | 215 |
| | -1872/177 | -104 | -312 | -312 |
| | 1278/177 | 71 | 213 | 781 |
| TOTAL | 0 | 0 | 0 | 0 |

TABLE XX

OUTLINE FOR COMPUTATIONAL PROCEDURES FOR CUBIC COEFFICIENTS

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| $X_i$ | $r_i$ | $L_i$ | $Q_i$ | $r_i C'_i r_i (X^3_i c_3 X^2_i b_3 X_i a_3)$ | $(r_i C'_i) L_i$ |
| 0 | 3 | -9 | 76 | $+3a_3$ | $-27a_3$ |
| 1 | 3 | -5 | -43 | $3+3c_3+3b_3+3a_2$ | $-15-15c_3-15b_3-15a_3$ |
| 3 | 3 | 3 | -104 | $81+27c_3+9b_3+3a_3$ | $243+81c_3+27b_3+9a_3$ |
| 5 | 3 | 11 | 71 | $375+75c_3+15b_3+3a_3$ | $4125+825c_3+165b_3+33a_3$ |
| | TOTAL | | | $459+105c_3+27b_3+12a_3=0$ | $4353+891c_3+177b_3=0$ |
| | | | | $a_3=-480/199$ | $b_3=2687/199$ |

TABLE XX

OUTLINE FOR COMPUTATIONAL PROCEDURES FOR CUBIC COEFFICIENTS
(continued)

| 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|
| $(r_iC'_i)Q_i$ | $r_iC'_i$ | $C_i$ | $r_iC_i$ | $r_iC_iL_i$ | $r_iC_iQ_i$ |
| $228a_3$ | -1440/199 | -8 | -24 | 216 | -1824 |
| $-129-129a_3-129b_3-129a_3$ | 2770/199 | 15 | 45 | -225 | -1935 |
| $-8424-2808c_3-936b_3-312a_3$ | -1800/199 | -10 | -30 | -90 | 3120 |
| $26625+5325c_3+1065b_3+213a_3$ | 540/199 | 3 | 9 | 99 | 639 |
| $18072+4916c_3=0$ | 0 | 0 | 0 | 0 | 0 |
| $c_3=-1506/199$ | | | | | |

TABLE XXI

ORTHOGONAL COEFFICIENTS

| Percent Replacement | Coefficients | | |
|---|---|---|---|
| | Linear | Quadratic | Cubic |
| 0% | -9 | +76 | -8 |
| 10% | -5 | -43 | +15 |
| 30% | +3 | -104 | -10 |
| 50% | +11 | +71 | +3 |

# APPENDIX E

## Translating Trends into Equations

# APPENDIX E

## Translating Trends into Equations

This method calls for the utilization of constants called "divisors" to formulate the equational trends. These values were calculated by squaring the coefficients at 0, 10, 30, and 50 percent replacement levels, adding the results and taking the sum times the number of replications of each treatment level for linear, quadratic and cubic trends. For linear, quadratic, and cubic trends these values were 708, 70446, and 1194 respectively.

Two examples are briefly described: one with a linear trend and the other with a quadratic trend. No data were found to have a cubic trend.

In Table XXII the data for percent air voids in the Black Clawson series is given and the technique for determining the values for the cross products and sums of squares for linear, quadratic, and cubic trends is shown.

A partial analysis of variance table is set up as shown. The linear, quadratic and cubic mean square values are compared with the error term mean square value using an F test. From tables, the critical F at the 95 percent confidence level for the degrees of freedom of 1 and 6 is 5.99. The calculated F values are examined. The highest order trend with a significant F test is selected to represent the data. In this case, the data is represented by a linear trend.

After the trend has been selected, the equation is then derived. The average value of the data and the linear coefficient are found as shown. From these values the expected value equation is derived.

In the expected value equation, C1F1 represents the original linear coefficient at the percent replacement level under consideration. As an example, the zero percent expected value is calculated as shown. Finally a table showing actual data plus expected values is given.

In Table XXIII the data for percent air voids for the Black Clawson series using clean glass replacement are given. The cross products and the sums of squares for linear, quadratic, and cubic trends were again calculated.

A partial analysis of variance table was set up comparing linear, quadratic, and cubic mean square values with the error term mean square value using an F test.

Since the degrees of freedom remained the same, the significant F value remained at 5.99. The highest order trend with a significant F was selected to represent the data. For this case, though, the data was represented by a quadratic trend.

After the trend had been selected, the equation was again derived. The average values of the data and the linear and quadratic coefficients were found as shown. From these values the expected value equation was derived. In the expected value equation, C1F1 and C2F2 represent the original linear and quadratic coefficients respectively at the percent replacement level under consideration. As an example of the use of the equation, the zero percent expected value is calculated. Finally a table showing actual data vs. expected value data is given.

TABLE XXII

TRANSLATING TRENDS INTO EQUATIONS
FOR THE BLACK CLAWSON SERIES AIR VOIDS

| Replicate | Addition Level | | | |
|---|---|---|---|---|
| | 0% | 10% | 30% | 50% |
| 1 | 3.54 | 3.20 | 3.37 | 2.75 |
| 2 | 3.90 | 2.97 | 2.55 | 2.41 |
| 3 | 3.98 | 3.03 | 3.26 | 3.08 |
| Treatment Summation | 11.42 | 9.20 | 9.18 | 8.24 |

CROSS PRODUCTS

Linear Trend

$$(11.42)(-9)+(9.20)(-5)+(9.18)(3)+(8.24)(11)=-30.60$$

Quadratic Trend

$$(11.42)(76)+(9.20)(-43)+(9.18)(-104)+(8.24)(71)=102.64$$

Cubic Trend

$$(11.42)(-8)+(9.20)(15)+(9.18)(-10)+(8.24)(3)=-20.24$$

SUM OF SQUARES

Linear Trend

$$(-30.60)^2/708=1.32$$

Quadratic Trend

$$(102.64)^2/70446=0.15$$

Cubic Trend

$$(-20.24)^2/1194=0.35$$

TABLE XXII

TRANSLATING TRENDS INTO EQUATIONS FOR THE BLACK CLAWSON SERIES AIR VOIDS (continued)

PARTIAL ANOVA TABLE

| Source | Degrees of Freedom | Sum of Squares | Mean Square | F Test |
|---|---|---|---|---|
| Treatments | | | | |
| Linear | 1 | 1.32 | 1.32 | 17.40 |
| Quad | 1 | 0.15 | 0.15 | 1.97 |
| Cubic | 1 | 0.35 | 0.35 | 4.51 |
| Error | 6 | 0.458 | 0.076 | |

EQUATIONAL DATA

Average Value

$(38.04)/12=3.17$

Linear Coefficient

$(-30.60)/708=-0.043$

EQUATION

Expected Value Equation

$\hat{x}=3.17+C1F1(-0.043)$

Expected Value for Zero Percent

$\hat{x}=3.17+(-9)(-0.043)$

$\hat{x}=3.56$

DATA TABLE

| Percent Replacement | Actual Data | Expected Values |
|---|---|---|
| 0% | 3.81 | 3.56 |
| 10% | 3.07 | 3.39 |
| 30% | 3.06 | 3.04 |
| 50% | 2.75 | 2.69 |

TABLE XXIII

TRANSLATING TRENDS INTO EQUATIONS
FOR THE BLACK CLAWSON SERIES AIR VOIDS (CLEAN GLASS)

| Replicate | Addition Level | | | |
|---|---|---|---|---|
| | 0% | 10% | 30% | 50% |
| 1 | 3.54 | 2.92 | 2.84 | 3.19 |
| 2 | 3.90 | 3.66 | 3.06 | 3.37 |
| 3 | 3.98 | 3.05 | 2.98 | 3.08 |
| Treatment Summation | 11.42 | 9.63 | 8.88 | 9.64 |

CROSS PRODUCTS

Linear Trend

(11.42)(-9)(9.63)(-5)(8.88)(3)(9.64)(11)-18.25

Quadratic Trend

(11.42)(76)(9.63)(-43)(8.88)(-104)(9.64)(71)214.75

Cubic Trend

(11.42)(-8)(9.63)(15)(8.88)(-10)(9.64)(3)-6.79

SUM OF SQUARES

Linear Trend

$(-18.25)^2/708$ 0.47

Quadratic Trend

$(214.75)^2/70446$ 0.65

Cubic Trend

$(-6.79)^2/1194$ 0.04

TABLE XXIII

TRANSLATING TRENDS INTO EQUATIONS
FOR THE BLACK CLAWSON SERIES AIR VOIDS (CLEAN GLASS)
(continued)

PARTIAL ANOVA TABLE

| Source | Degrees of Freedom | Sum of Squares | Mean Square | F Test |
|---|---|---|---|---|
| Treatments | | | | |
| Linear | 1 | 0.47 | 0.47 | 14.11 |
| Quad | 1 | 0.65 | 0.65 | 19.64 |
| Cubic | 1 | 0.04 | 0.04 | 1.16 |
| Error | 6 | 0.20 | 0.033 | |

EQUATIONAL DATA

Average Value of Data

(39.57/12-3.30

Linear Coefficient

(-18.25)/708=-0.026

Quadratic Coefficient

(214.75)/70446=0.003

EQUATION

Expected Value Equation

$\hat{x}=3.30+C1F1(-0.026)+C2F2(0.003)$

Expected Value for Zero Percent

$\hat{x}=3.30+(-9)(-0.026)+(76)(0.003)$

$\hat{x}=3.76$

DATA TABLE

| Percent Replacement | Actual Data | Expected Values |
|---|---|---|
| 0% | 3.81 | 3.76 |
| 10% | 3.21 | 3.30 |
| 30% | 2.96 | 2.91 |
| 50% | 3.21 | 3.23 |