# DEVELOPMENT OF A 3/4-INCH MINUS BASE COURSE TYPE A SPECIFICATION FOR MONTANA

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*Final Report*

*prepared for*
THE STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION

*in cooperation with*
THE U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

*December 2016*

*prepared by*
Eli Cuelho

Western Transportation Institute
Montana State University - Bozeman

RESEARCH PROGRAMS

MDT

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**16. Abstract**
Gravel bases are a critical component of roads, providing drainage, structural support, and load distribution within the pavement structure. Montana specifications currently exist for a 2-inch minus (Grade 5A) and 1½-inch minus (Grade 6A) crushed base course; however, gravel sources in parts of Montana are becoming limited, making the option to use a ¾-inch gravel base desirable. The objective of this project was to develop a standard specification for a new gravel base course with nominal maximum aggregate size of ¾ in. This was accomplished by conducting a review of current ¾-inch minus specifications from around the U.S., using that information to generate a preliminary specification to create ¾-inch minus mixes, testing the material properties of these mixes, and modifying these mixes to determine the effect changes in the gradation primarily had on its strength, stiffness and permeability. Based on the results of multiple statistical evaluations as well as qualitative comparisons, it was concluded that a ¾-inch minus gradation specification will perform at least as well as Montana's existing CBC-6A materials and better than CBC-5A materials. Gradation limits for a new ¾-inch minus, Grade 7A, crushed base course were suggested; however, the practicality of producing mixes that fit within the suggested gradation limits still needs to be determined.



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# EXECUTIVE SUMMARY

Highway base courses are typically constructed using crushed and processed aggregate. Crushed base aggregates are typically a cost effective means of carrying loads and reducing the thickness of the asphalt layer in paved roads. For some projects in Montana, however, obtaining materials that meets the current specifications for CBC-5A or CBC-6A crushed base course is becoming uneconomical due to declining resources. This project was initiated to determine the viability of a ¾-inch minus gradation specification for crushed base course materials for the state of Montana to allow gradations with smaller nominal aggregate sizes to be produced for road construction purposes.

The first step in this investigation was to review U.S. state and federal standard specifications to document existing ¾-inch minus base course specifications. Standard specifications from all 50 states were reviewed to extract gradation specifications for ¾-inch minus base course aggregates used as the compacted structural layer in highway construction. Information from that review helped identify a starting point from which to develop a standard specification for Montana crushed aggregate courses. A ¾-inch minus specification from the state of Colorado was used as a preliminary specification in order to produce ¾-inch minus mixes with Montana aggregates for testing purposes.

Samples of aggregate were collected from eight different gravel pits geographically located throughout Montana. Portions of these gravel samples were crushed to create ¾-inch minus mixes (Prepared mixes). These gradations were further modified to evaluate the effect that gradation had on their engineering properties (Modified mixes). The following lab tests were conducted to characterize the physical attributes and material properties of these gravel mixes.

- Particle size distribution
- Fractured face count
- Modified Proctor density
- Relative density (maximum and minimum index densities)
- Specific gravity
- R-value (tested by MDT)
- Direct shear
- Permeability

The primary objective of this project was met by analyzing two specific aspects of the ¾-inch minus gradations: 1) whether aggregates whose maximum particle size was ¾ inch would perform at least as good as Montana's current 5A and/or 6A crushed aggregate base course materials, and 2) what the effect changes in the gradation had on the material properties within the specified limits. The first goal was accomplished by comparing data from the ¾-inch minus materials tested during this project to the results from laboratory tests conducted on CBC-6A and CBC-5A materials (Mokwa et al., 2007). The second goal was accomplished by qualitatively analyzing the

performance data from finer and coarser gradations for each of the eight Montana sources. The results from this analysis were used to suggest a viable ¾-inch minus gradation specification for crushed base course materials for the state of Montana.

Statistical analyses of average values were conducted using a two-sided t-test (for samples having unequal variance) to determine if apparent trends in measured laboratory test results represent true differences between aggregate types. The two-sample t-test is a statistical test used to determine if the averages of the two data sets are statistically different from one another based on a mathematical evaluation of the data scatter. In cases where the averages are statistically different, a direct comparison of the mean values indicates which value is greater. Otherwise, the means are considered statistically equal.

The analysis showed that, overall, ¾-inch minus base course materials are expected to perform at least as well as Montana CBC-6A and better than Montana CBC-5A materials based on the material properties determined during this study. It also showed that ¾-inch minus materials within the preliminary specified range performed better near the bottom of the specified range (i.e., coarser materials) than finer materials. The specification used in the Glendive district is similar to the Colorado specification (used as the preliminary specification in this project). Based on these results, it was recommended that a modified version of the Glendive specification be adopted as a viable ¾-inch minus base course specification within the state of Montana, now known as Montana CBC-7A. The practicality and constructability of producing mixes that fit within these suggested gradation limits needs to be determined.

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# INTRODUCTION AND BACKGROUND

Gravel bases are a critical component of roads, providing drainage, structural support, and load distribution to reduce pressures on subgrade soils. Roadway designers currently have a number of options for specifying the base course material on Montana Department of Transportation (MDT) highway projects. Montana specifications currently exist for a 2-inch minus (Grade 5A) and 1½-inch minus (Grade 6A) crushed base course (Section 701.02.4); however, gravel sources in Montana are becoming limited, particularly in the eastern regions of the state, making the option to use a ¾-inch gravel base desirable. The objective of this project was to develop a standard specification for a new gravel base course with nominal maximum aggregate size of ¾ in. The first step in this investigation was to review other state and federal standard specifications to document whether or not a standard ¾-inch minus base course specification had been implemented. Information from that review helped identify a starting point from which to develop a standard specification for Montana crushed aggregate courses.

The most important engineering characteristics of base course aggregates are strength, stiffness, and drainage capacity. Each of these properties can have a large impact on the performance of a flexible pavement. For example, increasing the strength and stiffness of the base course results in less rutting, smaller pavement deflections, and ultimately less cracking of the pavement surface. The damaging effects of water in the structural layers of roadways have been well documented. Specific modes of these damaging effects include pumping of fines, frost heave, asphalt stripping, and reduction of shear strength. Ensuring that a new aggregate gradation will perform at least as well as the currently specified base course aggregates is important in order to assure proper performance. Therefore, the second step in this investigation was to test a variety of crushed aggregates from several sources throughout the state of Montana having a ¾-inch minus gradation. In addition to general characterization of the materials, several engineering properties were also examined, including: compaction, durability, strength, stiffness, and drainage. These properties were quantified by synthesizing and analyzing results from the following laboratory tests: geotechnical index tests, direct shear, R-value, and permeability.

Several years ago, the engineering characteristics of three crushed aggregates commonly used on Montana highway projects (CBC-6A, CBC-5A and CTS-2A) were determined and documented by the Western Transportation Institute (Mokwa et al., 2007) using an extensive suite of geotechnical laboratory tests. The results from these tests were used as a baseline by which to compare the results of testing of the ¾-inch minus aggregate gradations. The following chapters outline the various tasks associated with this effort and how they were analyzed to develop a viable ¾-inch minus gradation specification for the state of Montana.

# REVIEW AND COMPARISON OF STATE AND FEDERAL ¾-INCH MINUS BASE COURSE SPECIFICATIONS

Current Montana specifications exist for a 2-inch minus (Grade 5A) and 1½-inch minus (Grade 6A) crushed aggregate course (MDT, 2014 – §701.02.4). Because gravel sources in Montana are becoming limited, investigating the use of a gravel specification for maximum particle sizes less than ¾ inch is desirable. The first step in this investigation was to review other state's standard specifications to document whether or not a standard ¾-inch minus base course specification is currently being utilized. Information from these specifications helped identify a starting point from which to develop a standard specification for Montana crushed aggregate courses.

Standard specifications from all 50 states were reviewed to extract gradation specifications for ¾-inch minus base course aggregates used as the compacted structural layer in highway construction. Many states have specifications that accommodate a ¾-inch minus material by specifying a range of percent passing the ¾-inch sieve (generally 80 to 100 percent); however, the majority of these aggregate blends are for materials that pass the 1-inch sieve. Only a few states (Colorado, Indiana, Iowa and Nebraska) had a standard specification for a ¾-inch minus material where 100 percent of the particles must pass the ¾-inch sieve (CDOT, 2011; INDOT, 2014; Iowa DOT, 2012; NDOR, 2007). The ranges of acceptable gradations for these four states are shown in Figure 1.

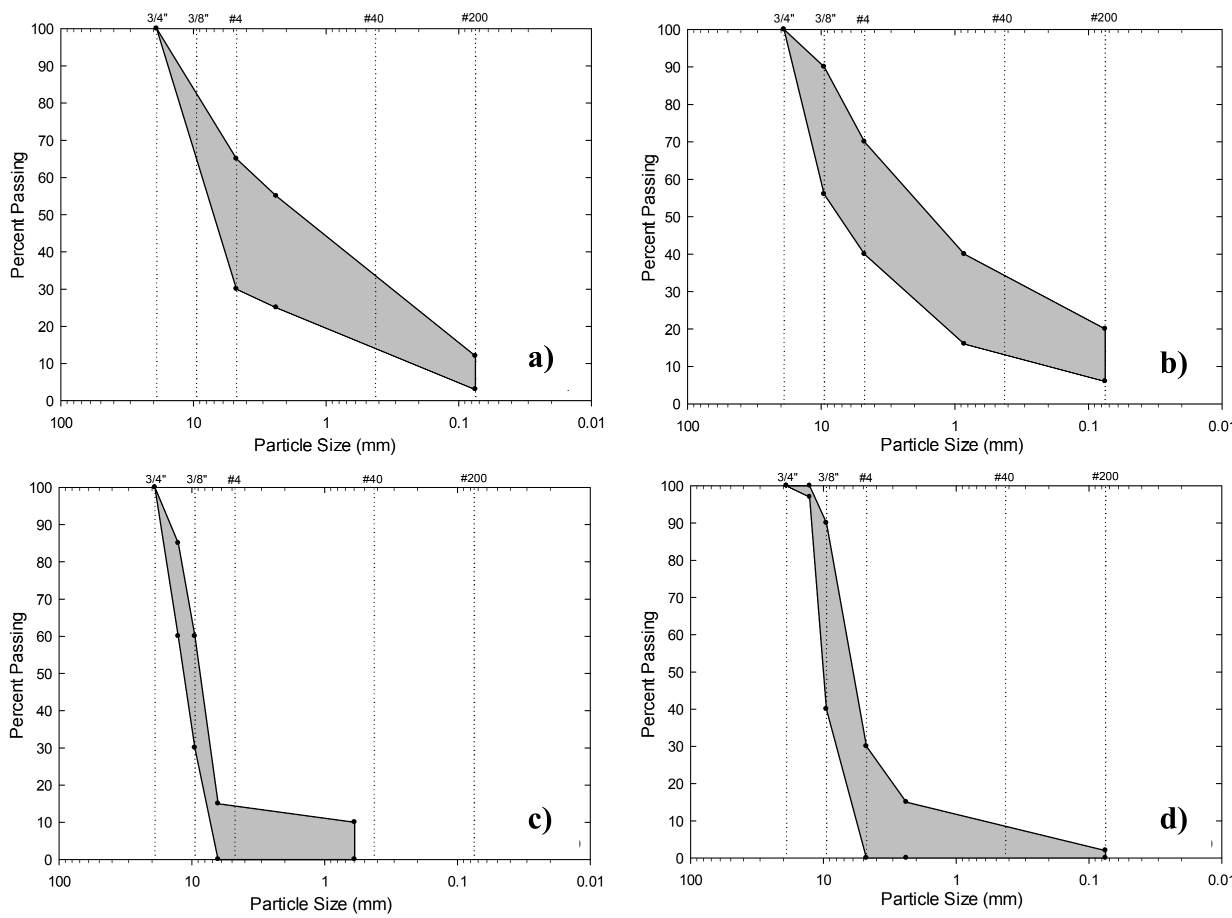


**Figure 1: ¾-inch minus specification ranges for a) Colorado, b) Nebraska, c) Indiana and d) Iowa.**

Of the four ¾-inch minus gradation specifications, only the ones from Colorado and Nebraska were considered useful as base course materials for Montana. The specification from Indiana is generally for coarse grained material used as borrow and structural backfill, not for dense graded materials such as base course directly under pavement. This material is relatively uniform in size (as perceived in Figure 1c). Likewise, the material specification for Iowa also resembles a uniformly graded material, although it is smaller in size (refer to in Figure 1d). The Iowa specification is not typically used for base course because it is a finer grained aggregate blend typically used as cover aggregate. Furthermore, it also accommodates a ½-inch minus material, making it somewhat small for Montana base course aggregates. This leaves the Colorado and Nebraska base specifications. Discussions with Colorado DOT personnel indicated that this ¾-inch minus specification is used extensively for base course aggregate. It was also discovered that the development of this specification was thought to originate with a ¾-inch minus specification from the Federal Highway Administration (FHWA). Further investigation found federal ¾-inch minus base specifications that dated back more than a half century. Gradations for the federal specifications are summarized in Table 1.

**Table 1: Federal ¾-inch Minus Base Course Specifications**

| Sieve (nom.) | Sieve (mm) | Specification Year | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1957[a] | 1969[b] | 1974[c] | 1979[d] | 2003[e] | 2014[f] |
| 3/4-inch | 19 | 100 | 100 | 100 | 100 | 100 | 100 |
| 3/8-inch | 9.5 | | 57-89 | 60-90 | | 56-96 | 56-96 |
| #4 | 4.75 | 45-80 | 38-70 | 41-71 | 41-71 | 30-80 | 30-80 |
| #8 | 2.38 | | 24-54 | | | | |
| #10 | 2.00 | 25-60 | | 26-50 | | | |
| #30 | 0.595 | | 11-30 | | | | |
| #40 | 0.425 | | 0-16 | 12-28 | 12-28 | 8-30 | 8-30 |
| #200 | 0.075 | 0-12 | 2-14 | 5-17 | 5-17 | 1-10 | 1-10 |

References:
[a] DOC (1957)
[b] FHWA (1969)
[c] FHWA (1974)
[d] FHWA (1979)
[e] FHWA (2003)
[f] FHWA (2014)

The specifications from Colorado, Nebraska and FHWA were suggested as a starting point for development of a ¾-inch minus base course specification for Montana. The ranges for each of these specifications are listed in Table 2 along with Montana 5A and 6A for comparison. An average of the Colorado, Nebraska and 2014 FHWA specifications is also provided as a comparison. A plot of the Colorado, Nebraska and 2014 FHWA specifications is provided in

Figure 2, along with the average of these three specifications. For the purposes of this research effort, the Colorado ¾-inch minus specification was selected as the interim ¾-inch minus specification to produce material mixes for this project. The Colorado specification is shown with respect to the current Montana 5A and 6A specifications for comparison in Figure 3.

**Table 2: Relevant ¾-inch Minus Base Course Specifications**

| Sieve (nom.) | Sieve (mm) | Percent Passing | | | | | |
|---|---|---|---|---|---|---|---|
| | | **MT-5A** | **MT-6A** | **CO** | **NE** | **FHWA** | **Average*** |
| 3/4-in. | 19 | 70-88 | 74-96 | 100 | 100 | 100 | 100 |
| 3/8-in. | 9.5 | 50-70 | 40-76 | 65-83 | 56-90 | 56-96 | 59-90 |
| #4 | 4.75 | 34-58 | 24-60 | 30-65 | 40-70 | 30-80 | 33-72 |
| #40 | 0.425 | 6-30 | 6-34 | 14-34 | 13-34 | 8-30 | 12-33 |
| #200 | 0.075 | 0-8 | 0-8 | 3-12 | 6-20 | 1-10 | 3-14 |

* average of Colorado, Nebraska and FHWA

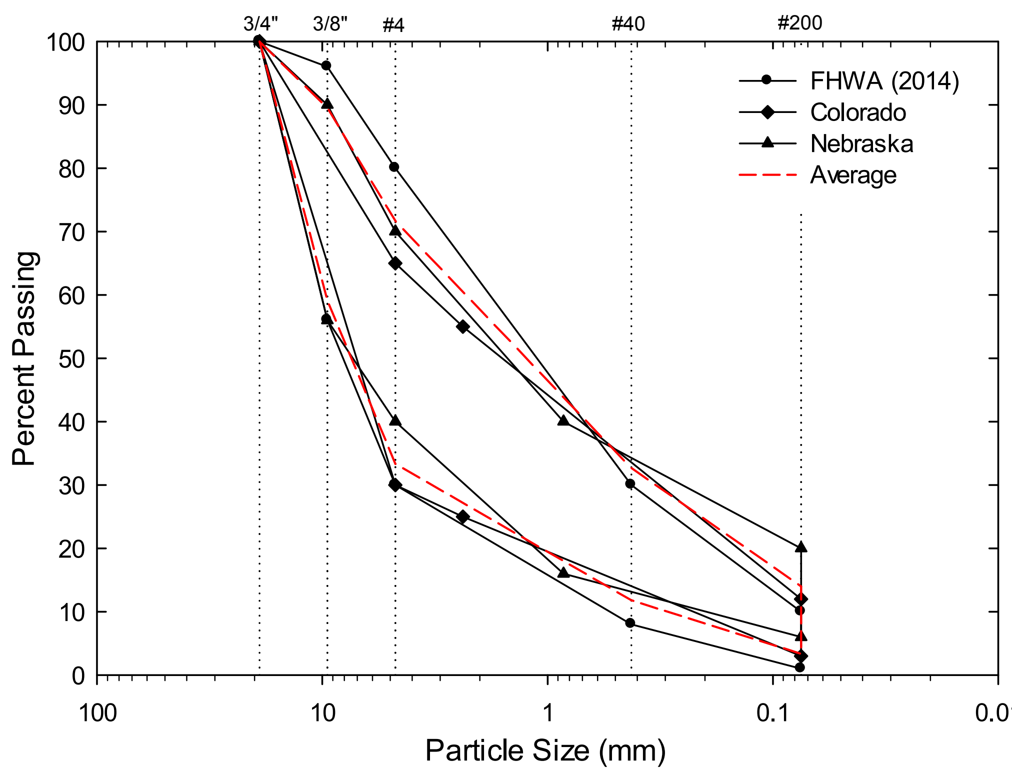


**Figure 2: 2014 FHWA, Colorado, Nebraska, and average base course specifications.**

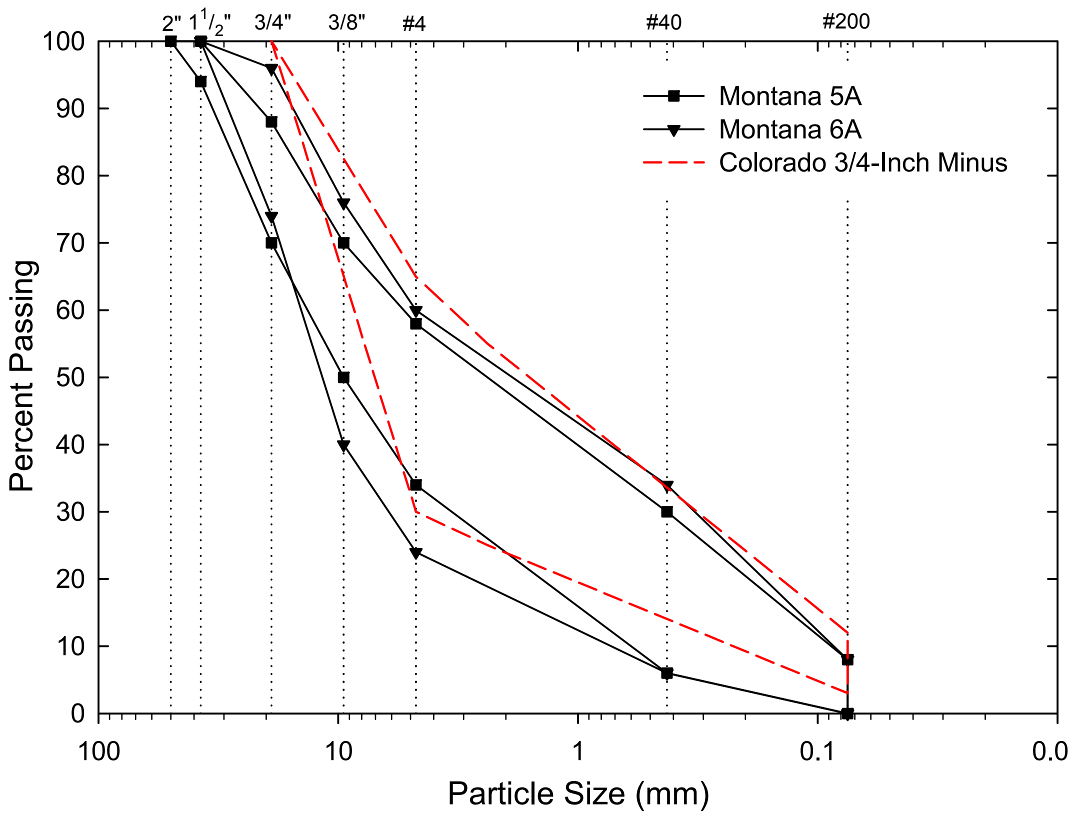


**Figure 3: Montana 5A and 6A specifications compared to Colorado ¾-inch minus specification.**

More recently, a ¾-inch minus base course specification has successfully been used by Montana Department of Transportation in the Glendive District. This specification is presented in Table 3 and is plotted in comparison with the Colorado, Nebraska and FHWA specifications in Figure 4.

**Table 3: ¾-inch Minus Base Course Specification Used by MDT near Glendive**

| Sieve (nom.) | Sieve (mm) | Percent Passing |
|---|---|---|
| 3/4-in. | 19 | 100 |
| 3/8-in. | 9.50 | 57-81 |
| #4 | 4.75 | 36-60 |
| #10 | 2.00 | 27-47 |
| #200 | 0.075 | 2-8 |

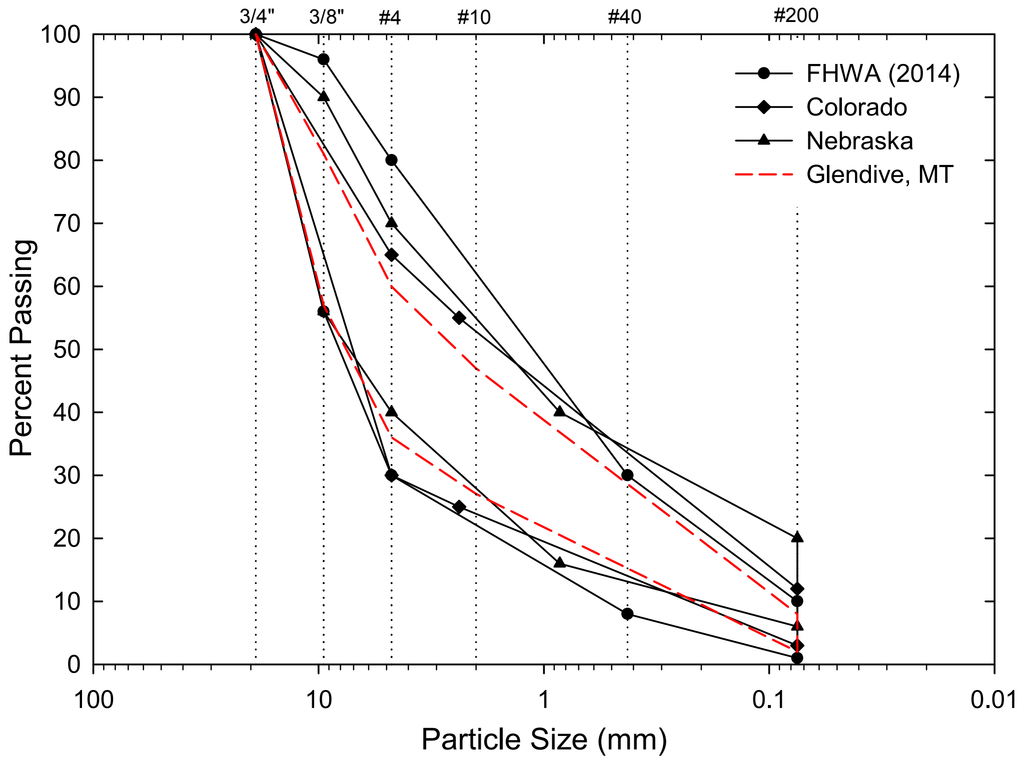


**Figure 4: Montana Glendive specification compared to CO, NE and 2014 FHWA.**

The percent of fractured particles, liquid limit, and plasticity index requirements were also collected. These specifications are summarized in Table 4 for the three specifications of focus (Colorado, Nebraska, and 2014 FHWA). Montana's 5A and 6A specifications are also listed in Table 4 as a comparison.

**Table 4: Fractured, Liquid Limit, and Plasticity Index Specifications**

| | Fractured Particles* (%) | Liquid Limit (%) | Plasticity Index (%) |
|---|---|---|---|
| **MT 5A** | > 35 | < 25 | < 6 |
| **MT 6A** | > 35 | < 25 | < 6 |
| **Colorado** | NP | < 30 | < 6 |
| **Nebraska** | NP | NP | < 4 |
| **2014 FHWA** | > 50 | < 25 | NP |

* for material retained on the #4 sieve
NP = information not provided

# CHARACTERIZATION OF ¾-INCH MINUS BASE COURSE MATERIALS FROM MONTANA

Samples of aggregate were collected from eight different gravel pits geographically located throughout Montana. Portions of these gravel samples were crushed to create ¾-inch minus mixes. These gradations were further modified to evaluate the effect that gradation had on their engineering properties. The lab tests listed below were conducted as part of this study. All tests were conducted at the Western Transportation Institute Materials laboratory and the Civil Engineering Department Geotechnical laboratory at Montana State University. The results from the tests listed below are summarized in the following subsections.

- Particle size distribution
- Fractured face count
- Modified Proctor density
- Relative density (maximum and minimum index densities)
- Specific gravity
- R-value (tested by MDT)
- Direct shear
- Permeability

## Material Sources

Crushed aggregates samples were collected from the eight locations within Montana listed in Table 5 and shown in Figure 5. Samples were obtained from all five transportation districts in Montana, and are generally representative of aggregates used for road construction purposes within those districts. For simplicity, each of the aggregate sources was assigned a letter name that will be used throughout the remainder of this report. Five of the eight sources were Montana Type 6A CBC aggregates (1½-inch minus); and three sources (A, D and E) were ¾-inch minus materials. For the 1½-inch minus materials, stones larger than ¾ inch were crushed using a miniature jaw crusher until all of the material passed the ¾-inch sieve. The crushed material was simply added back to the entire mix creating a simulated ¾-inch minus mix, hereafter referred to as the “Prepared” mix. Using the Prepared gradation as a base, a second mix was created by making it coarser or finer to determine the effect that changes in the gradation had on its engineering properties. This mixture is hereafter referred to as the “Modified” mix. The percent gravel (material above the #10 sieve), percent sand (material between the #10 and #200 sieves) and percent fines (material passing the #200 sieve) for each of the gravel sources and mixes is summarized in Table 6 to show their general composition. Photos of each of these materials by source and gradation is provided in Appendix A. The gravel mixes classified as either A-1-a or A-1-b according to the AASHTO classification method (AASHTO M 145).

**Table 5: Material Sources and Classification**

| Source | District (Location) | Pit/Source Name | Classification | |
|---|---|---|---|---|
| | | | Prepared | Modified |
| A | Butte District (Belgrade, MT) | Knife River Pit | A-1-a | A-1-a |
| B | Missoula District (Kalispell, MT) | Pit name not provided | A-1-a | A-1-a |
| C | Missoula District (Hamilton, MT) | Blahnik Pit | A-1-a | A-1-a |
| D | Glendive District (Forsyth, MT) | Kevin Brewer Pit | A-1-b | A-1-a |
| E | Glendive District (Glendive, MT) | Fischer Sand and Gravel Pit | A-1-b | A-1-a |
| F | Glendive District (Wolf Point, MT) | Sterling Carroll Pit | A-1-a | A-1-a |
| G | Billings District (Lewistown, MT) | Arrow Creek Slide Repair | A-1-a | A-1-a |
| H | Great Falls District (Fort Benton, MT) | Lonesome Dove Grain Company Pit | A-1-a | A-1-b |

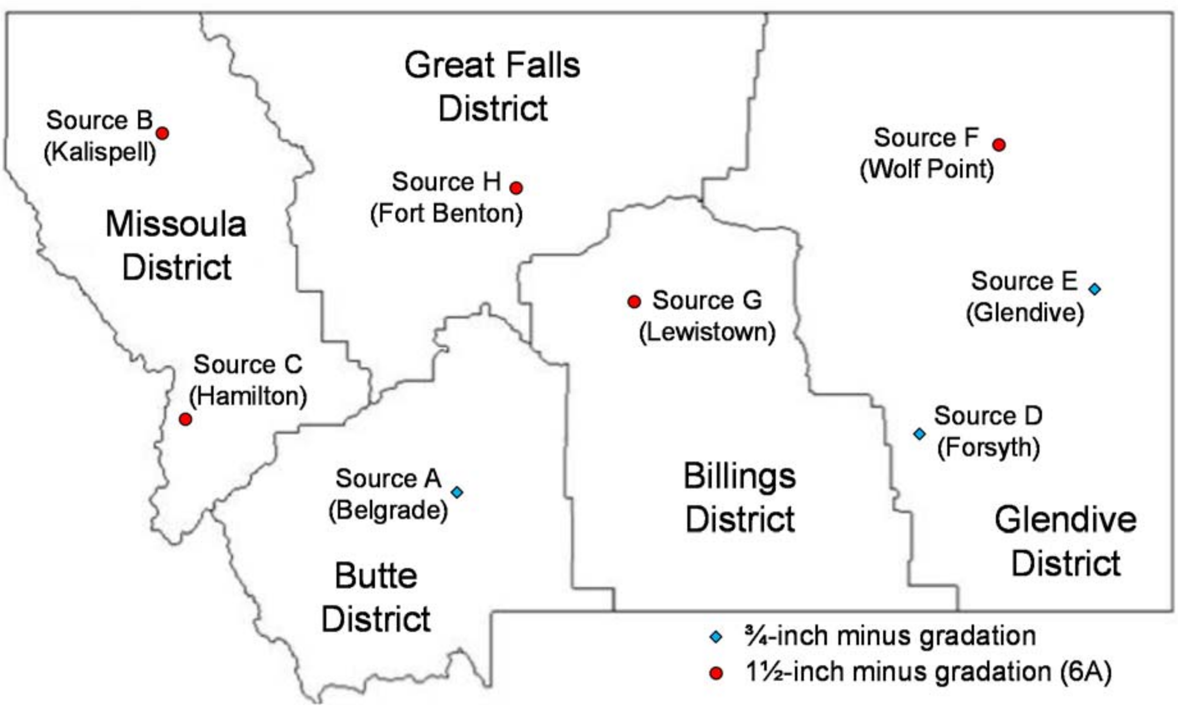


**Figure 5: Map of material sources in Montana.**

**Table 6: General Composition of Prepared and Modified Mixes**

| Source | Gradation | % Gravel | % Sand | % Fines |
|---|---|---|---|---|
| A | Prepared | 55 | 40 | 5 |
| | Modified | 64 | 31 | 5 |
| B | Prepared | 75 | 18 | 7 |
| | Modified | 78 | 15 | 7 |
| C | Prepared | 88 | 11 | 1 |
| | Modified | 65 | 33 | 2 |
| D | Prepared | 79 | 18 | 3 |
| | Modified | 61 | 34 | 5 |
| E | Prepared | 71 | 25 | 4 |
| | Modified | 56 | 40 | 5 |
| F | Prepared | 57 | 37 | 6 |
| | Modified | 73 | 18 | 9 |
| G | Prepared | 60 | 30 | 10 |
| | Modified | 75 | 19 | 6 |
| H | Prepared | 63 | 34 | 3 |
| | Modified | 44 | 51 | 5 |

## Particle Size Distribution

Washed sieve analyses were completed on the Original, Prepared and Modified gradations in accordance with ASTM test methods D6913 and D1140 (Particle Size Distribution of Soils Using Sieve Analysis, and Amount of Material in Soils Finer than No. 200 Sieve), and MDT202 (Sieve Analysis of Fine and Course Aggregates), for each of the eight samples. Particle size distributions were compared to the upper and lower gradation limits associated with Colorado's ¾-inch minus specification, which was identified by the Technical Panel as the target gradation for this effort. The sieve sizes used for gradation analyses are shown in Table 7. Gradation results from the Prepared and Modified mixes are plotted with respect to the Colorado ¾-inch minus specification upper and lower limits, as shown in Figure 6 and Figure 7, respectively. These gradations are also presented in tabular format in Table 8 and Table 9 for the Prepared and Modified mixes, respectively. Individual plots of the grain-size distribution for each source are provided in Appendix B.

**Table 7: Sieve Sizes Utilized in This Study**

| Sieve Opening Size (mm) | U.S. Sieve Size |
|---|---|
| 37.5 | 1½ in. |
| 25 | 1 in. |
| 19 | ¾ in |
| 12.5 | ½ in |
| 9.50 | ⅜ in |
| 4.75 | No. 4 |
| 0.850 | No. 20 |
| 0.425 | No. 40 |
| 0.150 | No. 100 |
| 0.075 | No. 200 |

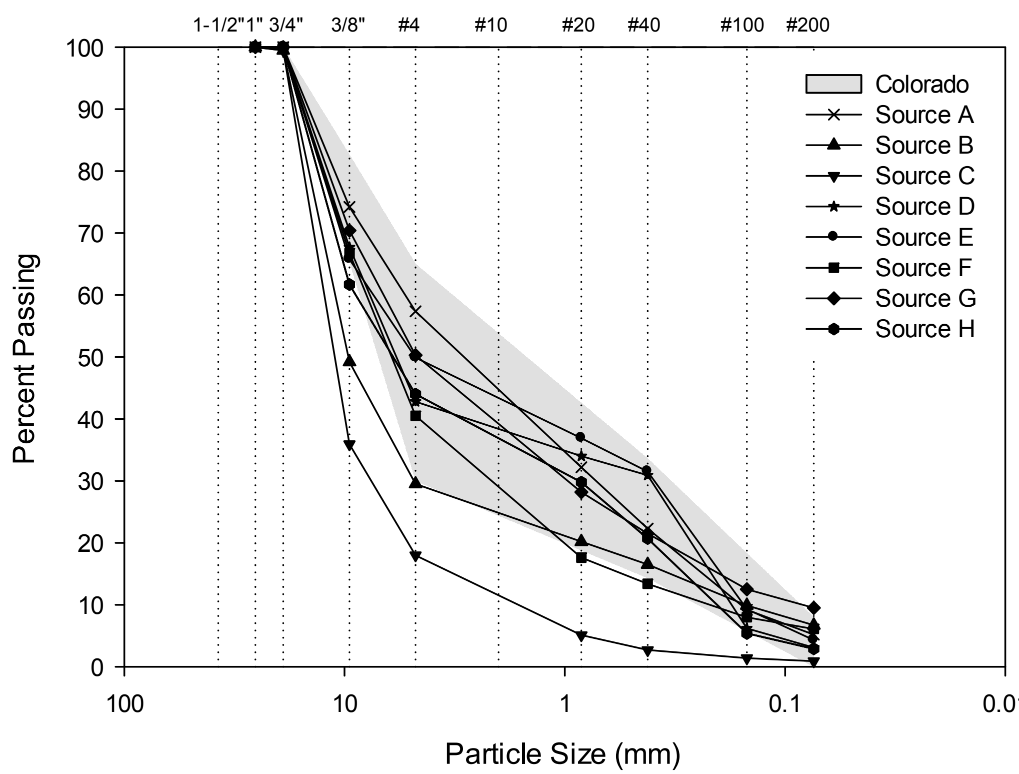


**Figure 6: Sieve analysis results of Prepared gradations with respect to Colorado specification limits.**

**Table 8: Sieve Analysis Results of Prepared Gradations**

| Sieve Size (mm) | U.S. Sieve Size | Source | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | G | H |
| 19 | ¾ in | 100.0 | 99.5 | 99.5 | 99.8 | 100.0 | 100.0 | 100.0 | 100.0 |
| 9.50 | ⅜ in | 74.2 | 49.2 | 35.9 | 67.7 | 65.8 | 66.8 | 70.4 | 61.7 |
| 4.75 | No. 4 | 57.4 | 29.5 | 18.0 | 42.8 | 49.9 | 40.5 | 50.3 | 44.0 |
| 2.00* | No. 10* | 44.6 | 25.1 | 11.5 | 38.7 | 28.9 | 43.4 | 39.1 | 37.0 |
| 0.850 | No. 20 | 32.2 | 20.2 | 5.1 | 34.0 | 36.9 | 17.6 | 28.2 | 29.8 |
| 0.425 | No. 40 | 22.3 | 16.5 | 2.7 | 30.9 | 31.5 | 13.4 | 21.5 | 20.7 |
| 0.150 | No. 100 | 9.2 | 9.9 | 1.4 | 6.2 | 9.3 | 8.0 | 12.5 | 5.4 |
| 0.075 | No. 200 | 5.2 | 6.7 | 0.9 | 3.1 | 4.3 | 6.1 | 9.5 | 2.9 |

* No. 10 sieve not used in sieve analysis – percent passing inferred from gradation curve

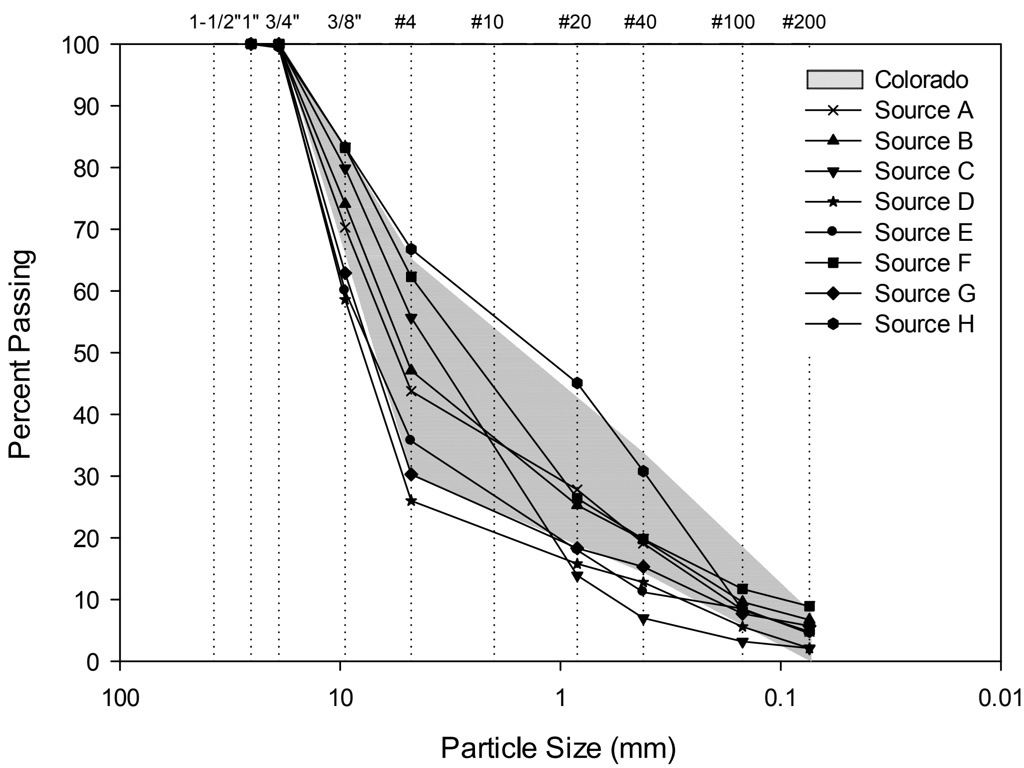


**Figure 7: Sieve analysis results of Modified gradations with respect to Colorado specification limits.**

**Table 9: Sieve Analysis Results of Modified Gradations**

| Sieve Size (mm) | U.S. Sieve Size | Source | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | G | H |
| 19 | ¾ in | 100.0 | 100.0 | 100.0 | 100.0 | 99.4 | 100.0 | 100.0 | 99.6 |
| 9.50 | ⅜ in | 70.3 | 74.1 | 79.9 | 58.6 | 60.0 | 83.2 | 62.9 | 83.3 |
| 4.75 | No. 4 | 43.8 | 47.1 | 55.7 | 26.0 | 35.7 | 62.3 | 30.3 | 66.8 |
| 2.00* | No. 10* | 35.7 | 36.5 | 34.6 | 21.1 | 43.9 | 26.7 | 24.1 | 55.8 |
| 0.850 | No. 20 | 27.8 | 25.3 | 13.9 | 15.8 | 18.0 | 26.4 | 18.3 | 45.1 |
| 0.425 | No. 40 | 19.1 | 19.7 | 7.0 | 12.8 | 11.2 | 19.8 | 15.3 | 30.8 |
| 0.150 | No. 100 | 8.3 | 9.6 | 3.2 | 5.6 | 8.5 | 11.7 | 7.7 | 8.3 |
| 0.075 | No. 200 | 4.8 | 6.7 | 2.1 | 2.1 | 4.5 | 8.9 | 5.7 | 4.8 |

* No. 10 sieve not used in sieve analysis – percent passing inferred from gradation curve

## Fractured Faces

Fractured face analyses were completed on each of the eight sources on both the Prepared and Modified gradations in substantial accordance with MDT Test Method MDT217 (Method of Test for Determining Percentage of Mechanically Fractured Particles) and ASTM Test Method D5821 (Determining the Percentage of Fractured Particles in Coarse Aggregate). ASTM Test Method D5821 considers a fractured face as an angular, rough or broken surface of an aggregate particle by crushing, by artificial means or by nature. A single face is considered fractured if the projected area of the fractured portion is ≥ 25 percent of the maximum particle cross-sectional area. The fractured particle content was evaluated using material above the No. 4 sieve. The material was washed to remove fine particles and then dried to a constant mass. Each rock was visually inspected to determine if at least one face was fractured according to the criteria described above. Rocks were either fractured (F), questionable or borderline (Q), or non-fractured (N). The individual mass of each of the three categories was taken and percentage of fractured faces was determined using Equation 1. Fractured face percentages of Prepared and Modified materials by source are summarized in Table 10. In general, the fractured face counts for these materials was lower than the desired minimum specification of 50 percent. Change in the fractured face count changed only slightly for the Modified mixes.

$$\boldsymbol{P = \frac{F+\frac{Q}{2}}{(F+Q+N)} * 100} \qquad \textbf{Equation 1}$$

**Table 10: Summary of Fractured Face Results**

| Source | % Fractured Faces | |
|---|---|---|
| | Prepared | Modified |
| A | 29 | 31 |
| B | 44 | 47 |
| C | 35 | 40 |
| D | 33 | 35 |
| E | 27 | 25 |
| F | 35 | 34 |
| G | 36 | 41 |
| H | 22 | 25 |

## Specific Gravity

Specific gravity ($G_s$) tests were conducted on the Prepared and Modified gradations of the eight aggregate sources in substantial accordance with MDT Test Methods MT205 (Method of Test for Specific Gravity and Absorption of Coarse Aggregate) and MT220 (Specific Gravity of Soils), and general accordance with ASTM Test Method D854 (Specific Gravity of Soil Solids by Water Pycnometer) and ASTM Test Method C127 (Relative Density (Specific Gravity) and Absorption of Coarse Aggregate). The final value of $G_s$ was determined by taking a weighted average from the fine and coarse fractions of each soil sample. Values of $G_s$ ranged from 2.55 to 2.71, within the typical range reported for these material types. Specific gravity results are summarized in Table 11. Changes in gradation from the Prepared to Modified mixes had little effect on the average specific gravity of the materials. Sources A and B exhibited the largest change.

**Table 11: Summary of Specific Gravity Results**

| Source | Average Specific Gravity | |
|---|---|---|
| | Prepared | Modified |
| A | 2.67 | 2.71 |
| B | 2.57 | 2.67 |
| C | 2.55 | 2.66 |
| D | 2.71 | 2.70 |
| E | 2.68 | 2.67 |
| F | 2.66 | 2.64 |
| G | 2.68 | 2.69 |
| H | 2.67 | 2.66 |

## Relative Density

Relative density testing was conducted in substantial accordance with ASTM Test Method D4253 (Maximum Index Density and Unit Weight of Soils Using a Vibratory Table) and ASTM Test Method D4254 (Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density). ASTM D4253 provides the option of conducting either dry or saturated testing. It was observed in this study that saturated testing yielded significantly lower minimum void ratios (higher maximum densities) than dry testing. Consequently, all maximum index density results reported herein are based on tests performed under saturated conditions. The size of the mold used for testing was governed by the ASTM specification, which is based on the maximum particle size of the sample. All samples were tested in the 6-inch diameter (volume = 0.100 ft$^3$) mold. Relative density can be calculated in terms of either void ratio or dry density as:

$$\boldsymbol{D_r = \frac{e_{max}-e}{e_{max}-e_{min}} = \left[\frac{\rho_d - \rho_{d(min)}}{\rho_{d(max)}-\rho_{d(min)}}\right]\left[\frac{\rho_{d(max)}}{\rho_d}\right]} \qquad \textbf{Equation 2}$$

where, $D_r$ = relative density, $e_{max}$ = maximum void ratio, $e_{min}$ = minimum void ratio, $e$ = in-situ void ratio, $\rho_d$ = in-situ density, $\rho_{d(max)}$ = maximum index density, and $\rho_{d(min)}$ = minimum index density. Maximum and minimum index density results are summarized in Figure 8 and Figure 9 in terms of void ratio for the Prepared and Modified gradations, respectively. The figures show range of expected values, ($e_{max}$-$e_{min}$) for each material source and gradation.

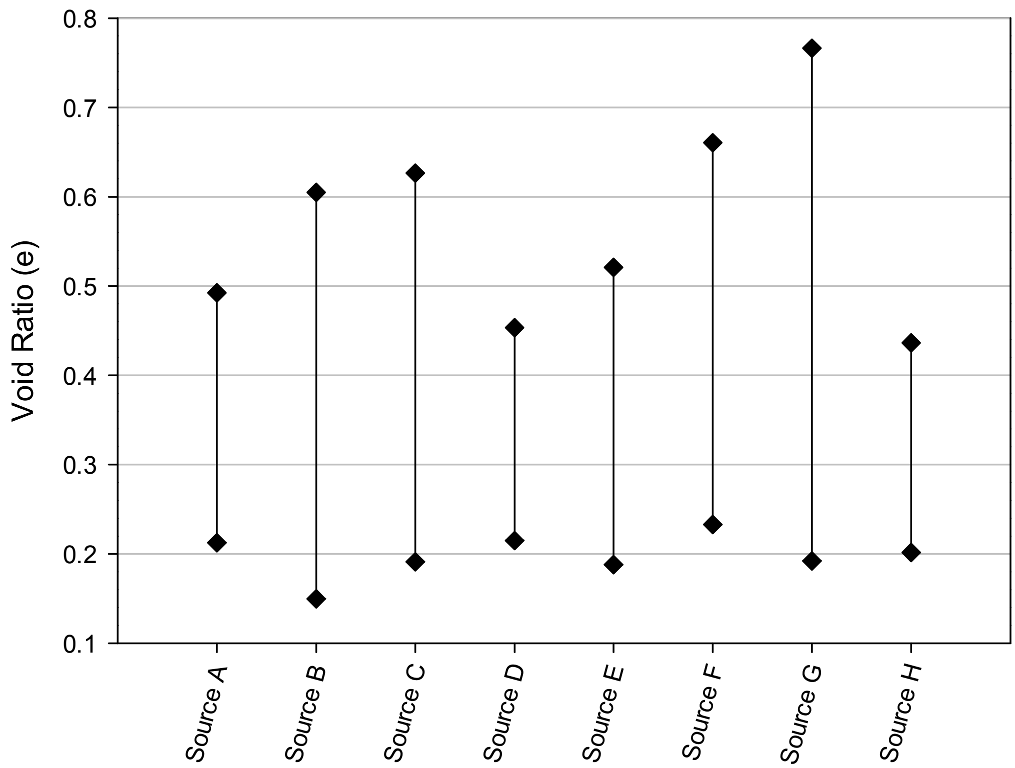


**Figure 8: Relative density of Prepared gradations in terms of void ratio.**

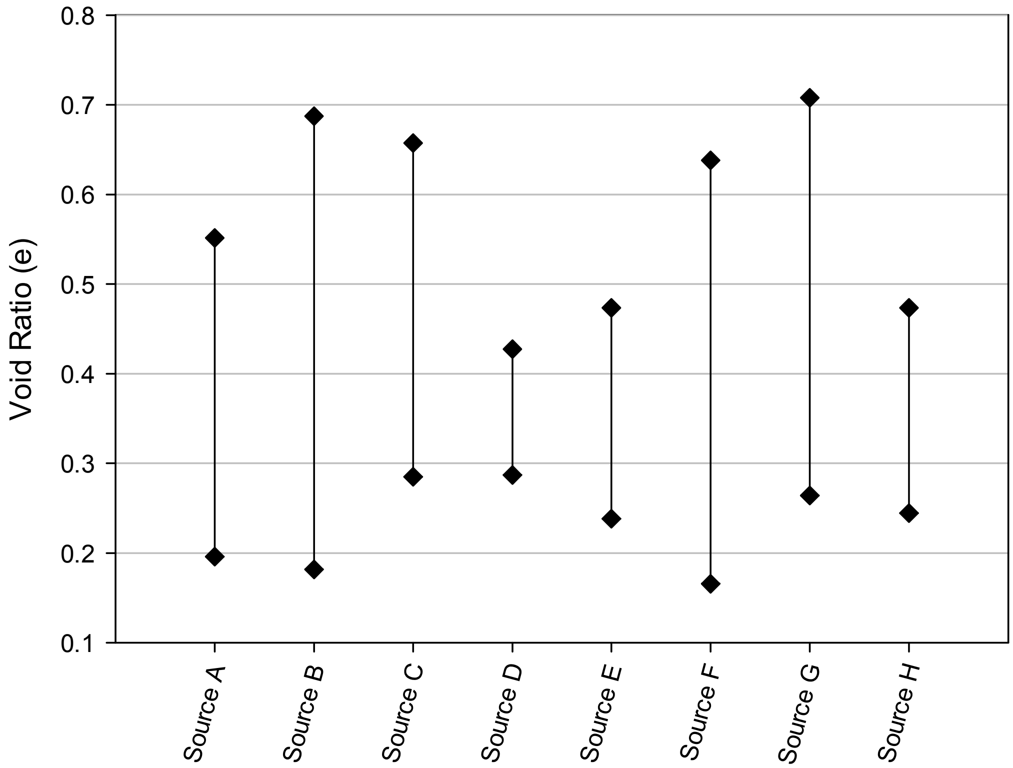


**Figure 9: Relative densities of Modified gradations in terms of void ratio.**

## Modified Proctor Compaction

Modified Proctor testing was conducted in substantial accordance with MDT Test Method MT230 (Method of Test for the Moisture-Density Relations of Soils Using a 10 lb. Rammer and a 18 in. Drop) and ASTM Test Method D1557 (Laboratory Compaction Characteristics of Soils Using Modified Effort). Because the aggregates had a maximum particle size of 0.75 inches, the 6-inch-diameter Proctor mold was used. ASTM Test Method D2049 (Relative Density of Cohesionless Soils) specifies that relative index density testing is appropriate for materials with less than 12% passing the No. 200 sieve. All aggregate samples evaluated in this study have less than 12% fines and are cohesionless. Nevertheless, modified Proctor tests were conducted on all of the aggregates. Moisture-density relationships derived from the Proctor tests at times resulted in unusual behaviors (refer to Appendix C for moisture density relationships for all materials and gradations). Maximum dry unit weight and optimum moisture contents derived from the modified Proctor tests are summarized in Table 12 for each of the materials and gradations. Densities obtained from maximum and minimum index density testing (ASTM D4253 – Maximum Index Density and Unit Weight of Soils Using a Vibratory Table and ASTM D4254 – Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density) were used in place of Proctor densities for evaluating relative densities in this study. Modified Proctor maximum dry densities for the samples were similar in magnitude to maximum dry densities (minimum void ratios) determined using the maximum index density method, as shown in Figure 10 (Prepared gradation results) and

Figure 11 (Modified gradation results). Density measurements are presented in terms of void ratio (e), which can be related to dry unit weight ($\gamma_d$) using Equation 3, as follows:

$$\gamma_d = \frac{G_s \gamma_w}{1+e} \quad \textbf{Equation 3}$$

where, $G_s$ = specific gravity, $\gamma_w$ = unit weight of water, and $e$ = void ratio. This indicates that either method for determining maximum density would be acceptable for the aggregates. For consistency, maximum dry densities obtained using the maximum index density tests were used in this study for all aggregate gradations.

**Table 12: Summary of Modified Proctor Results**

| | Modified Proctor | | | |
|---|---|---|---|---|
| | Prepared | | Modified | |
| Source | $\gamma_{d,max}$ (pcf) | $w_{opt}$ (%) | $\gamma_{d,max}$ (pcf) | $w_{opt}$ (%) |
| A | 133.6 | 4.9 | 133.5 | 4.7 |
| B | 142.5 | 3.3 | 138.5 | 5.1 |
| C | 127.2 | 2.2 | 126.1 | 3.3 |
| D | 134.4 | 3.5 | 132.3 | 6.2 |
| E | 137.9 | 6.9 | 138.4 | 7.4 |
| F | 142.8 | 4.3 | 138.8 | 5.3 |
| G | 140.5 | 6.9 | 135.6 | 5.3 |
| H | 136.8 | 6.3 | 131.7 | 8.0 |

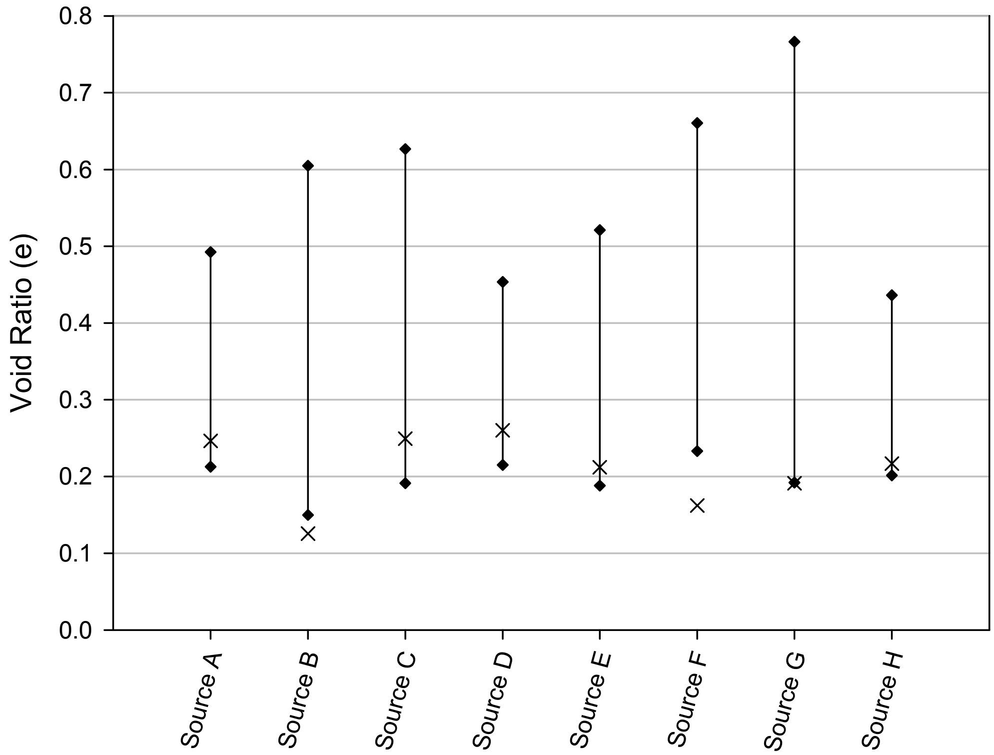


**Figure 10: Proctor densities in terms of void ratio for Prepared gradations.**

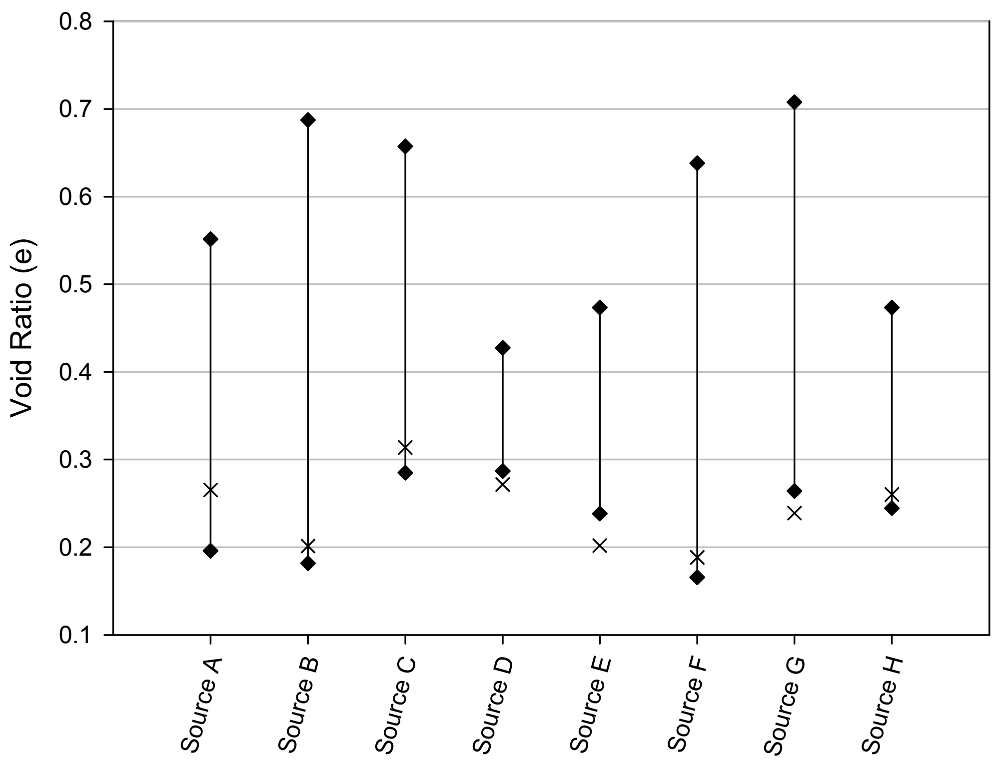


**Figure 11: Proctor densities in terms of void ratio for Modified gradations.**

## Resistance Value

The Resistance R-value and Expansion Pressure of Compacted Soils test (commonly referred to as the R-value test) is used by MDT to evaluate the strength and stability of subgrade and base materials. The test is standardized by AASHTO Test Method T190 and ASTM Test Method D2844. The R-value test output is a number ranging from 0 to 100, with 0 representing viscous liquid slurry with no shear resistance, and 100 representing a rigid solid. The R-value test is conducted using a stabilometer, in which a constant vertical pressure is added to the stabilometer and the corresponding increase in horizontal (fluid) pressure is measured. The R-value is calculated based on the measure of horizontal pressure increase.

R-value tests were completed by MDT at materials testing lab in Helena. R-value results are summarized in Table 13, and data sheets for the R-value tests are provided in Appendix D. R-values ranged from 70 to 80, within the anticipated range of values for these types of materials. Differences in the R-value between Prepared and Modified gradations are relatively small, with the exception of Source F.

**Table 13: Summary of R-Value Results**

| Source | R-value | |
|---|---|---|
| | Prepared | Modified |
| A | 72 | 76 |
| B | 80 | 78 |
| C | 77 | 73 |
| D | 78 | 74 |
| E | 74 | 71 |
| F | 63 | 77 |
| G | 70 | 76 |
| H | 75 | 74 |

## Direct Shear

Direct shear testing was performed to quantify shear strength parameters of the aggregate samples. Tests were performed in general accordance with AASHTO Test Method T236 (Standard Method of Test for Direct Shear Test of Soils under Consolidated Drained Conditions). A large, 12-inch by 12-inch, Brainard-Kilman direct shear testing apparatus was used to accommodate the maximum particle size of the aggregate samples. Shear resistance was measured using an S-type load cell and lateral displacement was measured using a linear variable displacement transducer (LVDT). Some of the main components and sample preparation steps of the direct shear device are shown in Figure 12.

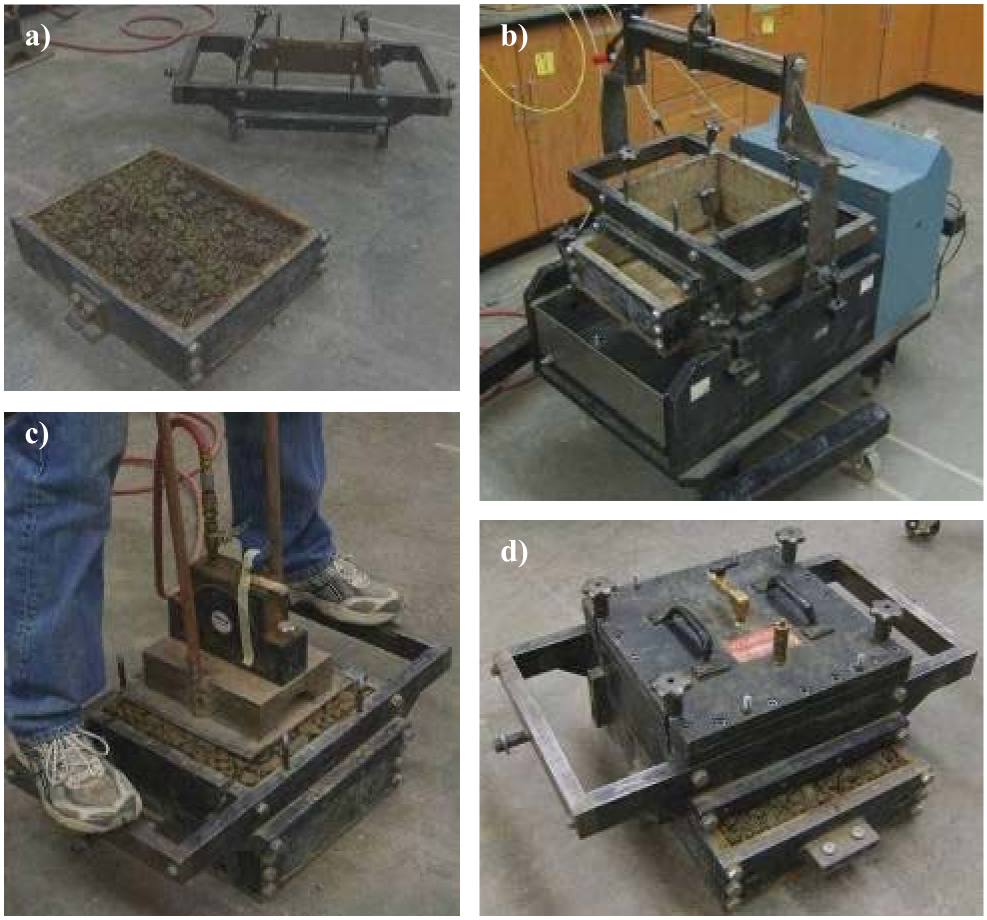

**Figure 12: Direct shear testing apparatus a) mold halves, b) mold placed in load frame, c) vibratory compactor, and d) assembled mold halves with air bladder and cover plate attached to top.**

### Apparatus and Sample Preparation

Soil was placed into the shear box in 1.3-inch compacted lifts. Compaction was performed using a 57-pound, pneumatic vibratory compactor with a 100 $in^2$ contact area (Figure 12c). Normal stress (pressure) was applied to the top surface of the sample using a pressurized rubber air bladder, which was located on the inside of the shear box lid (Figure 12d). The samples were sheared at a constant rate of 0.05 in/min to a maximum horizontal displacement of 3.8 inches.

### Compacted Density of Direct Shear Samples

In the field, large vibratory drum compactors pass over a material multiple times to impart weight and vibration to the underlying geomaterials. This process was simulated in the laboratory using a weighted vibratory plate. Vibration and impact compaction energy were applied until observable particle movement ceased, which generally occurred after approximately one minute of compaction for each soil layer. This method of compaction provided high densities with minimal compaction non-uniformities. All samples were compacted using an initial water content of approximately 4 percent to help minimize particle segregation and facilitate compaction. The dry density of the direct shear samples was determined using mass-volume relationships after each sample was compacted into the direct shear mold. Relative density ($D_r$) was calculated for each compacted sample using Equation 3. There was some variation in $D_r$ between aggregate types because of the differences in particle gradation, and particle shape; however, overall good repeatability was achieved using this method of compaction, as witnessed by the relatively small spread of compacted void ratios, as shown in Figure 13 and Figure 14 for the Prepared and Modified gradations, respectively.

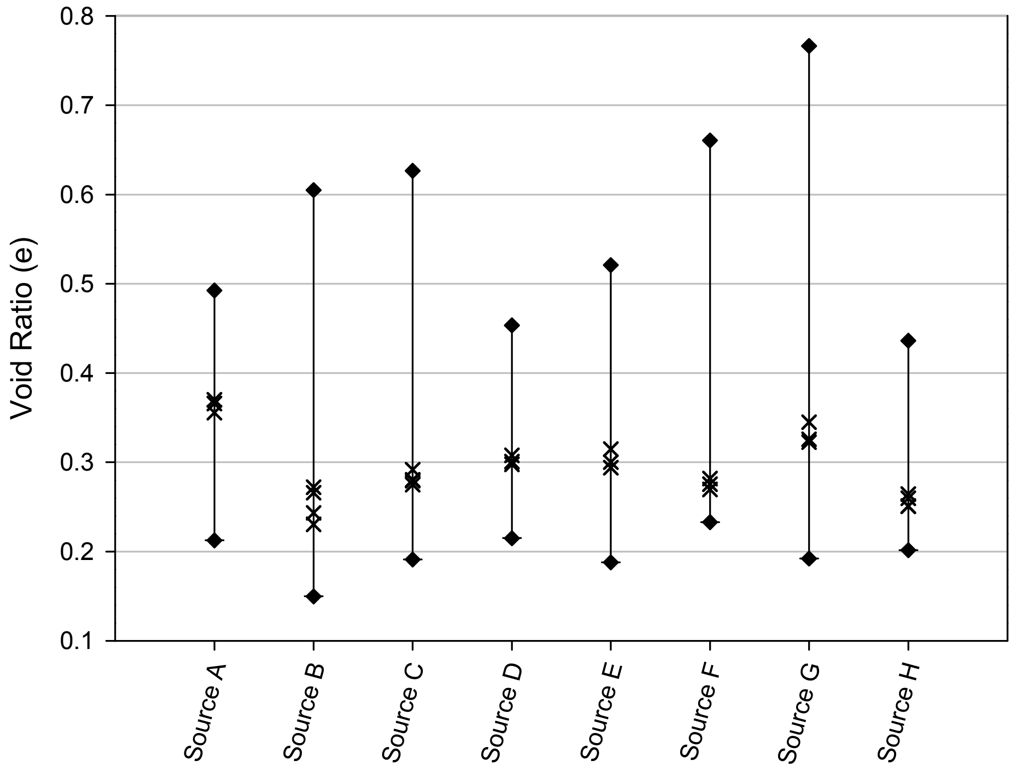


**Figure 13: Direct shear densities for Prepared gradations.**

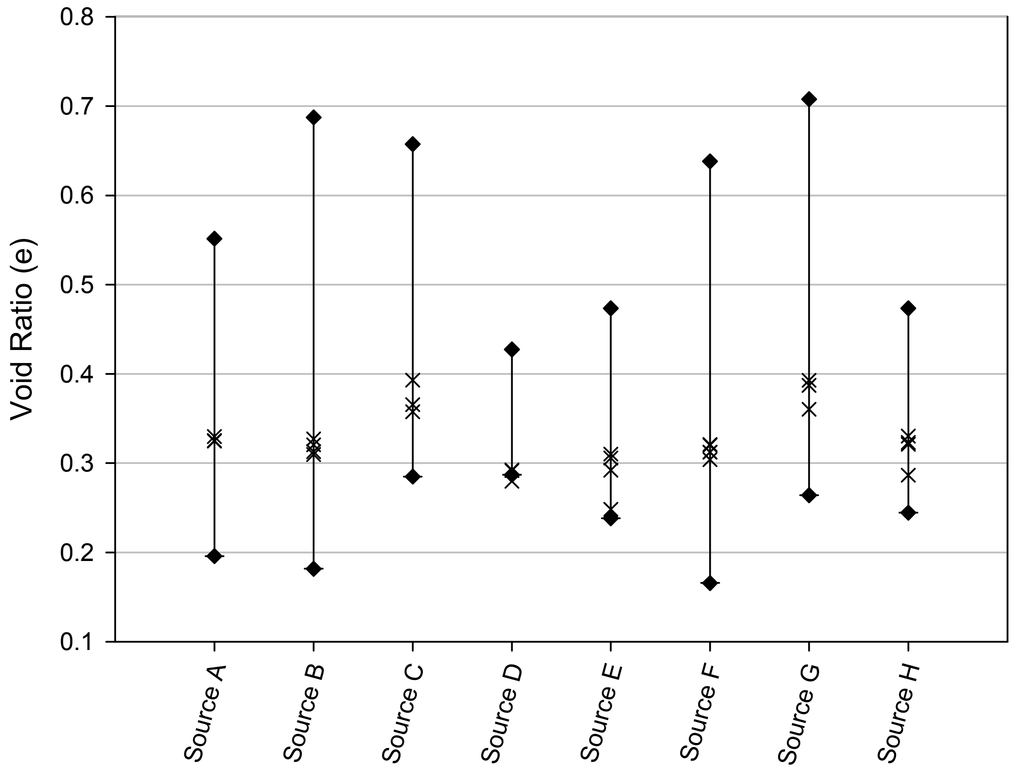


**Figure 14: Direct shear densities for Modified gradations.**

## Measured Parameters

Several parameters were obtained from direct shear testing including initial stiffness ($k_i$), ultimate secant stiffness ($k_u$), and ultimate shear stress ($\tau_u$). Mohr-Coulomb failure envelopes were determined using the ultimate shear strength of each material at the different normal stresses. Values of $k_i$ reported here are defined as the slope of the linear elastic portion of the stress-displacement curve, which occurs at low displacements. The ultimate secant stiffness, $k_u$, is defined as the slope of a line drawn from the origin to the shear stress at 8 percent strain, where the strain is averaged over the entire length of the sample. Percent strain in this context is thus defined as the measured displacement divided by sample length. $\tau_u$ was determined at 8 percent strain or the peak stress, whichever occurred first. Load versus horizontal displacement plots for all three normal stresses are presented in Appendix E for each material and gradation. Initial stiffness results are presented graphically in Figure 15 and Figure 16, ultimate secant stiffness results are presented in Figure 17 and Figure 18, and ultimate shear stress results are shown in Figure 19 and Figure 20, for the Prepared and Modified gradations, respectively.

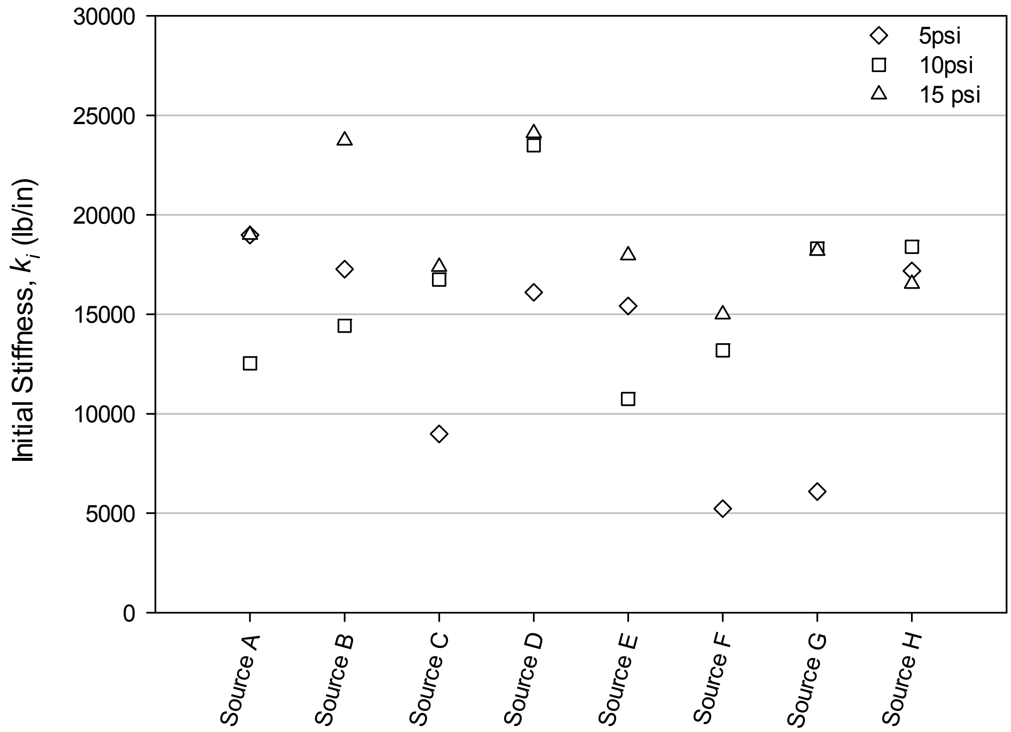


**Figure 15: Initial stiffness ($k_i$) results for the Prepared gradations.**

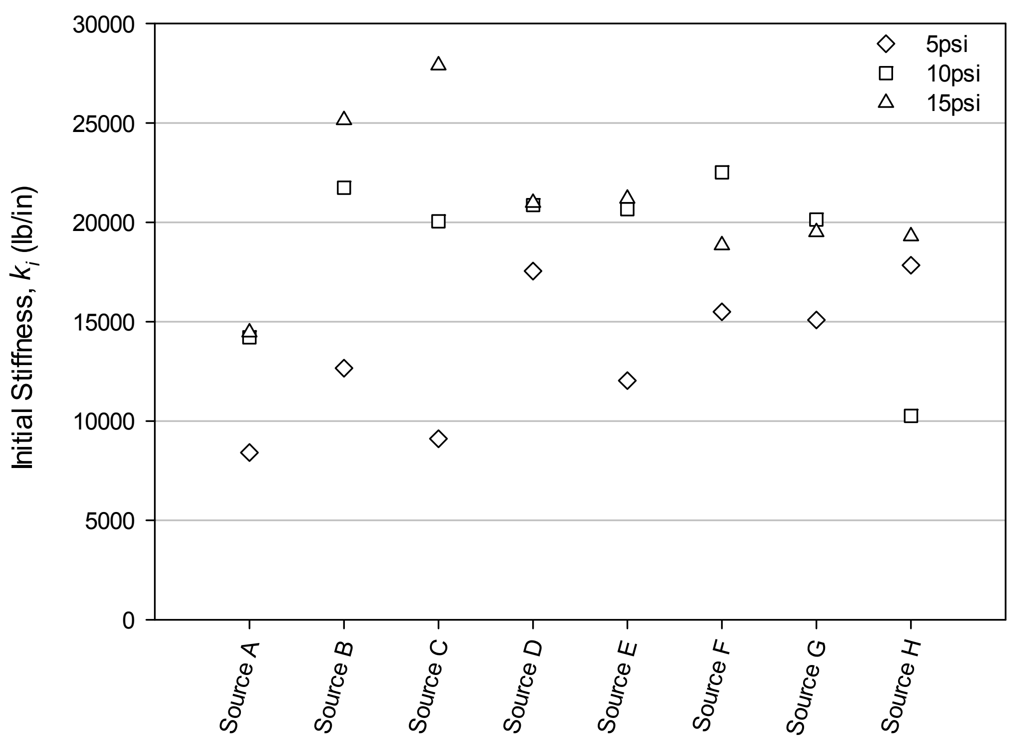


**Figure 16: Initial stiffness ($k_i$) results for the Modified gradations.**

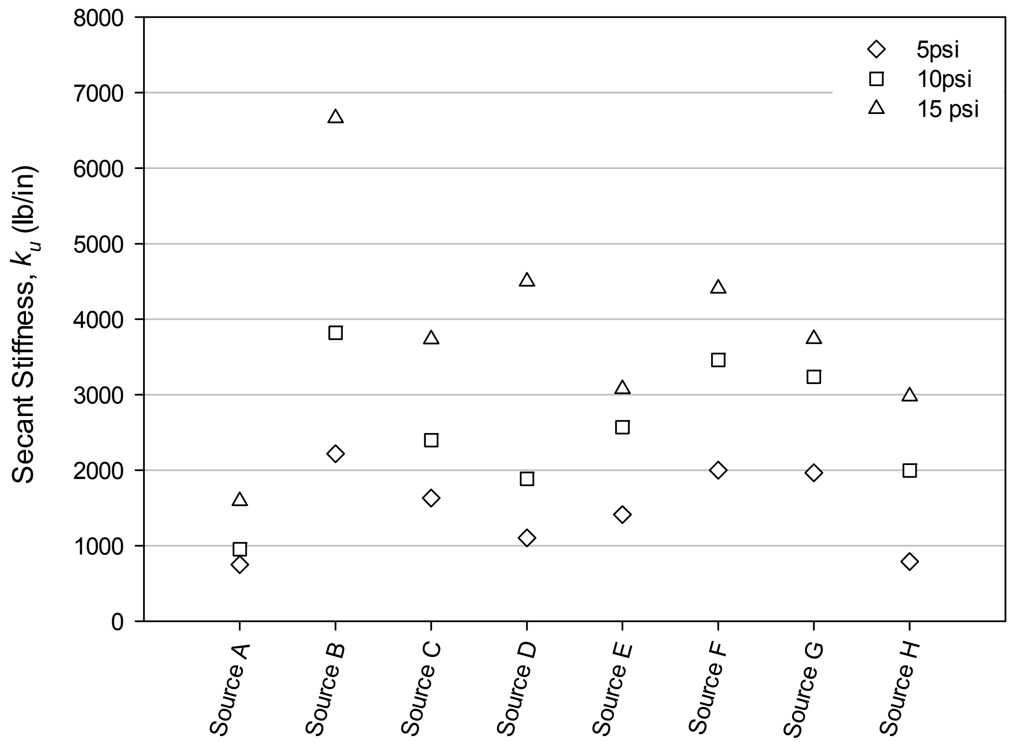


**Figure 17: Ultimate secant stiffness ($k_u$) results for the Prepared gradations.**

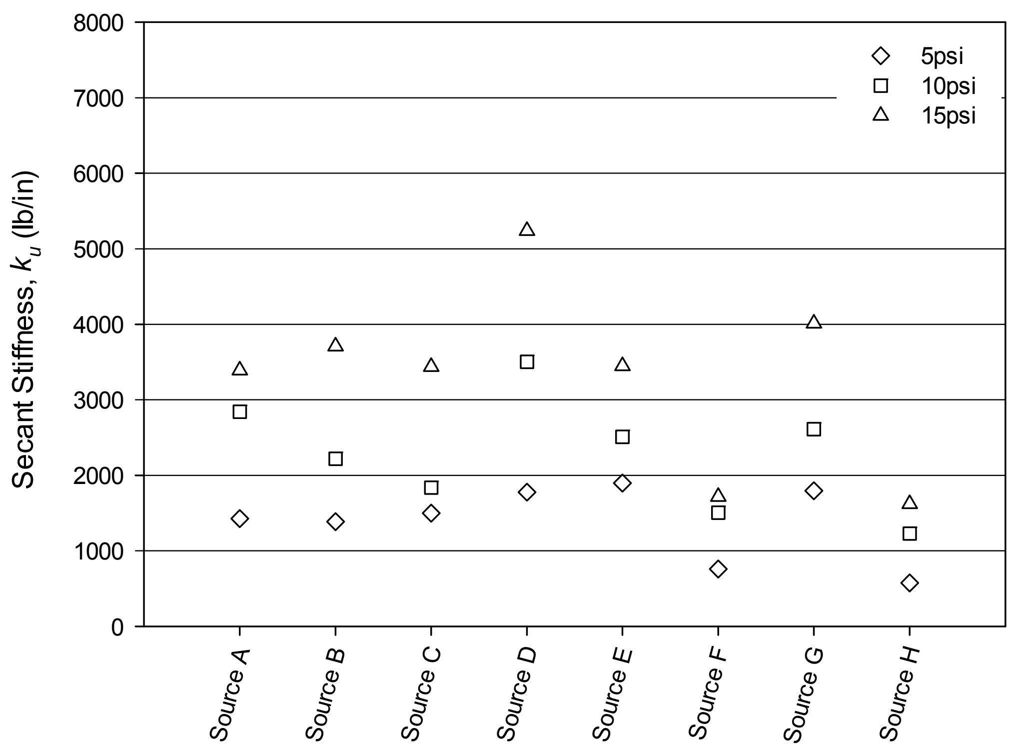


**Figure 18: Ultimate secant stiffness ($k_u$) results for the Modified gradations.**

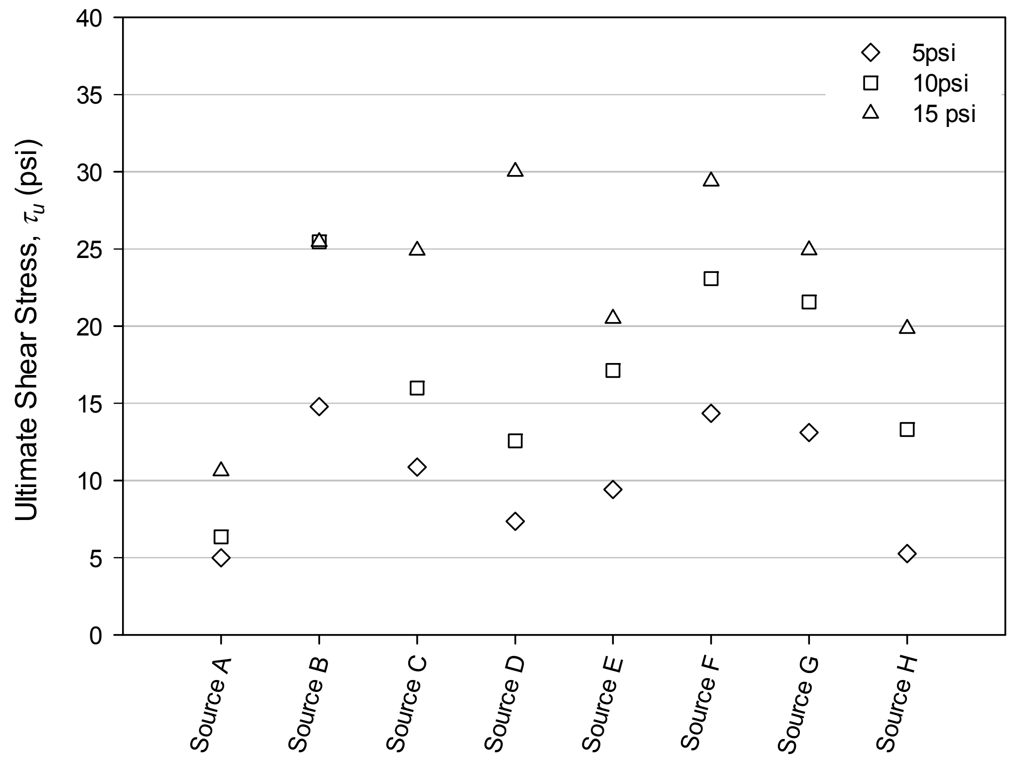


**Figure 19: Ultimate shear strength ($\tau_u$) results for the Prepared gradations.**

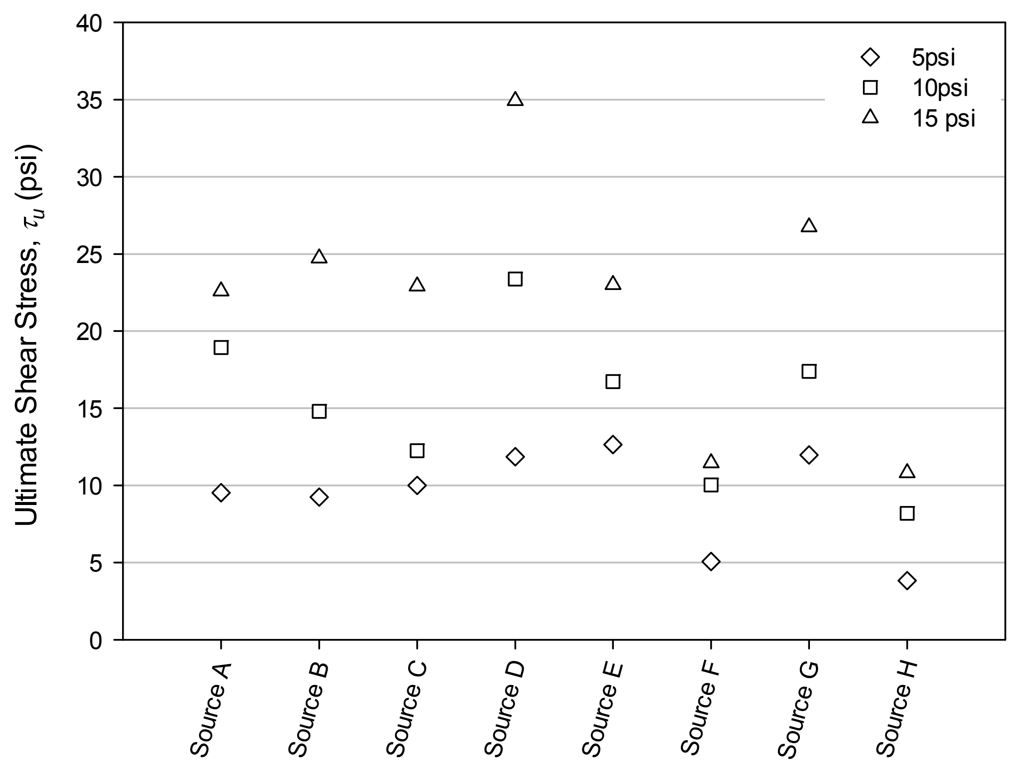


**Figure 20: Ultimate shear strength ($\tau_u$) results for the Modified gradations.**

### Friction Angle

The effective angle of internal friction ($\phi'$) was determined by testing three separately compacted samples at normal stresses of 5, 10, and 15 psi. In the field, these aggregates likely experience relatively low normal stresses because of the small overburden loads that are typical of highway pavement sections. Normal pressures of 5, 10, and 15 psi were used to simulate the low normal pressures typical of in-situ conditions. The spread of 5 psi between normal pressures is a practical measure necessary to provide accurate Mohr-Coulomb failure envelopes. Mohr-Coulomb failure envelope results are presented in Table 14 for the Prepared and Modified gradations. Effective friction angle plots provided in Appendix F are based on best-fit lines drawn through the origin. Measured $\phi'$ values were in the range of 35° to 71° for the prepared material, and 37° to 67° for the modified material, which represents a relatively large spread. Some of the changes between the Prepared and Modified gradations are significant, especially for Sources A, B, F and H.

**Table 14: Friction Angle Results**

| Source | Friction angle $\phi'$ | |
|---|---|---|
| | Prepared | Modified |
| A | 35 | 59 |
| B | 71 | 58 |
| C | 59 | 56 |
| D | 60 | 67 |
| E | 56 | 59 |
| F | 65 | 40 |
| G | 62 | 61 |
| H | 53 | 37 |

## Permeability

Drainage capacity of the aggregates was quantified by conducting saturated constant head hydraulic conductivity (permeability) tests. Permeability tests were performed in general accordance with ASTM Test Method D2434 and AASHTO Test Method T215 (Permeability of Granular Soils – Constant Head). Constant head testing was utilized (as opposed to falling head) to limit the amount of hydraulic head applied to the samples thus ensuring laminar flow conditions. Darcy's Law was used to compute permeability, as follows:

$$\boldsymbol{k = \frac{QL}{tHA}} \qquad \textbf{Equation 4}$$

where, $k$ = permeability, $Q$ = volume of water passed through the specimen, $L$ = length of the specimen, $t$ = elapsed time corresponding to $Q$, $H$ = total head across the specimen, and $A$ = cross sectional area of the specimen perpendicular to the flow direction.

Permeability is a highly variable soil property that can vary significantly with small variations in compaction and gradation. To minimize testing errors, average *k* values were obtained for each sample by conducting three separate tests, using virgin aggregate each time.

## Apparatus

A custom-built, large-diameter permeameter was utilized for this testing. The permeameter specimen mold has a diameter of 10 inches and an approximate height of 10 inches. The permeameter utilizes a unique Mariotte tube and integral upper reservoir arrangement to maintain constant pressure head and complete saturation of the soil sample and testing apparatus throughout the experiment. A photograph and schematic diagram of the permeameter are shown in Figure 21.

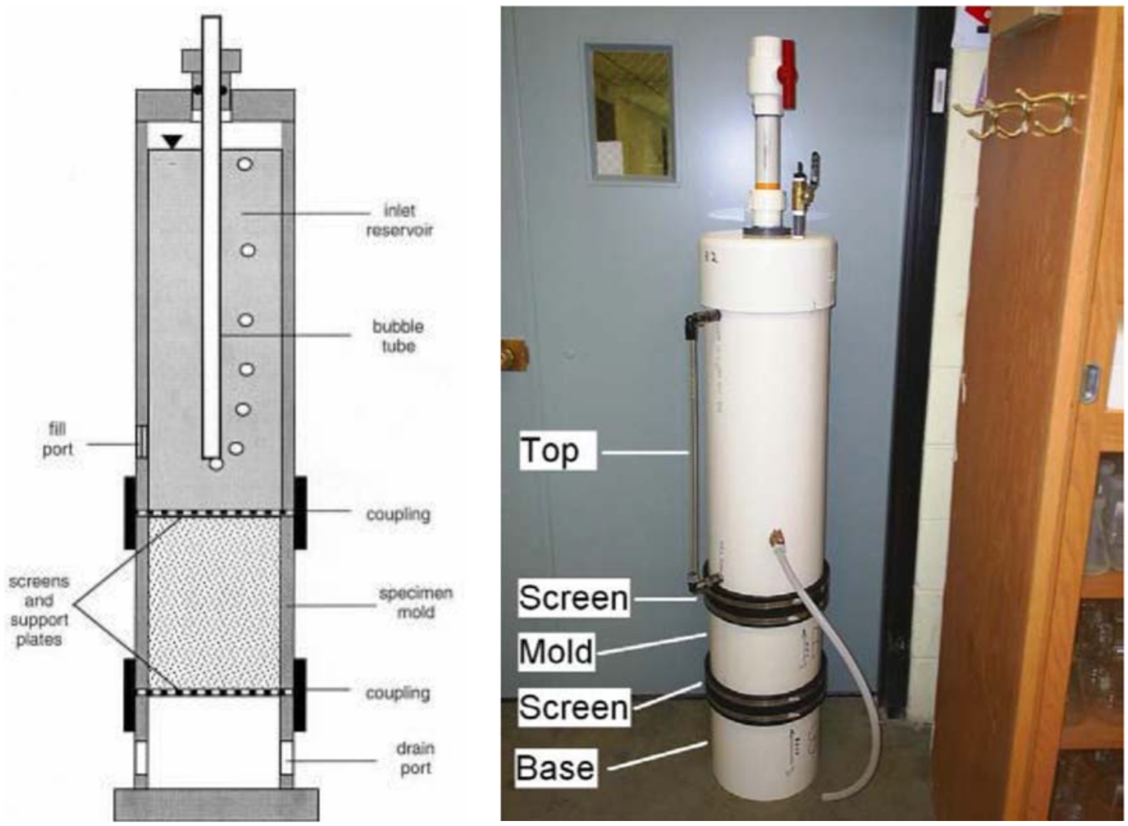


**Figure 21: Schematic and photograph of permeameter.**

The support plates consist of 0.25 in thick galvanized steel plates that have 0.25 in holes throughout to permit unrestricted flow of water. Two square mesh screens were placed between the sample and the support plates to reduce the washing of finer particles out of the specimen during testing. The screens were placed at 45° relative to each other to further reduce the opening size of the sieves, thereby reducing the movement of fines.

A 0.125-inch thick soft neoprene rubber liner was attached to the inside of the specimen mold with silicone adhesive to reduce edge effects. The liner was installed to alleviate high stress concentrations that may occur at the contact points of the larger particles on the smooth rigid interior wall of the mold, and to maintain a more uniform and representative distribution of particles near the sample edges. The liner was used for all tests performed in this study. Any effect imparted on the measured permeability from the presence of the liner was approximately the same for all samples.

## Sample Preparation

Samples of virgin aggregate were compacted into the 10-inch tall specimen mold in multiple lifts. Each lift received 25 blows of a tamper having a 3-inch diameter metal foot followed by ten 1-second tamps with a vibratory compactor having a 5.5-inch diameter base plate, followed by 40 rapid tamps with the vibratory compactor. For consistency, all samples were compacted at an initial water content of approximately 4 percent. Similar densities were targeted for the Prepared and Modified gradations. Density results are shown in Figure 22 and Figure 23 for the Prepared and Modified gradations, respectively. Every effort was made in the preparation, placement, and compaction of samples to minimize particle segregation and to ensure consistency between test specimens.

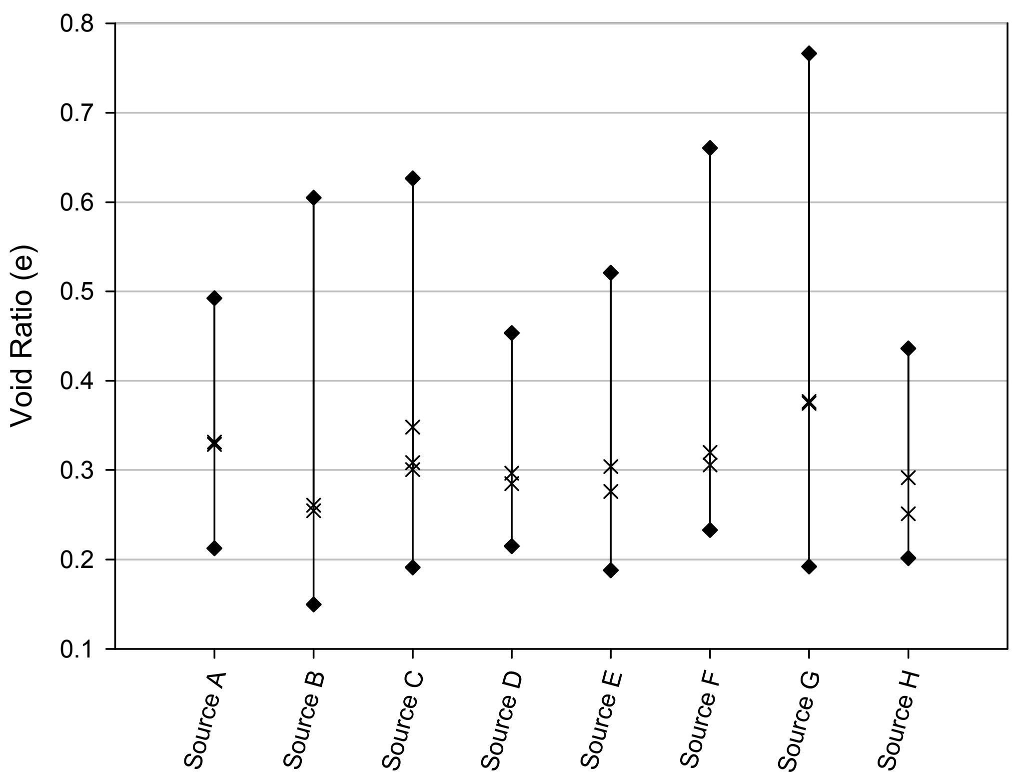


**Figure 22. Densities of permeability samples for Prepared gradations.**

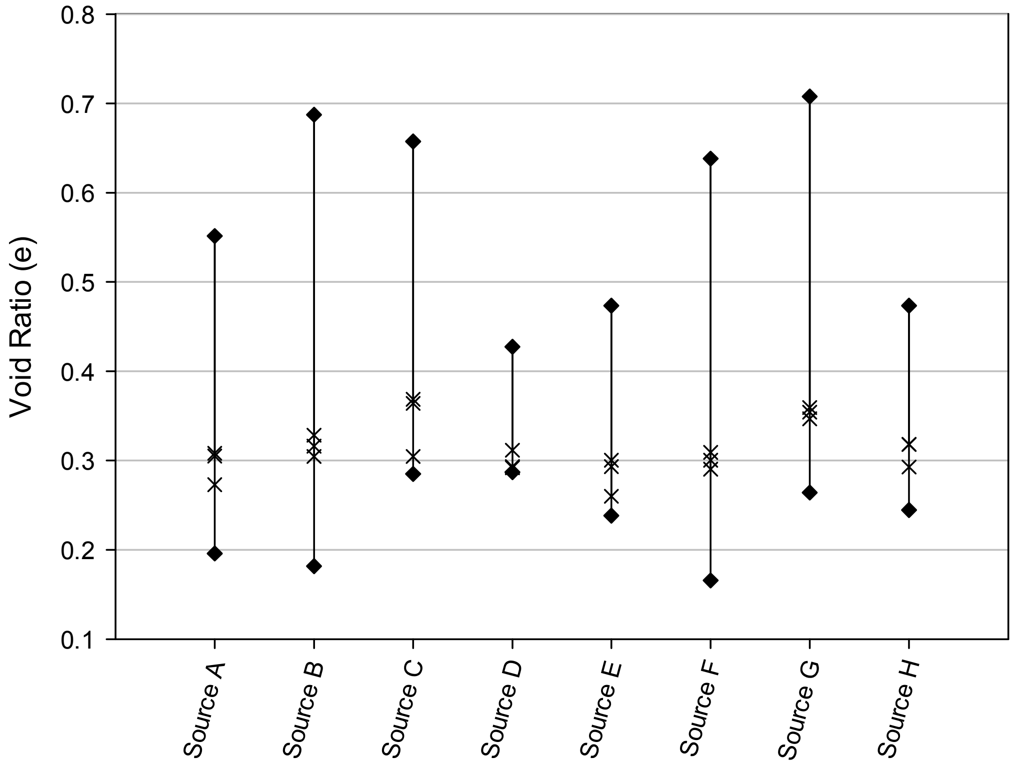


**Figure 23. Densities of permeability samples for Modified gradations.**

Sample preparation consisted of compacting the aggregate in layers in the permeameter mold, placing the screens in the proper orientation, and saturating the sample and apparatus. Approximately 35 to 40 gallons of water were prepared for each test. This included water for filling the tail water container, saturating the sample, and filling the upper reservoir. The use of 100% de-aired water was not practical in this study because of the large quantity of water used in each test. It is postulated that the small amount of entrapped air in the test water would have had only minor influences on the *absolute* results and no influence on the *relative* difference between results because identical procedures were used to prepare each sample.

A small negative pressure (vacuum) was applied to the reservoir tube to draw in head-water and to help saturate the soil specimen. While applying the vacuum through the vacuum port at the top of the reservoir tube, the side port was opened to allow water to fill the upper reservoir. This created a slight negative hydraulic gradient across the sample thereby causing water to be drawn up through the specimen. The vacuum forced entrapped air bubbles out of the sample and consequently enhanced the saturation process. The negative pressure was kept small to avoid washing fines from the specimen into the upper reservoir. Samples were filled under low vacuum at a rate of approximately 0.6 gal/min. This slow filling rate and low vacuum was selected to provide a balance between the removal of air bubbles and the control of fines migration.

Relatively low hydraulic gradients were used on all samples to ensure that the assumptions inherent in Darcy's Law were not violated and to provide consistency between tests. ASTM

D2434 recommends applying gradients of 0.2 to 0.3 ft/ft to coarse grained soils and gradients of 0.3 to 0.5 ft/ft to finer soils. All of the aggregate samples examined in this study were predominately coarse-grained; consequently, a hydraulic gradient of 0.26 ft/ft was used.

## Results

Saturated permeabilities were determined for each aggregate in this study by conducting three or more independent permeability tests (each using virgin aggregates). Permeability results for each test are summarized in Figure 24 and Figure 25 for the Prepared and Modified gradations, respectively. Average results for each source and gradation are summarized in Table 15.

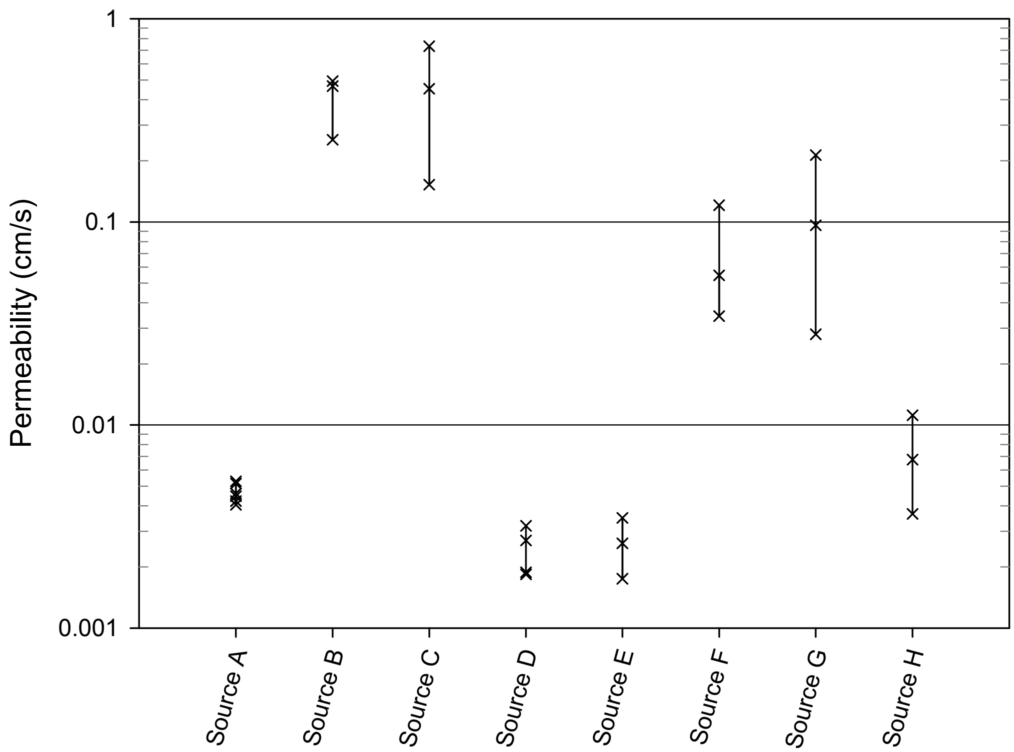


**Figure 24: Permeability results of Prepared gradations.**

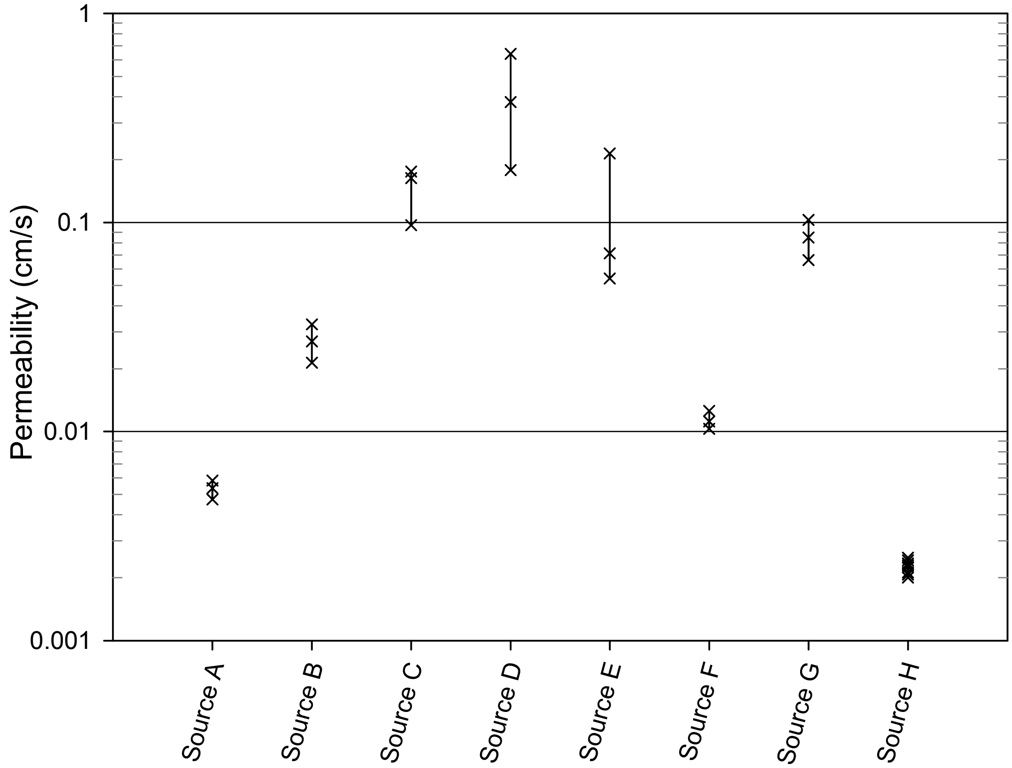


**Figure 25: Permeability results of Modified gradations.**

**Table 15: Summary of Permeability Results**

| | Average Permeability | | | | | |
|---|---|---|---|---|---|---|
| | Prepared | | | Modified | | |
| **Source** | **(cm/s)** | **(ft/hr)** | **Drainage Quality*** | **(cm/s)** | **(ft/hr)** | **Drainage Quality*** |
| A | 0.005 | 0.55 | Fair | 0.005 | 0.63 | Fair |
| B | 0.405 | 47.78 | Excellent | 0.027 | 3.19 | Fair |
| C | 0.446 | 52.72 | Excellent | 0.145 | 17.15 | Good |
| D | 0.002 | 0.28 | Poor | 0.399 | 47.12 | Excellent |
| E | 0.003 | 0.31 | Poor | 0.113 | 13.37 | Good |
| F | 0.070 | 8.26 | Good | 0.011 | 1.34 | Fair |
| G | 0.113 | 13.31 | Good | 0.085 | 10.00 | Good |
| H | 0.007 | 0.85 | Fair | 0.002 | 0.27 | Poor |

* Based on 1993 AASHTO minimum permeability recommendations (AASHTO, 1993):
$k > 41.67$ ft/hr = excellent
$3.54 < k < 41.67$ ft/hr = good
$0.46 < k < 3.54$ ft/hr = fair
$0.02 < k < 0.46$ ft/hr = poor
$0.0008 < k < 0.02$ ft/hr = very poor

## Summary

Crushed aggregates from eight sources were tested to determine their basic characteristics and their engineering properties. The particle size distribution of each of the source aggregates was manipulated to create a ¾-inch minus gradation (if all of the material did not already pass the ¾-inch sieve) – referred to as the Prepared gradation. These gradations were further manipulated to determine the effect gradation had on its properties – referred to as the Modified gradation. The basic characteristics and engineering properties of each of these sources and gradations is summarized in Table 16.

**Table 16: Summary of General Attributes and Engineering Properties of All Aggregates and Gradations**

| | Source A Butte[a] | | Source B Missoula[a] | | Source C Missoula[a] | | Source D Glendive[a] | | Source E Glendive[a] | | Source F Glendive[a] | | Source G Billings[a] | | Source H Great Falls[a] | | Information Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Prep. | Mod. | Prep. | Mod. | Prep. | Mod. | Prep. | Mod. | Prep. | Mod. | Prep. | Mod. | Prep. | Mod. | Prep. | Mod. | |
| **General Attributes** | | | | | | | | | | | | | | | | | |
| AASHTO Classification | A-1-a | A-1-a | A-1-a | A-1-a | A-1-a | A-1-a | A-1-b | A-1-a | A-1-b | A-1-a | A-1-a | A-1-a | A-1-a | A-1-a | A-1-a | A-1-b | Table 5 |
| Gravel (%)[b] | 55 | 64 | 75 | 78 | 88 | 65 | 79 | 61 | 71 | 55 | 57 | 73 | 60 | 75 | 63 | 44 | Table 6 |
| Sand (%)[c] | 40 | 31 | 18 | 15 | 11 | 33 | 18 | 34 | 25 | 40 | 37 | 18 | 30 | 19 | 34 | 51 | Table 6 |
| Fines (%)[d] | 5 | 5 | 7 | 7 | 1 | 2 | 3 | 5 | 4 | 5 | 6 | 9 | 10 | 6 | 3 | 5 | Table 6 |
| Fractured Faces (%) | 29 | 31 | 44 | 47 | 35 | 40 | 33 | 35 | 27 | 25 | 35 | 34 | 36 | 41 | 22 | 25 | Table 8 |
| Specific Gravity | 2.67 | 2.71 | 2.57 | 2.67 | 2.55 | 2.66 | 2.71 | 2.70 | 2.68 | 2.67 | 2.66 | 2.64 | 2.68 | 2.69 | 2.67 | 2.66 | Table 9 |
| **Properties** | | | | | | | | | | | | | | | | | |
| $e_{max}$[e] | 0.49 | 0.55 | 0.60 | 0.69 | 0.63 | 0.66 | 0.45 | 0.43 | 0.52 | 0.47 | 0.66 | 0.64 | 0.77 | 0.71 | 0.44 | 0.47 | Figures 7 & 8 |
| $e_{min}$[f] | 0.21 | 0.20 | 0.15 | 0.18 | 0.19 | 0.28 | 0.22 | 0.29 | 0.19 | 0.24 | 0.23 | 0.17 | 0.19 | 0.26 | 0.20 | 0.24 | Figures 7 & 8 |
| Modified Proctor Density ($e$) | 0.25 | 0.27 | 0.13 | 0.20 | 0.25 | 0.31 | 0.26 | 0.27 | 0.21 | 0.20 | 0.16 | 0.19 | 0.19 | 0.24 | 0.22 | 0.26 | Figures 9 & 10 |
| Modified Proctor $\gamma_{d,max}$ (pcf) | 133.6 | 133.5 | 142.5 | 138.5 | 127.2 | 126.1 | 134.4 | 132.3 | 137.9 | 138.4 | 142.8 | 138.8 | 140.5 | 135.6 | 136.8 | 131.7 | Table 10 |
| Modified Proctor $w_{opt}$ (%) | 4.9 | 4.7 | 3.3 | 5.1 | 2.2 | 3.3 | 3.5 | 6.2 | 6.9 | 7.4 | 4.3 | 5.3 | 6.9 | 5.3 | 6.3 | 8.0 | Table 10 |
| R-Value | 72 | 76 | 80 | 78 | 77 | 73 | 78 | 74 | 74 | 71 | 63 | 77 | 70 | 76 | 75 | 74 | Table 11 |
| Initial Stiffness, $k_i$ @ 10 psi (kip/in) | 12.5 | 14.2 | 14.4 | 21.7 | 16.7 | 20.1 | 23.5 | 20.9 | 10.7 | 20.7 | 13.2 | 22.5 | 18.3 | 20.1 | 18.4 | 10.3 | Figures 14 & 15 |
| Secant Stiffness, $k_u$ @ 10 psi (kip/in) | 0.95 | 2.84 | 3.82 | 2.22 | 2.40 | 1.84 | 1.88 | 3.51 | 2.57 | 2.51 | 3.46 | 1.50 | 3.24 | 2.61 | 1.99 | 1.23 | Figures 16 & 17 |
| Ultimate Stength, $\sigma_u$ @ 10 psi (psi) | 6.35 | 18.94 | 25.46 | 14.79 | 15.98 | 12.25 | 12.57 | 23.37 | 17.12 | 16.72 | 23.08 | 10.03 | 21.57 | 17.41 | 13.30 | 8.19 | Figures 18 & 19 |
| Friction Angle (deg) | 35 | 59 | 71 | 58 | 59 | 56 | 60 | 67 | 56 | 59 | 65 | 40 | 62 | 61 | 53 | 37 | Table 12 |
| Permeability (ft/hr)[g] | 0.55 | 0.63 | 47.78 | 3.19 | 52.72 | 17.15 | 0.28 | 47.12 | 0.31 | 13.37 | 8.26 | 1.34 | 13.31 | 10.00 | 0.85 | 0.27 | Table 13 |

[a] Montana DOT district
[b] Percent retained above the #10 sieve
[c] Percent retained between the #10 and #200 sieves
[d] Percent passing the #200 sieve
[e] Based on dry relative density tests
[f] Based on wet relative density tests
[g] Average of all permeability tests performed
N/A = not applicable

# DATA ANALYSIS AND RESULTS

The primary goals of this project were to 1) determine whether aggregates whose maximum particle size was ¾ inch would perform at least as good as Montana's current 5A and/or 6A crushed aggregate base course materials, and 2) determine the effect changes in the gradation had within the specified limits. The first goal was accomplished through multiple laboratory tests to characterize the material properties of the ¾-inch minus mixes from around Montana, and comparing that data to the results from laboratory tests conducted on CBC-6A and CBC-5A materials (Mokwa et al., 2007). The second goal was accomplished by qualitatively analyzing the performance data from a finer and coarser gradations for each of the eight Montana sources. The results from this analysis were used to suggest a viable ¾-inch minus gradation specification for crushed base course materials for the state of Montana.

## Statistical Analysis

The results of strength, stiffness and permeability tests conducted on the eight ¾-inch minus mixes from Montana were compared to the results from laboratory tests previously conducted on CBC-6A and CBC-5A materials (Mokwa et al., 2007). Statistical analyses of average values based were conducted using a two-sided t-test (for samples having unequal variance) to determine if apparent trends in measured laboratory test results represent true differences between aggregate types. The two-sample t-test is a statistical test used to determine if the averages of the two data sets are statistically different from one another based on a mathematical evaluation of the data scatter. In cases where the averages are statistically different, a direct comparison of the mean values indicates which values is greater. Otherwise, the means are considered statistically equal.

The output from this analysis is a parameter called a p-value. In this report, the p-value ranges from 0.500 to 1.000 (based on the one-tailed distribution). Although not typically shown this way, the p-values can be used to determine how two averages compare to one another. P-values closer to 0.500 indicate that the means are statistically more similar to one another and p-values closer to 1.000 indicate the means are statistically more different from one another. For the purposes of comparison, and taking into account the relatively variability typical observed in geotechnical test data, a p-value greater than 0.850 was selected to indicate that the two means were statistically different from one another, while p-values between 0.500 and 0.850 indicated that the means were statistically the same.

There are great number of comparisons that are possible to compare the performance of the ¾-inch minus materials to the 6A and 5A materials characterized in Mokwa et al. (2007); therefore, the number of these comparisons was limited to those most important to base course applications – strength, stiffness, and drainage. Material properties determined during this study related to these characteristics are R-value, friction angle, secant stiffness, initial stiffness and permeability. Comparisons were accomplished by grouping the data into meaningful data sets. The first comparisons were centered on data sets grouped by material type. The four different types of materials were 6A materials from Mokwa et al. (2007), 5A materials from Mokwa et al. (2007), ¾-inch minus Prepared materials, and ¾-inch minus Modified materials. However, because the Modified gradations were simply variations of the ¾-inch minus mixes, there was really no compelling reason to separate them from one another. Therefore, a single ¾-inch minus data set was used. In addition, a combined the 6A and 5A data set was also used in the analysis. The combined mean values associated with each of these data sets are listed in Table 17.

**Table 17: Combined Mean Values for General Comparisons**

| Performance Parameter | Combined Mean Values | | | |
|---|---|---|---|---|
| | 6A | 5A | 6A&5A | ¾-Inch |
| **R-value** | 74.5 | 72.0 | 73.7 | 74.1 |
| **Friction angle** | 58.9 | 56.3 | 58.0 | 56.1 |
| **$k_u$ @ 10 psi** | 2.71 | 2.08 | 2.50 | 2.41 |
| **$k_i$ @ 10 psi** | 21.23 | 14.59 | 19.02 | 17.39 |
| **Permeability (ft/hr)** | 11.2 | 1.5 | 7.9 | 11.5 |

The results of the various comparisons between these data sets are listed in Table 18. In general, it was observed that the ¾-inch minus materials are relatively similar in performance to the 6A materials, with the exception that the initial stiffness is slightly greater in the 6A materials. There are no statistically significant differences in the R-value or friction angle between any of the materials. The ¾-inch minus materials performed better than the 5A materials (similar to the 6A materials).

**Table 18: T-Statistic Results for General Comparisons**

| Performance Parameter | Comparison | | | |
|---|---|---|---|---|
| | 6A vs. 5A | ¾-Inch vs. 6A | ¾-Inch vs. 5A | ¾-Inch vs. 6A&5A |
| **R-value** | 0.742 | 0.557 | 0.748 | 0.577 |
| **Friction angle** | 0.792 | 0.791 | 0.531 | 0.738 |
| **$k_u$ @ 10 psi** | **0.976** | 0.849 | **0.876** | 0.632 |
| **$k_i$ @ 10 psi** | **0.990** | **0.986** | **0.903** | 0.815 |
| **Permeability (ft/hr)** | **0.986** | 0.527 | **1.000** | 0.821 |

An attempt was also made to determine the effect that modifying the gradation within the acceptable limits of the ¾-inch minus specified range had on its material properties. In this case, materials that were finer were compared to materials that were coarser. The percent of gravel was used as a means of separating the data sets into groups. A threshold of 70 percent gravel (defined as materials retained above the #10 sieve) was used to delineate between coarser and finer materials, with materials having greater than 70 percent gravel being coarser and with materials having less than 70 percent gravel being finer. Each of the broader groups of data (6A and 5A materials from Mokwa et al. (2007) and the ¾-inch minus materials) were split into these two categories based on this criteria. The few number of data points prevented further parsing of the data beyond the following four categories: 6A & 5A – coarser (6/5-C), 6A & 5A – finer (6/5-F), ¾-in minus – coarser (3/4-C), and ¾-inch minus – finer (3/4-F). For the purposes of this comparison, 6A and 5A were also combined into a single data set, mainly because there was not enough data to facilitate meaningful statistical comparisons if parsed too small. Two additional data sets were created by combining all of the coarser materials and finer materials, All-C and All-F, respectively. Combined mean values for each category are listed in Table 19. The two-sample t-test described above was used to compare the means from these data sets. The results of the statistical comparisons are summarized in Table 20. Bold numbers highlight values greater than 0.850 indicating a statistically relevant difference between the two means.

**Table 19: Combined Mean Values for Comparisons Based on Percent of Gravel**

| Performance Parameter | Combined Mean Values | | | | | |
|---|---|---|---|---|---|---|
| | **6/5-C** | **6/5-F** | **3/4-C** | **3/4-F** | **All-C** | **All-F** |
| **R-value** | 74.6 | 72.5 | 76.9 | 71.9 | 76.0 | 72.1 |
| **Friction angle** | 60.0 | 55.5 | 58.0 | 54.6 | 58.8 | 54.9 |
| **$k_u$ @ 10 psi** | 2.79 | 2.14 | 2.43 | 2.40 | 2.58 | 2.32 |
| **$k_i$ @ 10 psi** | 20.79 | 16.79 | 18.54 | 16.50 | 19.48 | 17.73 |
| **Permeability (ft/hr)** | 13.5 | 1.0 | 15.8 | 8.8 | 14.9 | 6.8 |

**Table 20: T-Statistic Results for Comparisons Based on Percent of Gravel**

| Performance Parameter | Comparison | | | | | | |
|---|---|---|---|---|---|---|---|
| | **6/5-C vs. 6/5-F** | **6/5-C vs. 3/4-C** | **6/5-C vs. 3/4-F** | **6/5-F vs. 3/4-C** | **6/5-F vs. 3/4-F** | **3/4-C vs. 3/4-F** | **All-C vs. All-F** |
| **R-value** | 0.706 | 0.745 | 0.769 | **0.955** | 0.604 | **0.997** | **0.984** |
| **Friction angle** | **0.926** | 0.687 | **0.879** | 0.731 | 0.585 | 0.739 | **0.871** |
| **$k_u$ @ 10 psi** | **0.979** | 0.835 | 0.837 | 0.816 | 0.765 | 0.531 | 0.815 |
| **$k_i$ @ 10 psi** | **0.905** | 0.820 | **0.970** | 0.721 | 0.544 | 0.812 | 0.844 |
| **Permeability (ft/hr)** | **0.992** | 0.625 | 0.812 | **0.995** | **0.997** | **0.878** | **0.972** |

Referring to Table 20, several statistically relevant differences are apparent. Perhaps most notably, the comparison between the coarser and finer 6A & 5A materials showed that mean friction angle, secant stiffness and initial stiffness, and permeability were all statistically greater in the coarser 6A & 5A materials (referring to far left column in Table 20). Likewise, the R-value, friction angle, and permeability were greater in the coarser materials in general (referring to far left column in Table 20). Other relevant comparisons showed that R-value and permeability were greater in the coarse ¾-inch minus material when compared to the finer 6A & 5A material. Also, the permeability in the finer ¾-inch minus material is greater than the finer 6A & 5A material. Lastly, the performance of the coarser ¾-inch minus material is generally similar to the coarser 6A & 5A material (refer to column second from the left in Table 20).

## Qualitative Analysis

As described earlier in the report, two gravel mixes were prepared for each of the eight Montana gravel sources by crushing materials greater than ¾-in. and adding them back into the mixture (Prepared mix), then modifying the gradation by removing and/or adding certain sized particles (Modified mix). These manipulations either made the gradations finer or coarser depending on the quantity and size of materials added or removed. While the degree of coarseness or fineness is somewhat arbitrary, for the purposes of this analysis, the area under the gradation curve was used as the means to quantitatively determine how much finer or coarser the Modified mixes were in comparison to the Prepared mix. Gradations with greater area were finer and those with lower areas were coarser. The amount of change in either direction was the most important outcome, and was expressed as a percent change. Differences in the material properties of finer or coarser mixes from each source were compared using the laboratory test data summarized in Table 16. Changes in the individual properties between the Prepared mixes to the Modified mixes were also expressed in terms of percent change. The results of this analysis are summarized in Table 21.

**Table 21: Percent Change in Material Properties as a Result in Changes in Gradation**

| **Property** | **Aggregate Source** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** |
| **Gradation change** | 7% coarser | 27% finer | 61% finer | 15% coarser | 12% coarser | 20% finer | 13% coarser | 24% finer |
| **R-value** | 6% | -2% | -6% | -4% | -4% | 22% | 9% | 0% |
| **Friction angle** | 66% | -18% | -6% | 11% | 4% | -38% | -1% | -30% |
| **$k_u$ @ 10 psi** | 198% | -42% | -23% | 86% | -2% | -57% | -19% | -38% |
| **$k_i$ @ 10 psi** | 13% | 51% | 20% | -11% | 92% | 71% | 10% | -44% |
| **Permeability** | 15% | -93% | -67% | 16490% | 4227% | -84% | -25% | -69% |

Referring to Table 21, each source was qualitatively evaluated to determine overall the effect was from adjusting the gradation finer or coarser for each source, the results of which are provided in the subsections below. Overall, making the mixes finer generally caused a decrease in the friction angle, secant strength and permeability. Materials that had a significant increase in fines showed the greatest decrease in permeability. These results indicate that the upper bound of the gradation is most critical. It is therefore recommended that the upper bound of finer materials be decreased to ensure that the permeability of these materials is not negatively affected. The effective diameter (i.e., the diameter of the particle size associated with 10 percent passing, or $D_{10}$) has been shown to influences the permeability of sands and gravels (Chapuis, 2004); however, the $D_{10}$ of the Source D and Source E materials showed only a modest change between the Prepared and Modified mixes. It was also noticed that the amount passing the #40 sieve in these two mixes greatly decreased, which may have also contributed to the improvement in permeability. Specifically, gradations with greater amounts passing the #40 sieve had significantly lower permeability (i.e., Source A-Prep, Source A-Mod, Source D-Prep, Source E-Prep, and Source H-Mod).

Source A – Butte District, Belgrade, MT

- Modification made the gradation only slightly coarser, and remained near the middle of the specified range.
- Only modest increase in R-value.
- Large increase in friction angle, perhaps mostly from the decrease in material passing the #4 sieve, as well as a large increase in $k_u$
- Moderate increase in $k_i$ and permeability.

Source B – Missoula District, Kalispell, MT

- Prepared mix was slightly coarser than specified range, and the modification brought the gradation within the specified range.
- Change seemed to negatively affect the strength properties (mostly $\phi$ and $k_u$) and permeability.

Source C – Missoula District, Hamilton, MT

- Prepared mix was much coarser than specified range, and the modification brought the coarser part of the gradation within the specified range. There was not enough raw material to bring the lower end of the gradation into range.
- Modification seemed to negatively affect the strength properties (R-value, $\phi$, and $k_u$) and permeability.

Source D – Glendive District, Forsyth, MT

- Modification to the gradation was more pronounced in the lower end of the gradation curve (i.e., in the finer materials).
- Only slight changes overall to the strength properties, other than the $k_u$, which was significantly greater.
- Permeability was dramatically improved from the change in the gradation, going from poor drainage to excellent. This is not surprising given that the finer materials have the greatest effect on water flow.

Source E – Glendive District, Glendive, MT

- Modification to the gradation made it coarser, mostly on the lower end (i.e., finer materials), similar to Source D.
- Also, similar to Source D, there was only slight differences in strength properties, other than $k_i$, which was significantly greater.
- Permeability was also considerably improved due to this modification.

Source F – Glendive District, Miles City, MT

- Modification to the gradation shifted it more toward the center of the specified range making it finer, but most of the change was on the upper end (i.e., coarser materials).
- Significant increase in the R-value, but large decrease in $\phi$ and $k_u$.
- Permeability was decreased due to the addition of finer materials.

Source G – Billings District, Lewistown, MT

- Modification to the gradation shifted it from the center of the specified range to the lower bound, making it coarser.
- This change had a relatively minor influence on the strength, stiffness and drainage properties of this aggregate mix.

Source H – Great Falls District, Fort Benton, MT

- Modification to the gradation resulted in a finer mix.
- This negatively affected the strength and stiffness of the material (lowering $\phi$, $k_i$, and $k_u$), as well as the permeability.

## MONTANA ¾-INCH MINUS SPECIFICATION

The purpose of this project was to determine whether crushed base course materials that had a maximum particle size of ¾-in. would perform at least as well as current CBC-6A and CBC-5A base course materials, and if so, establish the boundaries of a specification for these materials. The analysis conducted during this project showed that, overall, ¾-inch minus base course materials work at least as well as Montana CBC-6A and better than Montana CBC-5A materials. It also showed that ¾-inch minus materials within the preliminary specified range performed better near the bottom of the range (i.e., coarser materials) than finer materials. The specification used in the Glendive district is similar to the Colorado specification (used as the preliminary specification in this project), as illustrated in Figure 26. For the most part, the performance characteristics were acceptable for the ¾-inch minus materials tested. Notable exceptions included Source A and Source H, and to a lesser extent Source D-Prep, Source E-Prep and Source F-Mod. Sources A and H had lower friction angles, stiffnesses, and poor permeability. Sources D-Prep and E-Prep had poor drainage, and Source F-Mod had lower strengths and relatively low permeability.

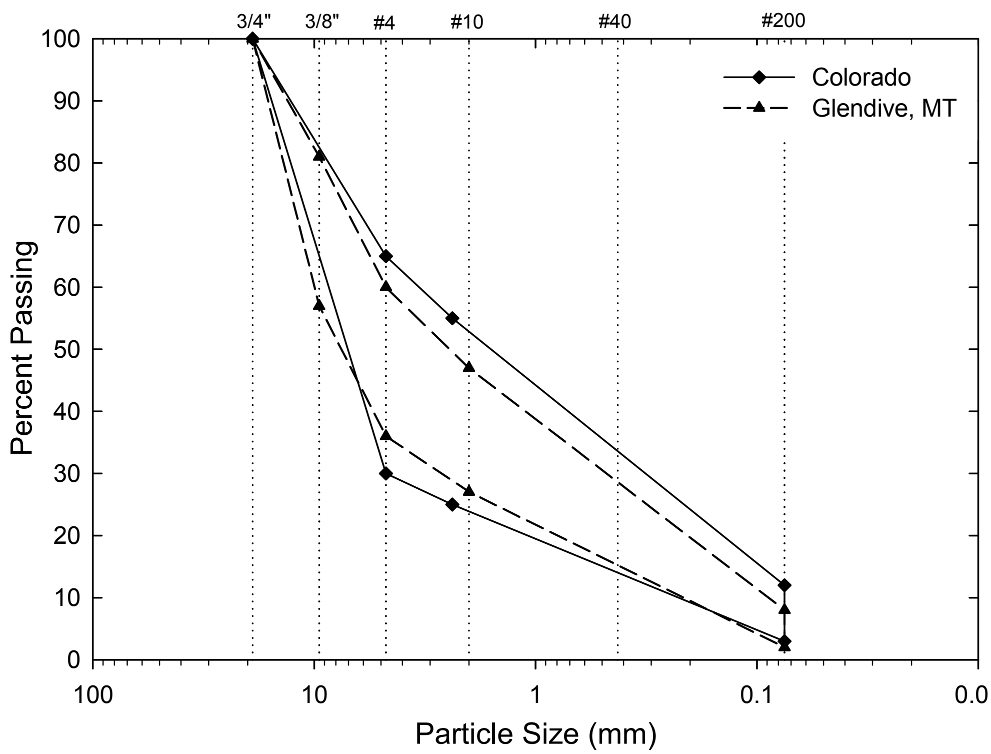


**Figure 26: ¾-inch minus specifications for Colorado and Glendive, MT.**

Based on the results of this project, it is recommended that a modified version of the Glendive specification be adopted as a viable ¾-inch minus base course specification within the state of Montana. This modification is mainly to reduce the allowable amount passing the #40 sieve to ensure good drainage in the base materials. The suggested specification as it might read in the Montana Standard Specifications, Section 701.02.4 – Crushed Base Course Type "A", is shown below, where the ¾-inch minus specification is designated as Grade 7A. The final gradation bounds of this suggested gradation are shown in Figure 27, as compared to the Montana 6A and 5A materials. No changes are suggested to the plasticity, wear factor, and fractured face requirements, as they seems to fall in line with what other states are doing and were not determined to have a significant impact on the strength, stiffness and permeability properties for the ranges of these properties tested. If it is believed that the lower bound of the ⅜-in. and #4 specification for the Montana 6A materials is the reason that they performed better than the 5A materials then it is also suggested that the lower bound of the new 7A material be lowered to accept coarser materials. The practicality and constructability of producing mixes that fit within these suggested bounds needs to be established.

**701.02.4 Crushed Base Course Type "A"**

Furnish crushed base course Type "A", including added binder or blending material in accordance with Table 701-8. Glass cullet meeting Subsection 701.11 requirements may be used as blending material.

**TABLE 701-8**
**TABLE OF GRADATIONS – CRUSHED BASE COURSE TYPE "A"**

| Percentage By Weight Passing Square Mesh Sieves | | | |
|---|---|---|---|
| **Sieve Size** | **Grade 5A** | **Grade 6A** | **Grade 7A** |
| 2-inch (50 mm) | 100 | | |
| 1½-inch (37.5 mm) | 94-100 | 100 | |
| ¾-inch (19.0 mm) | 70-88 | 74-96 | 100 |
| ⅜-inch (9.5 mm) | 50-70 | 40-76 | 57-81 |
| No. 4 (4.75 mm) | 34-58 | 24-60 | 36-60 |
| No. 40 (0.425 mm) | 6-30 | 6-34 | 6-25 |
| No. 200 (0.075 mm) | 0-8 | 0-8 | 2-8 |

Meet the following requirements for crushed base course Type "A":

1. For material passing the No. 40 (0.425 mm) sieve, the liquid limit must not exceed 25, and the plasticity index must not exceed 6;
2. Dust ratio limitations do not apply;
3. A wear factor not exceeding 50% at 500 revolutions;
4. Furnish binder meeting Subsection 301.02.2 requirements; and
5. At least 35% by weight of the aggregate retained on the No. 4 (4.75mm) sieve has at least one mechanically fractured face.

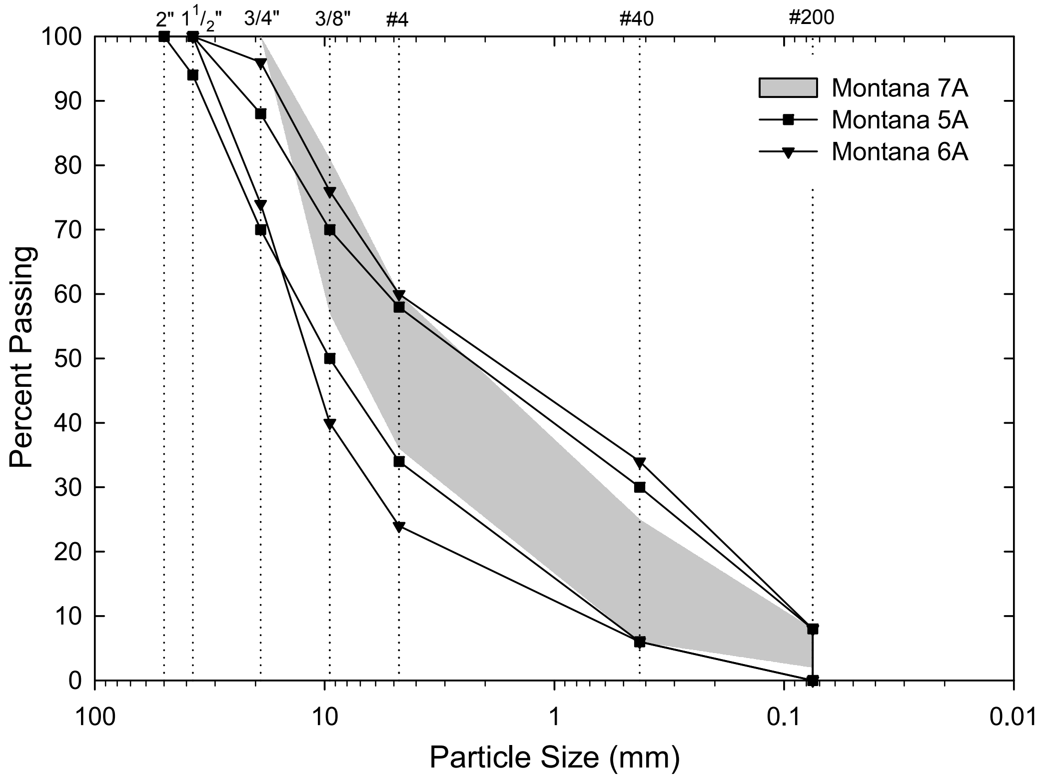


**Figure 27: Final suggested ¾-inch minus specifications (MT 7A) as compared to MT 6A and 5A.**

# SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Gravel bases are a critical component of roads, providing drainage, structural support, and load distribution. Montana specifications currently allow 2-inch minus (Grade 5A) and 1½-inch minus (Grade 6A) crushed base course materials (Section 701.02.4); however, gravel sources in Montana are becoming limited, particularly in the eastern regions of the state, making the option to use a ¾-inch gravel base desirable. The objective of the proposed project was to develop a standard specification for a new gravel base course with nominal maximum aggregate size of ¾ in. The first step in this investigation was to review other state and federal standard specifications to document existing ¾-inch minus base course specifications. Information from that review helped identify a starting point from which to develop a standard specification for Montana crushed aggregate courses. A ¾-inch minus specification from the state of Colorado was used as a preliminary specification in order to produce ¾-inch minus mixes with Montana aggregates for testing purposes.

The most important engineering characteristics of any base course aggregate are strength, stiffness, and drainage capacity. Therefore, the second step in this investigation was to test a variety of crushed aggregates from several ¾-inch minus gradations from various sources throughout Montana to determine their general properties and performance characteristics. Material properties were quantified by synthesizing and analyzing results from the following laboratory tests: geotechnical index tests (particle size distribution, fractured face count, modified Proctor density, relative density, and specific gravity), direct shear, R-value, and permeability.

Data from these tests were compared to existing performance data from crushed base course mixes CBC-6A and CBC-5A documented by the Western Transportation Institute (Mokwa et al., 2007). A two-sided t-test was used to determine whether the averages of the two data sets were statistically different from one another based on a mathematical evaluation of the data scatter. When the performance characteristics of the ¾-inch minus materials were compared to those of the 6A and 5A materials, the following conclusions were made.

- The ¾-inch minus materials perform similarly to the CBC-6A materials, with the exception that the initial stiffness is slightly greater in the 6A materials.
- Similar to the 6A materials, the ¾-inch minus materials performed better than the 5A materials.
- There were no statistically significant differences in the R-value or friction angle between any of the materials.

A second analysis was conducted to evaluate the effect that modifying the gradation had on the performance of the ¾-inch minus gravel. A threshold of 70 percent gravel was used to delineate between coarser and finer materials, with materials having greater than 70 percent gravel being coarser and with materials having less than 70 percent gravel being finer. The following general conclusions were made based on statistical comparisons of these data sets.

- The mean friction angle, secant stiffness and initial stiffness, and permeability were all statistically greater in the coarser 6A & 5A materials when compared to the finer 6A & 5A materials.
- The R-value, friction angle, and permeability were greater in the coarser materials in general when compared to the finer materials.
- The R-value and permeability were greater in the coarser ¾-inch minus materials when compared to the finer 6A & 5A materials.
- The permeability in the finer ¾-inch minus materials are greater than the finer 6A & 5A materials.
- The performance of the coarser ¾-inch minus materials are generally similar to the coarser 6A & 5A materials.

A qualitative analysis was also performed to determine the effect that modifying the mixes by making them either finer or coarser had on their material properties. The following conclusions were drawn from this analysis.

- Overall, making the mixes finer caused a decrease in the friction angle, secant strength and permeability.
- Materials that had a significant increase in fines showed the greatest decrease in permeability.
- Specifically, gradations with greater amounts passing the #40 sieve had significantly lower permeability (i.e., Source A-Prep, Source A-Mod, Source D-Prep, Source E-Prep, and Source H-Mod).

Based on the results of this project, it is recommended that a modified version of the Glendive specification be adopted as a viable ¾-inch minus base course specification within the state of Montana, now known as Montana CBC-7A. This modification is mainly to reduce the allowable amount passing the #40 sieve to ensure good drainage in the base materials. No changes are suggested to the plasticity, wear factor, and fractured face requirements, as they seems to fall in line with what other states are doing and were not determined to have a significant impact on the strength, stiffness and permeability properties for the ranges of these properties tested. If it is believed that the lower bound of the ⅜-in. and #4 specification for the Montana 6A materials is the reason that they performed better than the 5A materials then it is also suggested that the lower bound of the new 7A material be lowered to accept coarser materials. The practicality and constructability of producing mixes that fit within these suggested bounds needs to be determined.

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# Appendix A – Photos of Aggregate Materials and Gradations

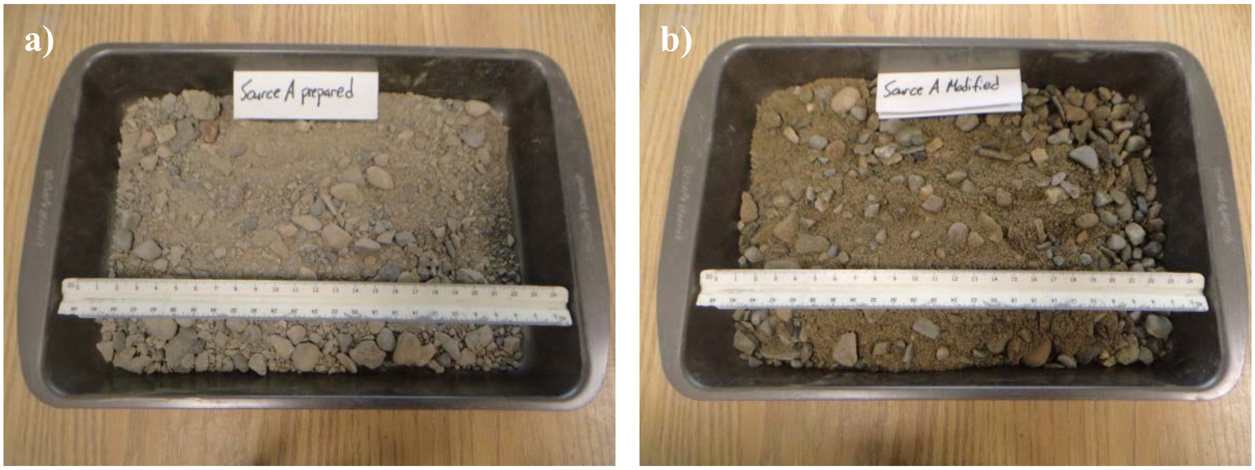



**Figure A-1: Photo of Source A a) Prepared gradation and b) Modified gradation.**

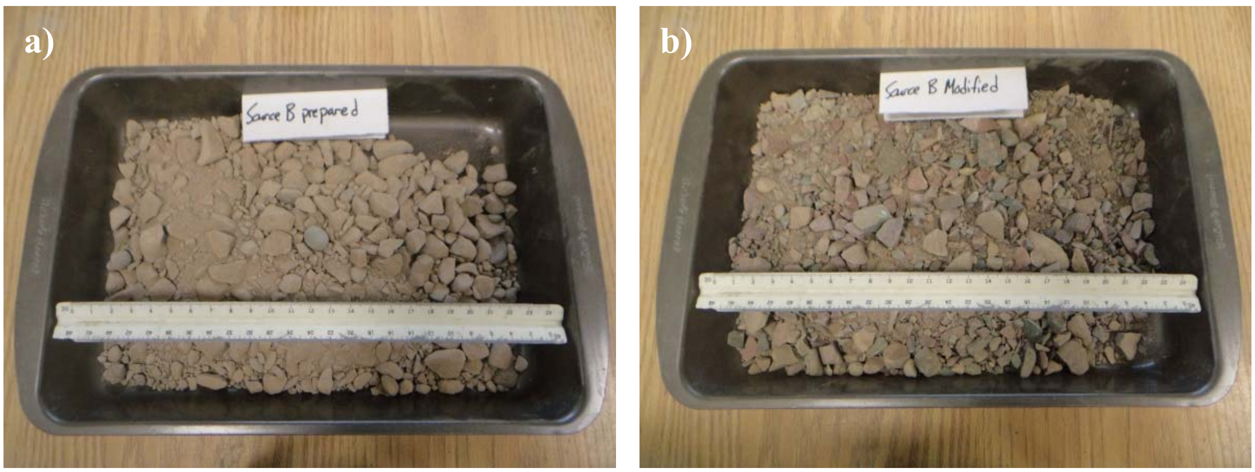



**Figure A-2: Photo of Source B a) Prepared gradation and b) Modified gradation.**

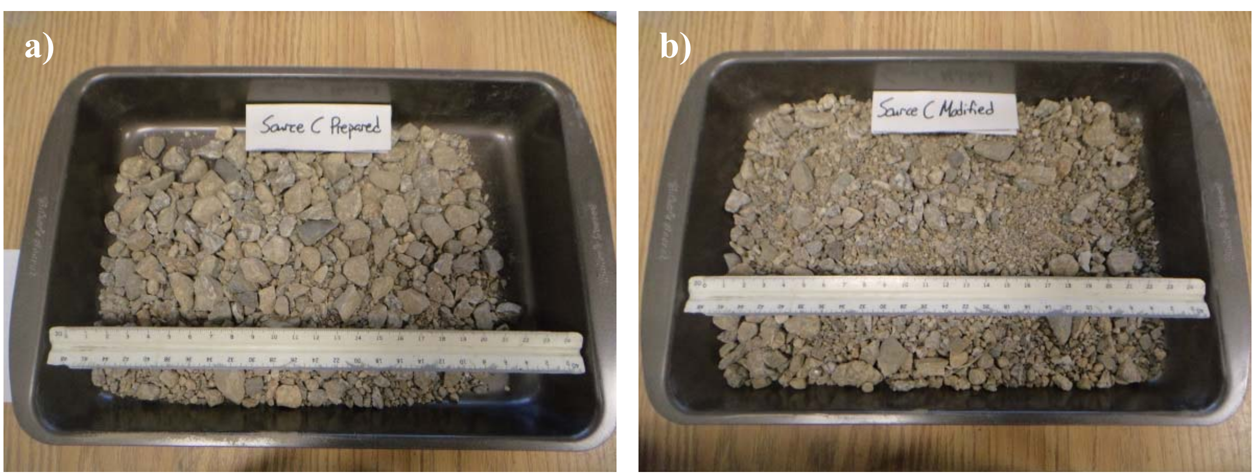



**Figure A-3: Photo of Source C a) Prepared gradation and b) Modified gradation.**

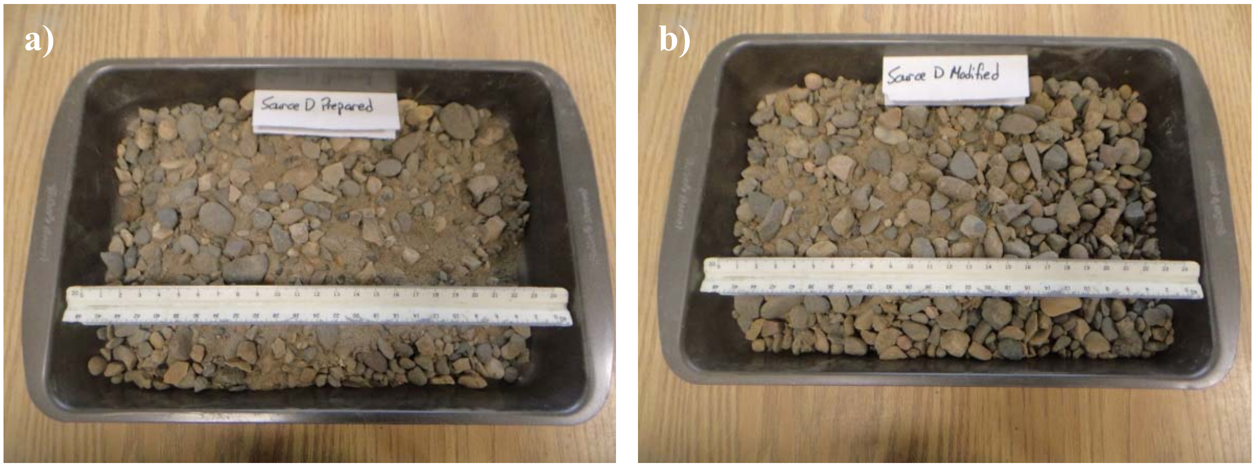



**Figure A-4: Photo of Source D a) Prepared gradation and b) Modified gradation.**

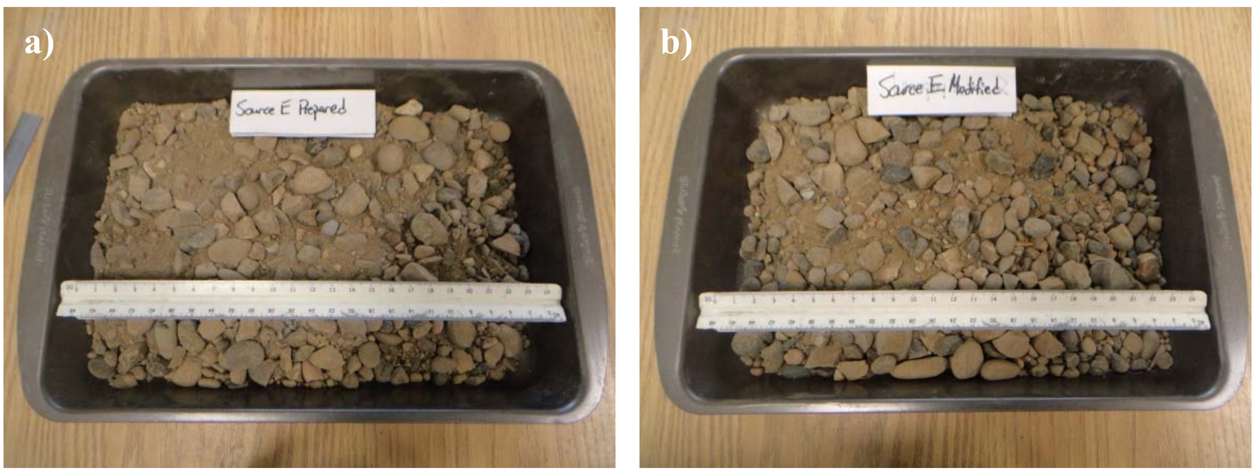



**Figure A-5: Photo of Source E a) Prepared gradation and b) Modified gradation.**

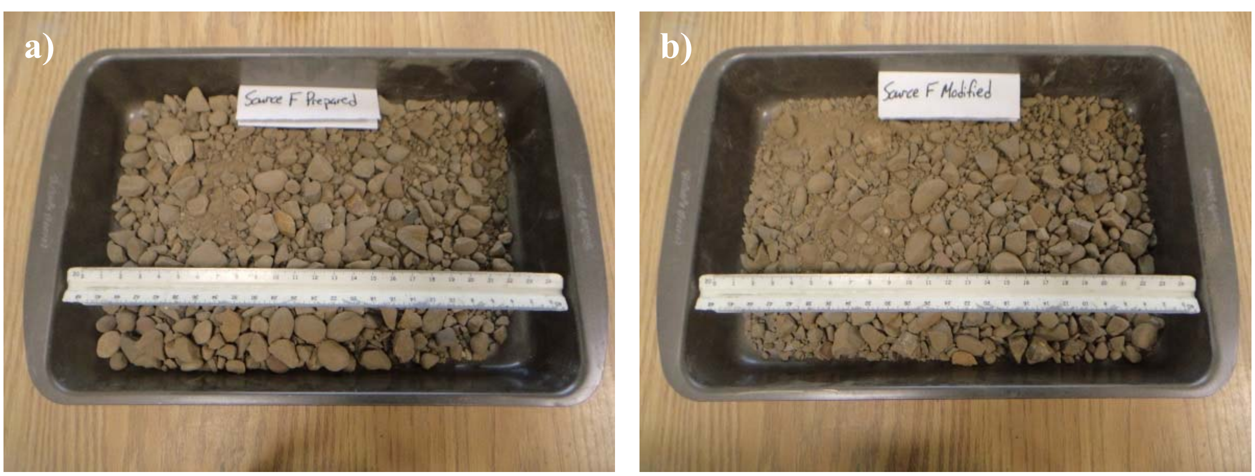



**Figure A-6: Photo of Source F a) Prepared gradation and b) Modified gradation.**

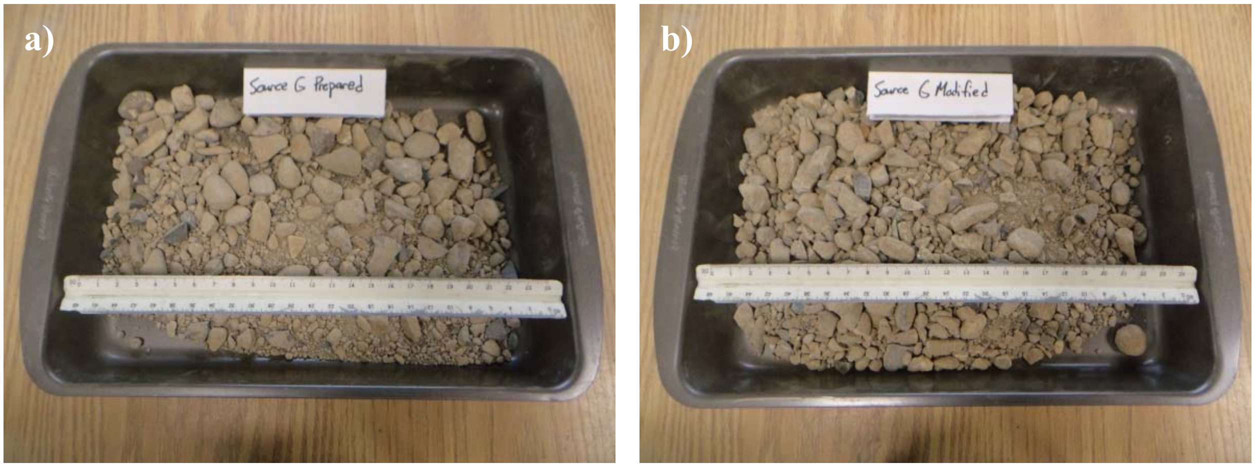



**Figure A-7: Photo of Source G a) Prepared gradation and b) Modified gradation.**

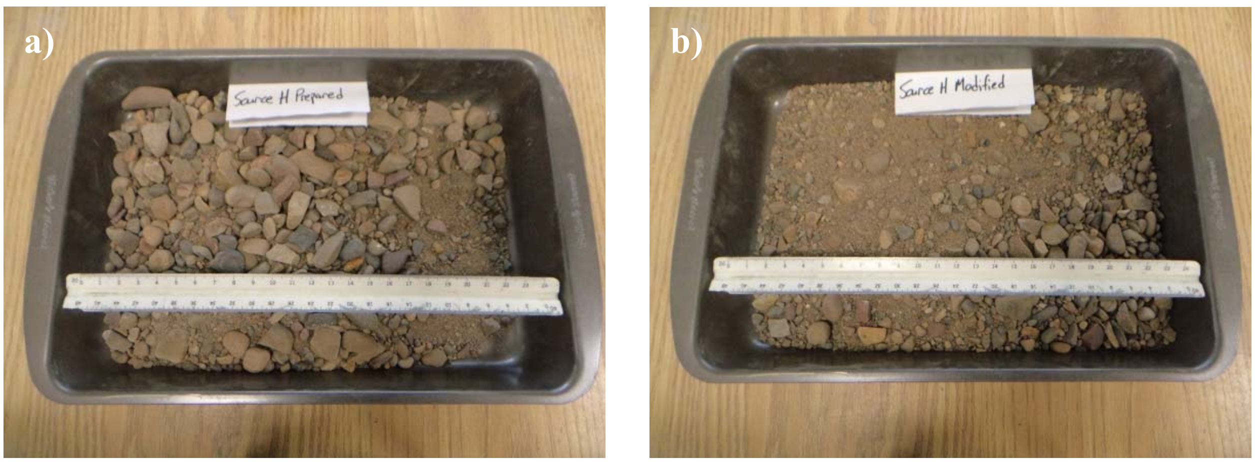



**Figure A-8: Photo of Source H a) Prepared gradation and b) Modified gradation.**

# Appendix B – Grain-Size Distribution Plots

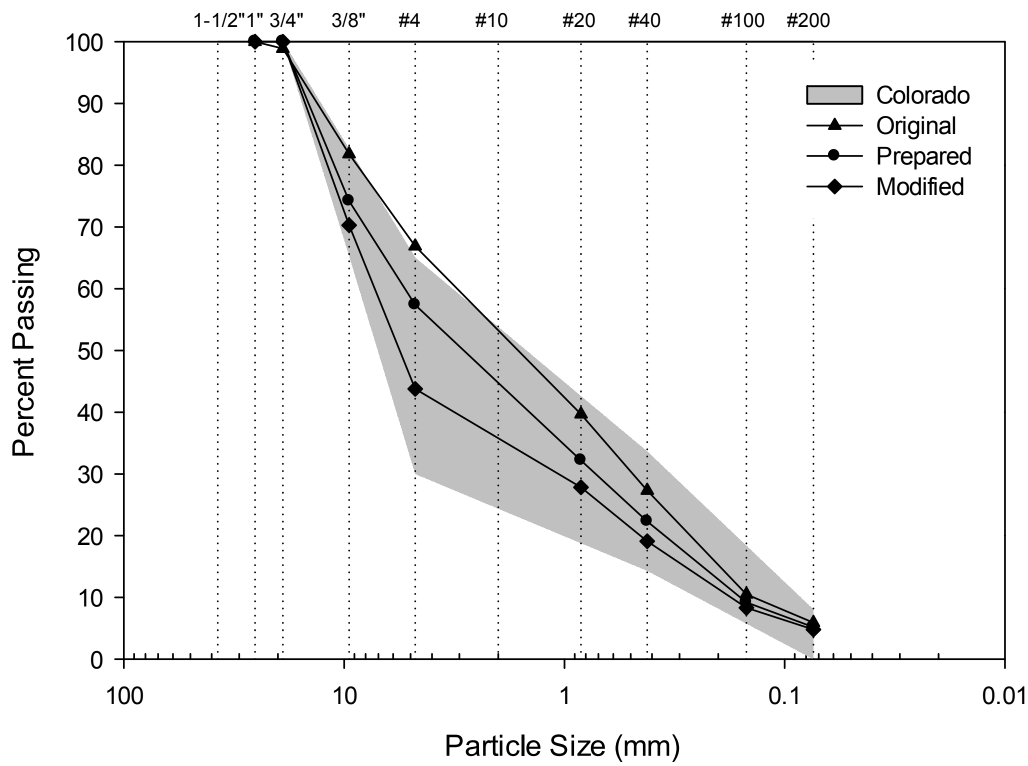



**Figure B-1: Grain-size distribution of Source A gradations compared to Colorado specification.**

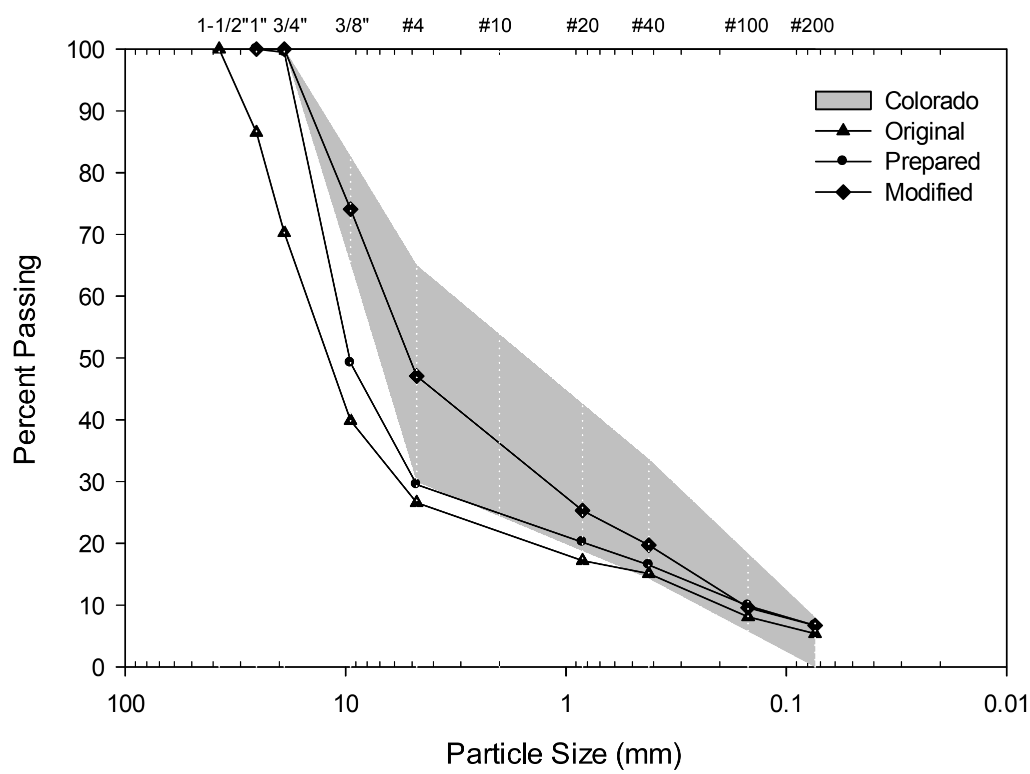



**Figure B-2: Grain-size distribution of Source B gradations compared to Colorado specification.**

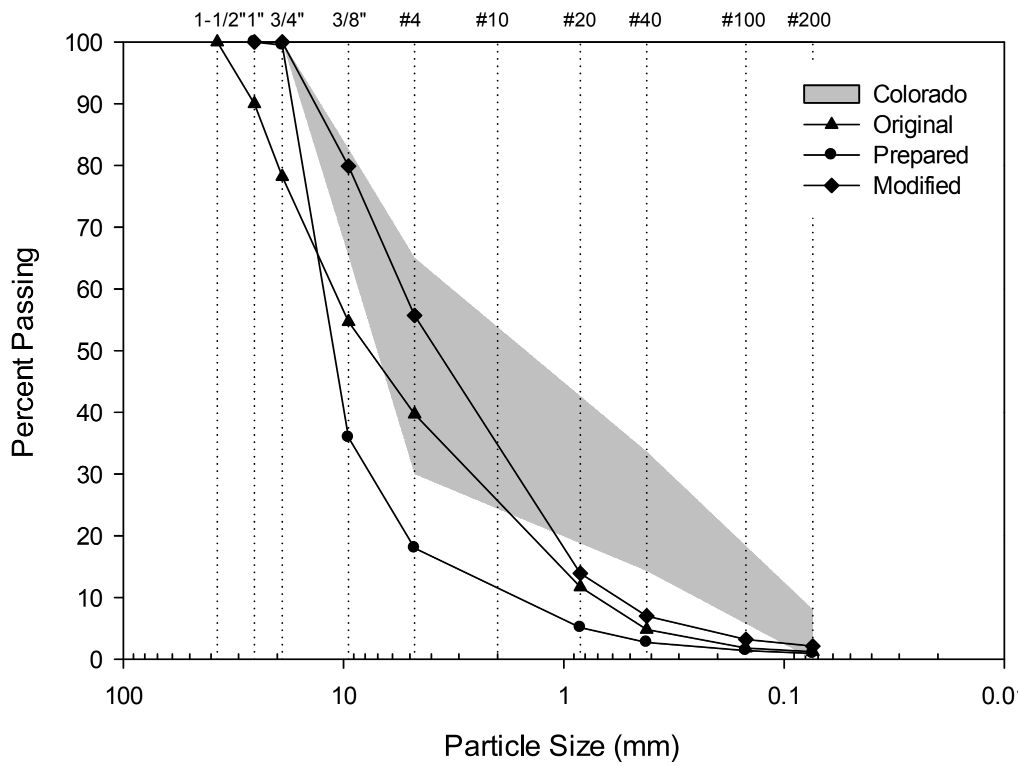



**Figure B-3: Grain-size distribution of Source C gradations compared to Colorado specification.**

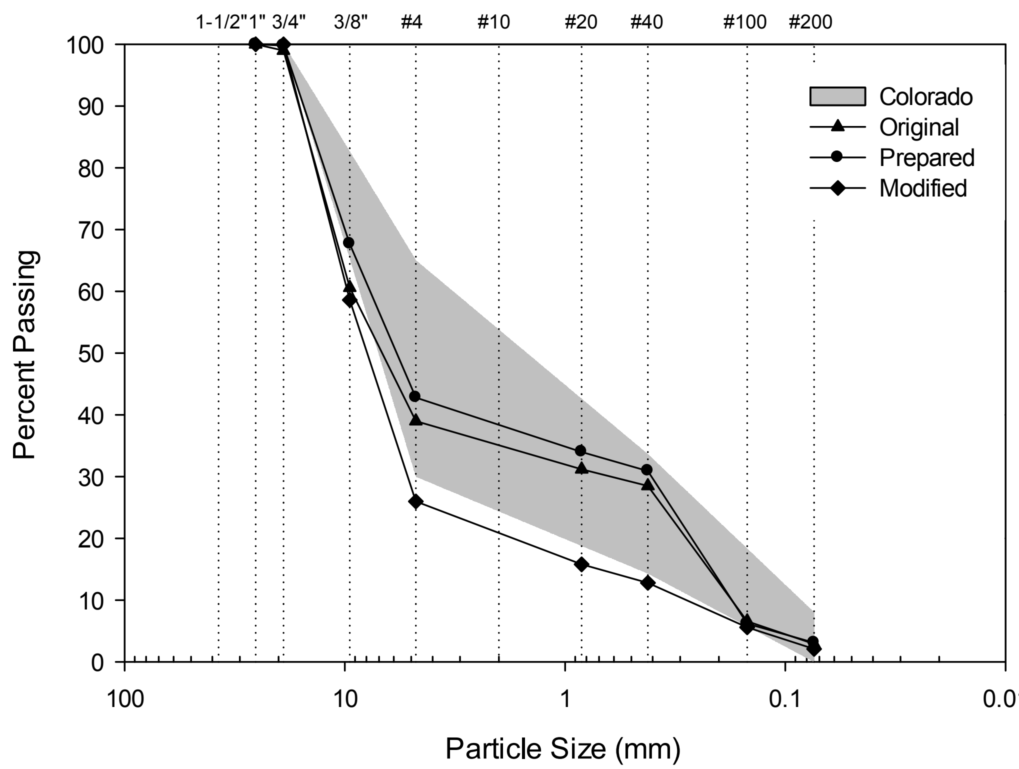



**Figure B-4: Grain-size distribution of Source D gradations compared to Colorado specification.**

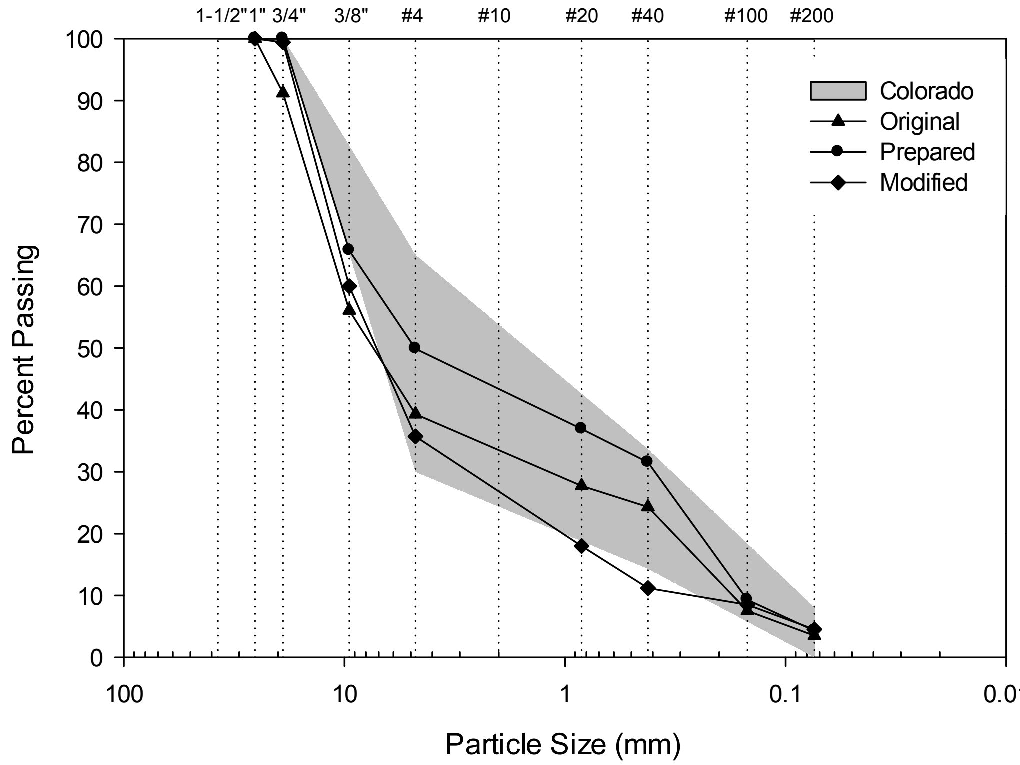



**Figure B-5: Grain-size distribution of Source E gradations compared to Colorado specification.**

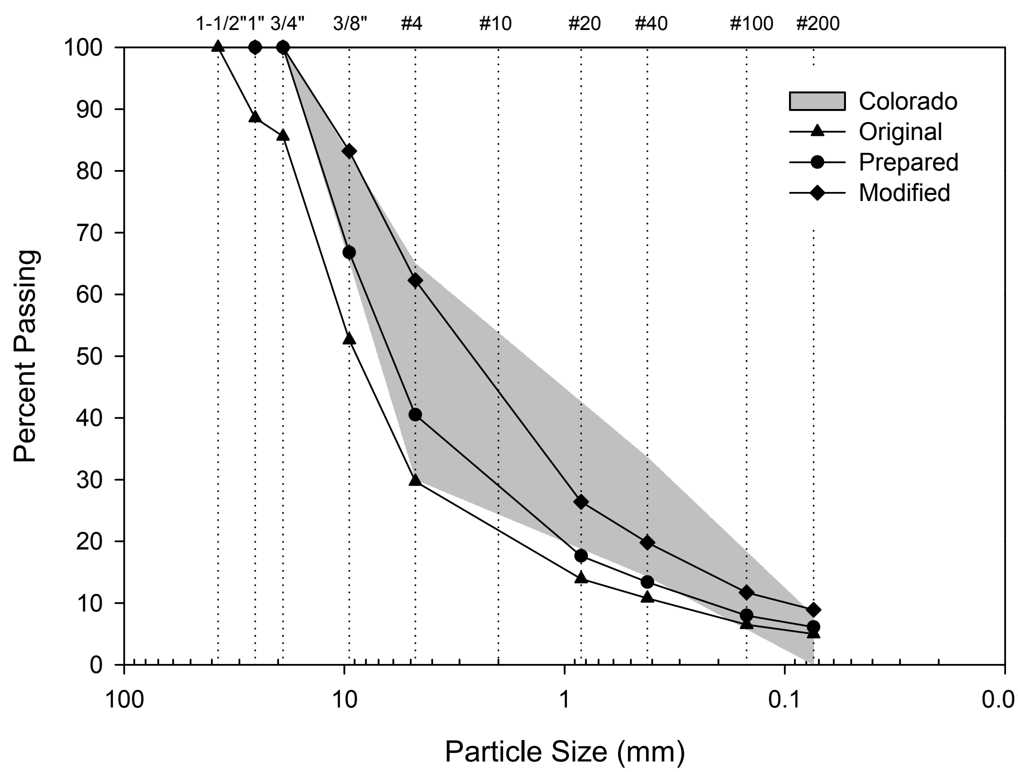



**Figure B-6: Grain-size distribution of Source F gradations compared to Colorado specification.**

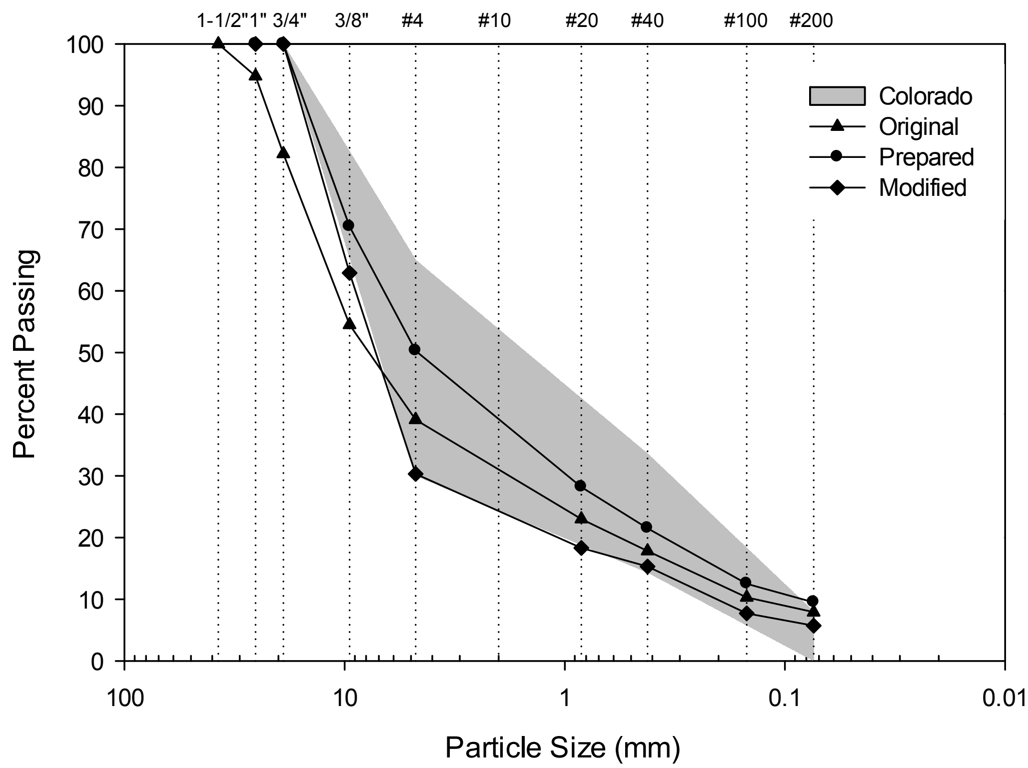



**Figure B-7: Grain-size distribution of Source G gradations compared to Colorado specification.**

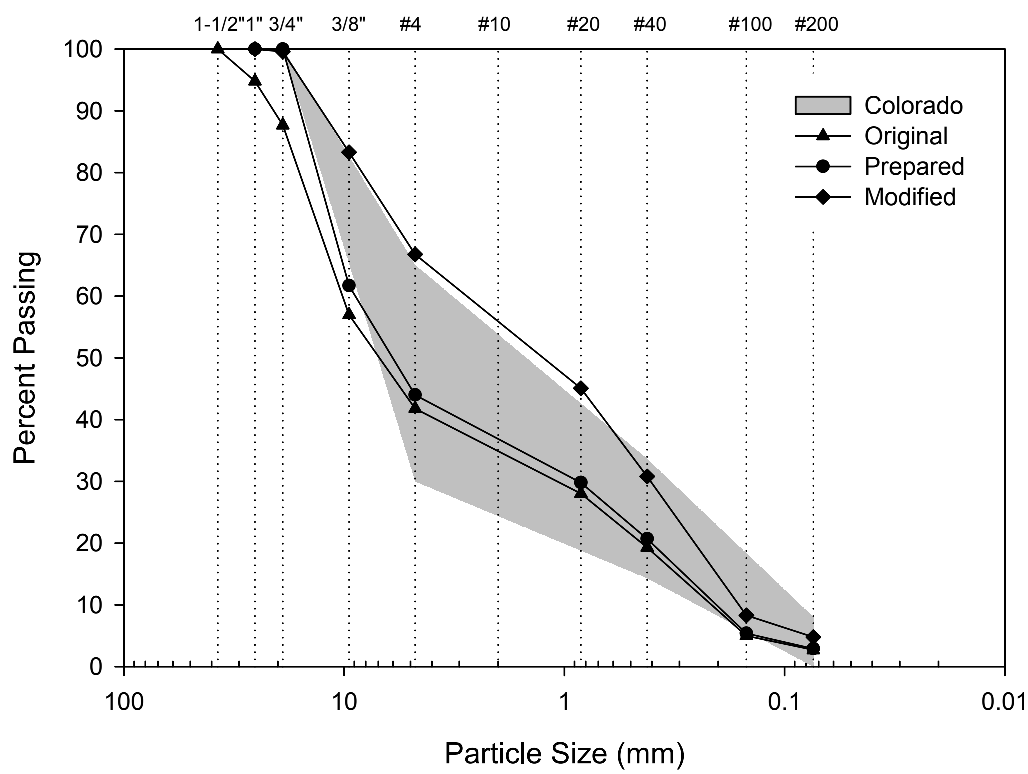



**Figure B-8: Grain-size distribution of Source H gradations compared to Colorado specification.**

# Appendix C – Modified Proctor Compaction Results

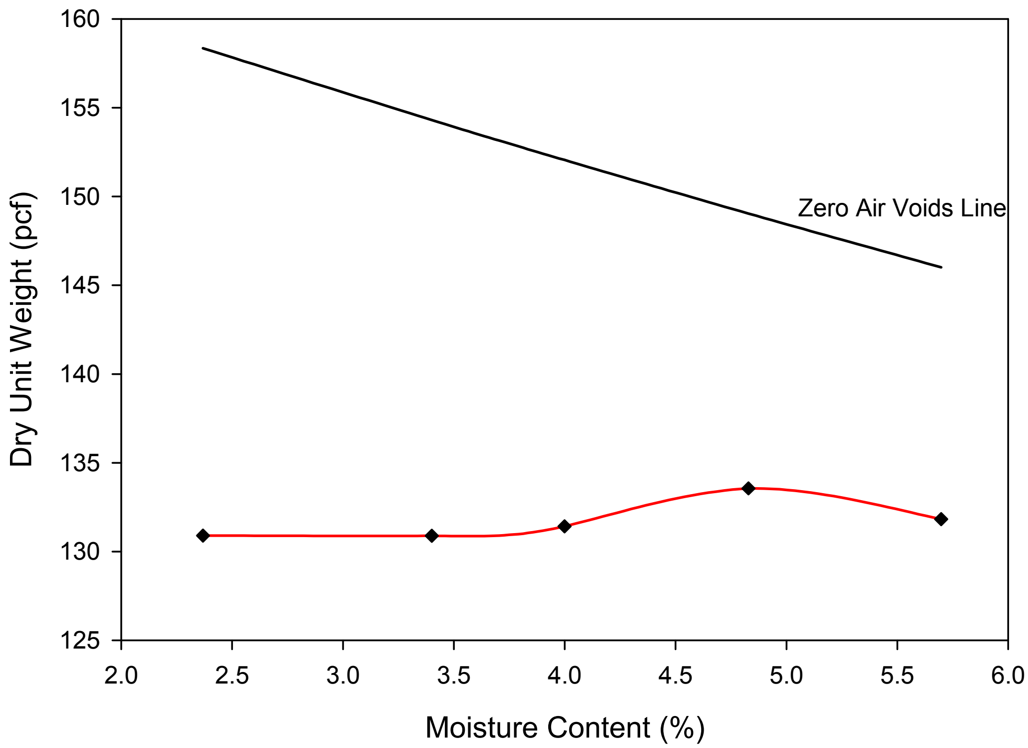



**Figure C-1: Modified Proctor results for Source A Prepared gradation.**

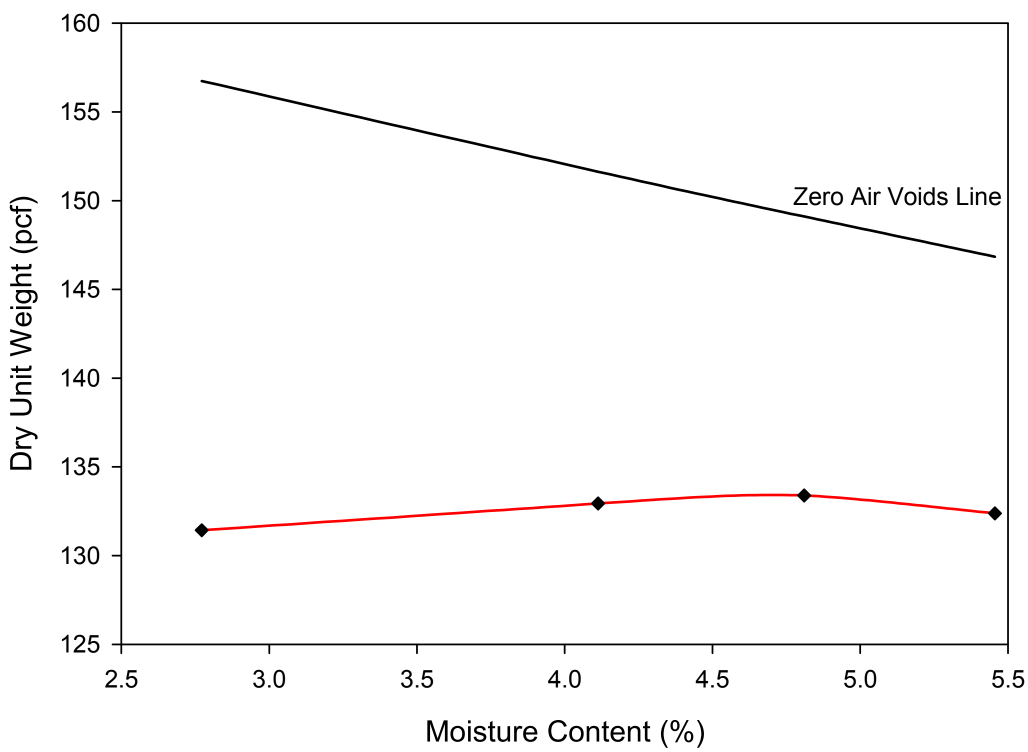



**Figure C-2: Modified Proctor results for Source A Modified gradation.**

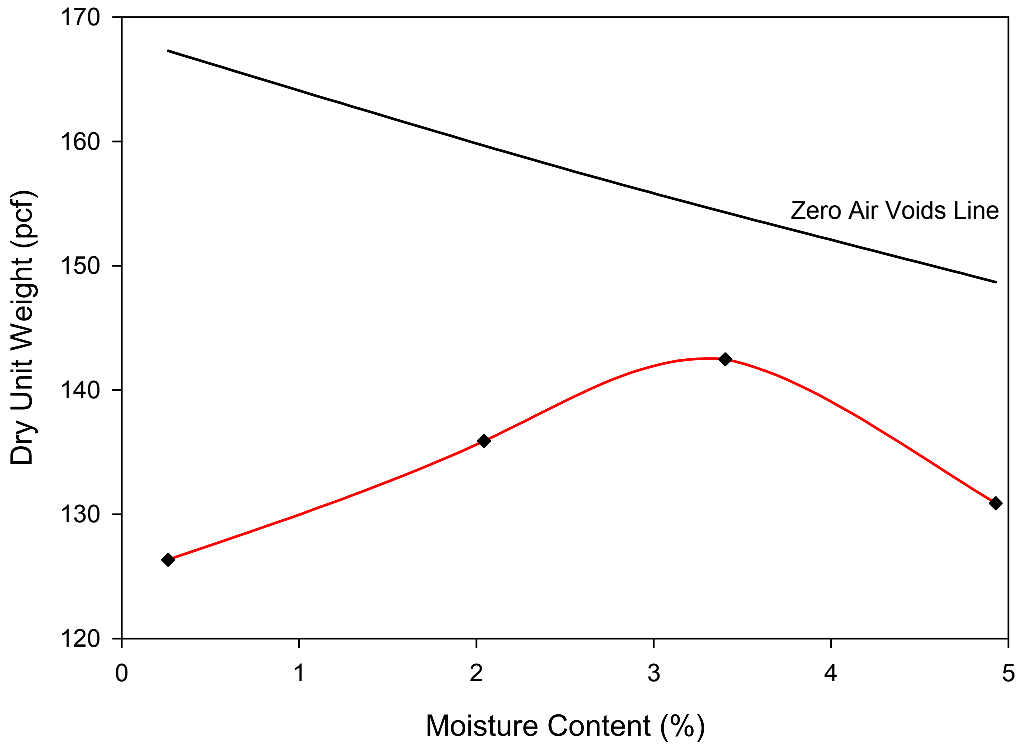



**Figure C-3: Modified Proctor results for Source B Prepared gradation.**

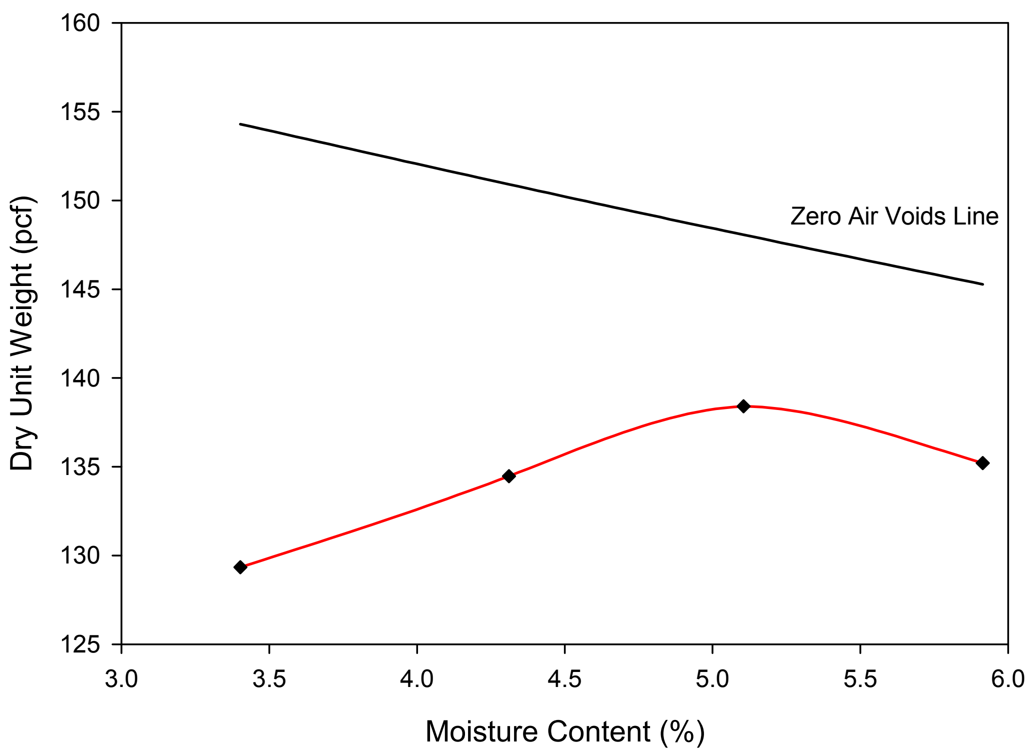



**Figure C-4: Modified Proctor results for Source B Modified gradation.**

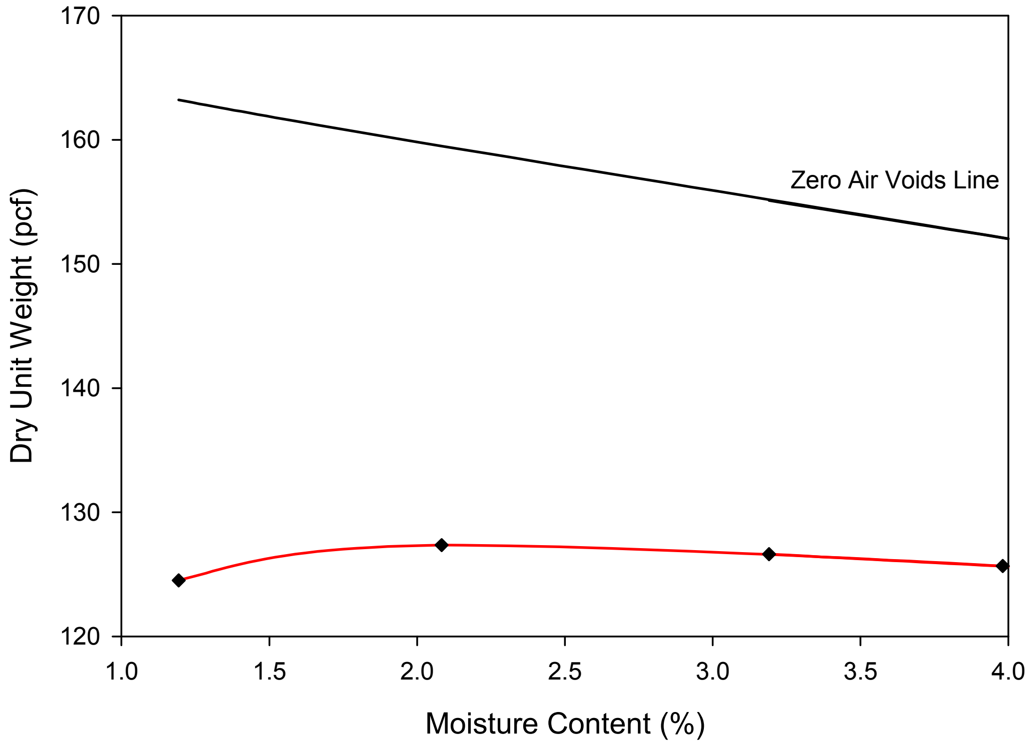



**Figure C-5: Modified Proctor results for Source C Prepared gradation.**

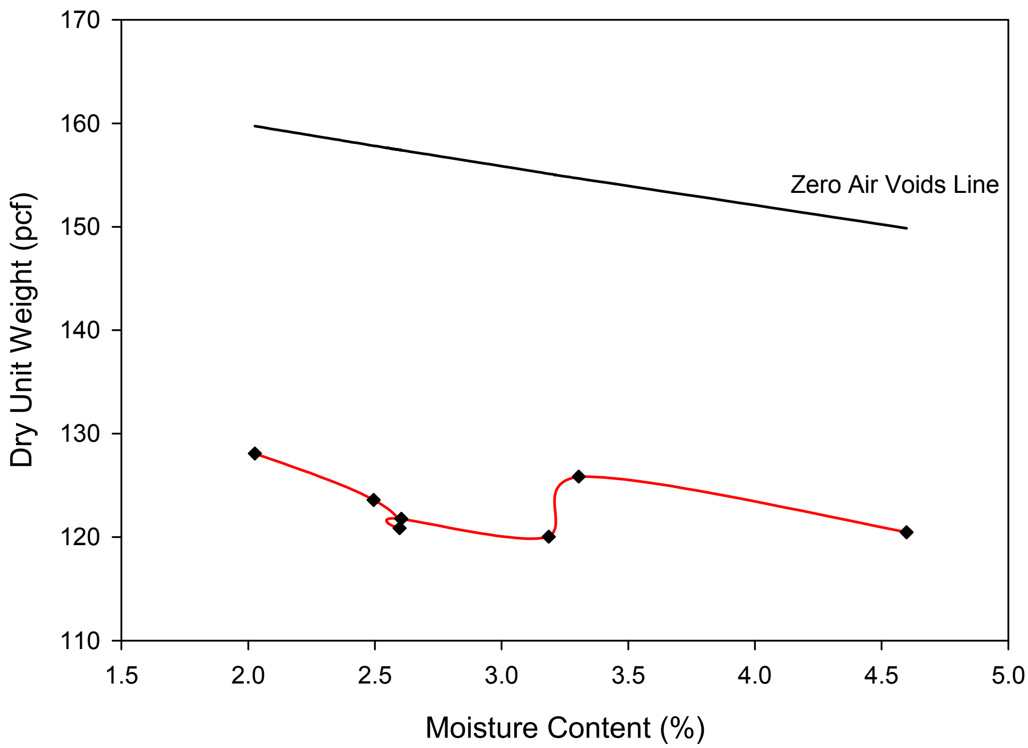



**Figure C-6: Modified Proctor results for Source C Modified gradation.**

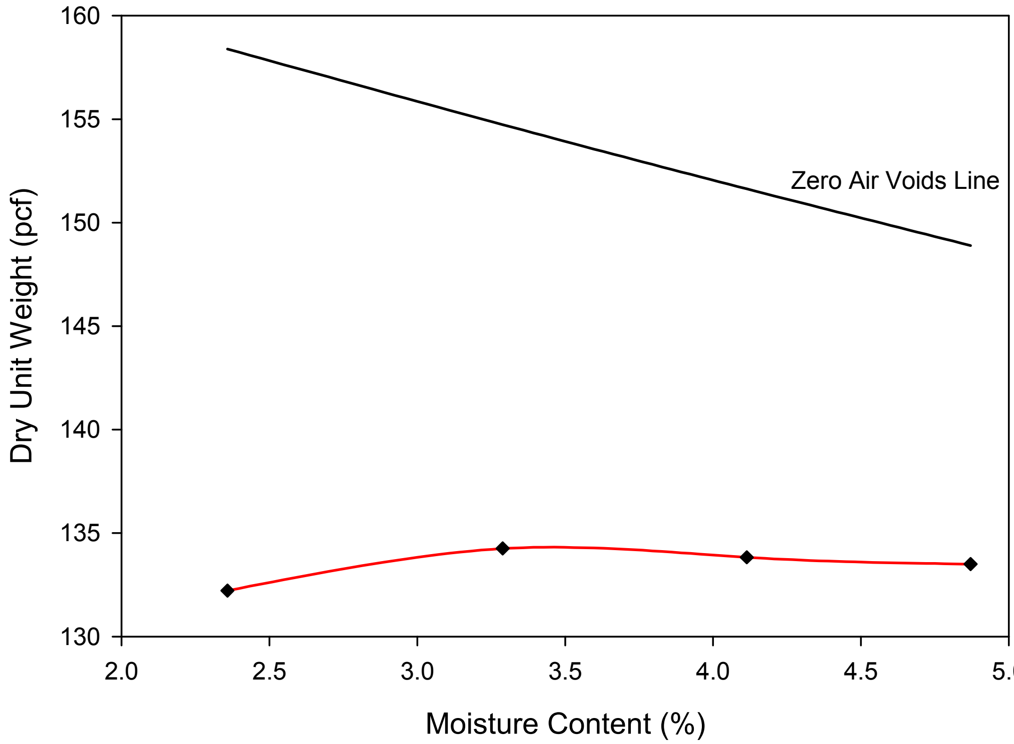



**Figure C-7: Modified Proctor results for Source D Prepared gradation.**

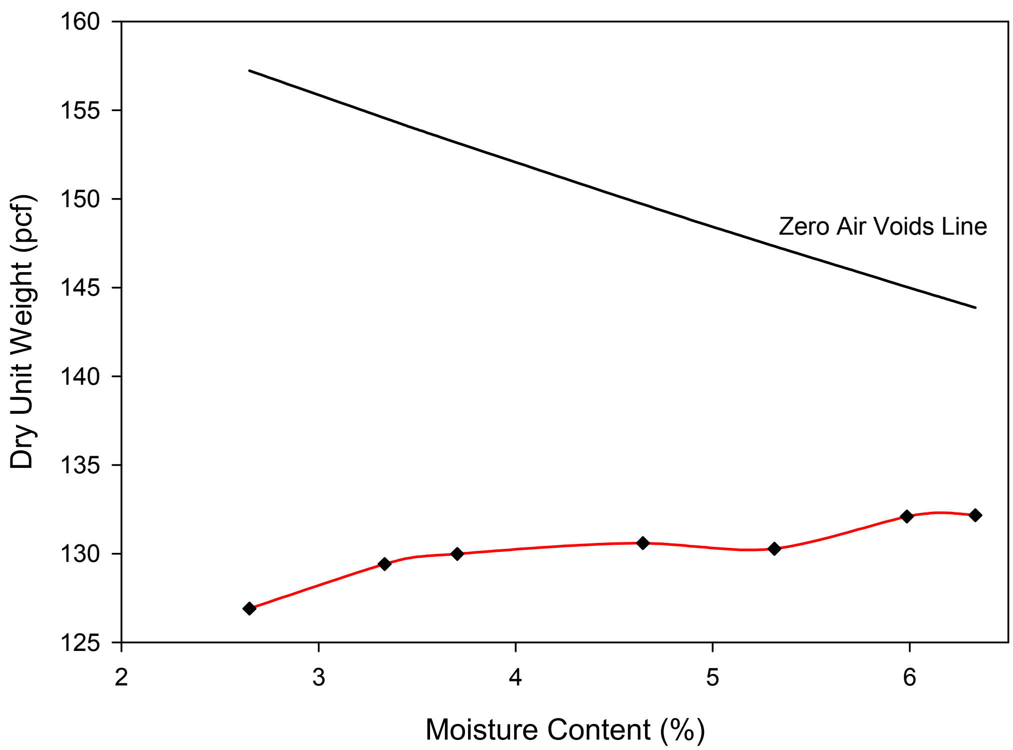



**Figure C-8: Modified Proctor results for Source D Modified gradation.**

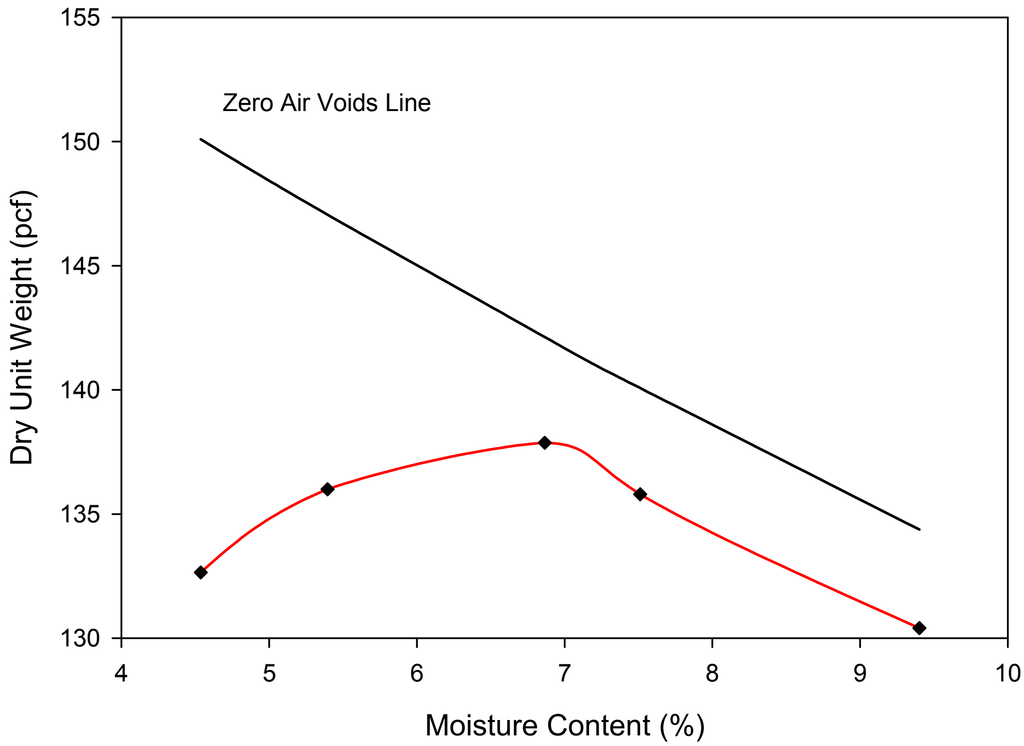



**Figure C-9: Modified Proctor results for Source E Prepared gradation.**

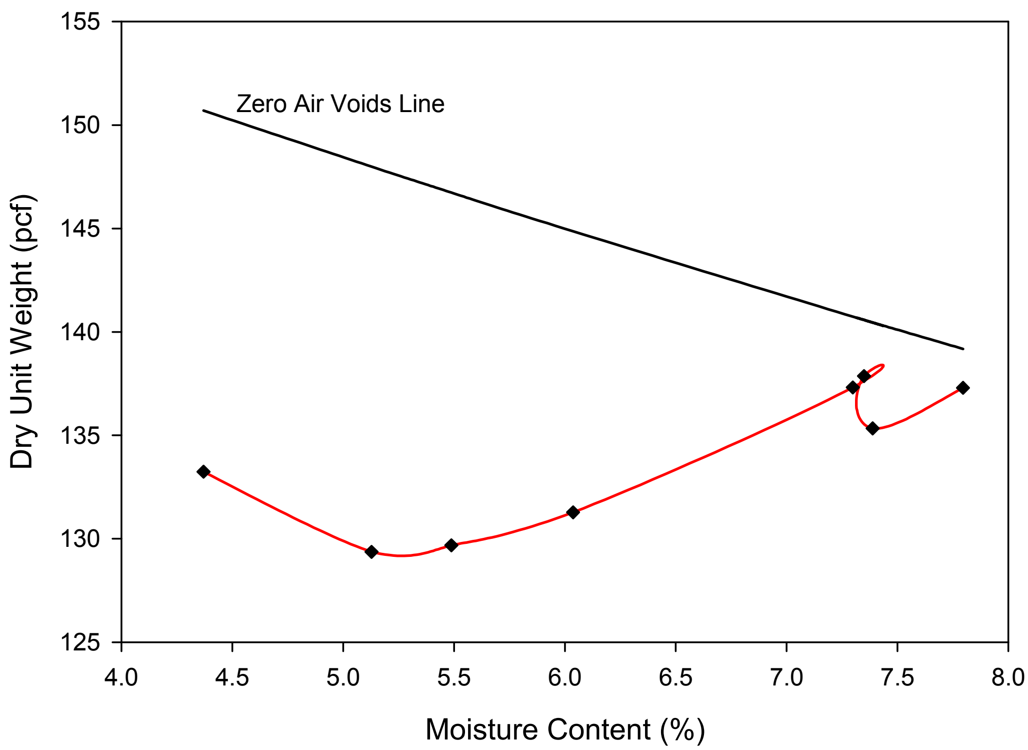



**Figure C-10: Modified Proctor results for Source E Modified gradation.**

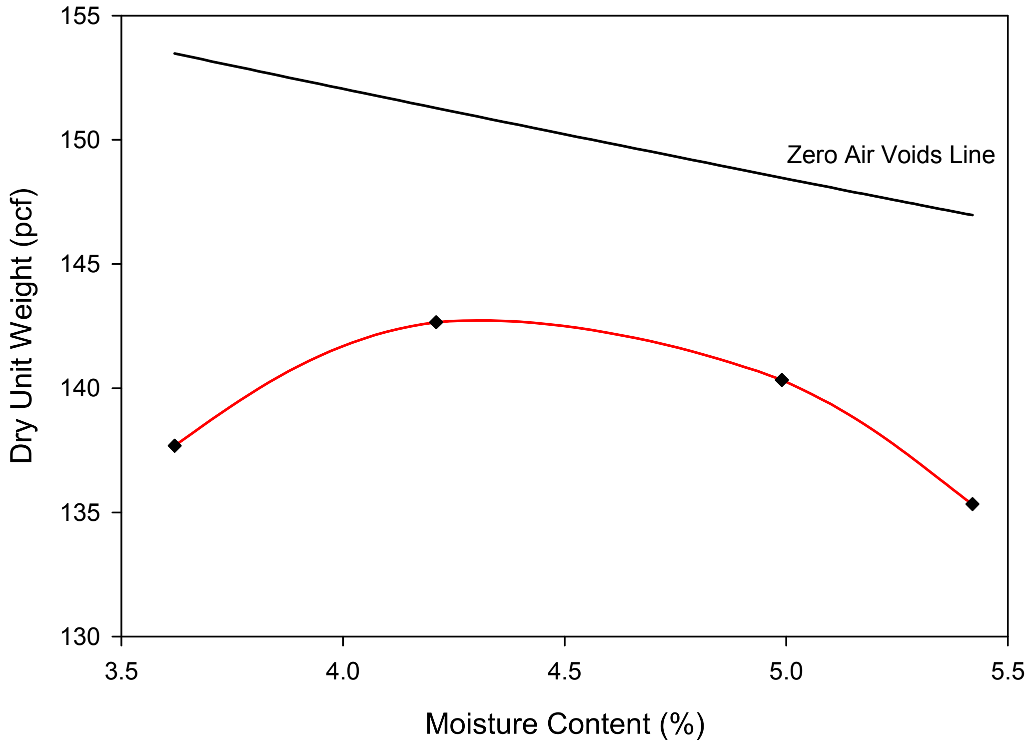



**Figure C-11: Modified Proctor results for Source F Prepared gradation.**

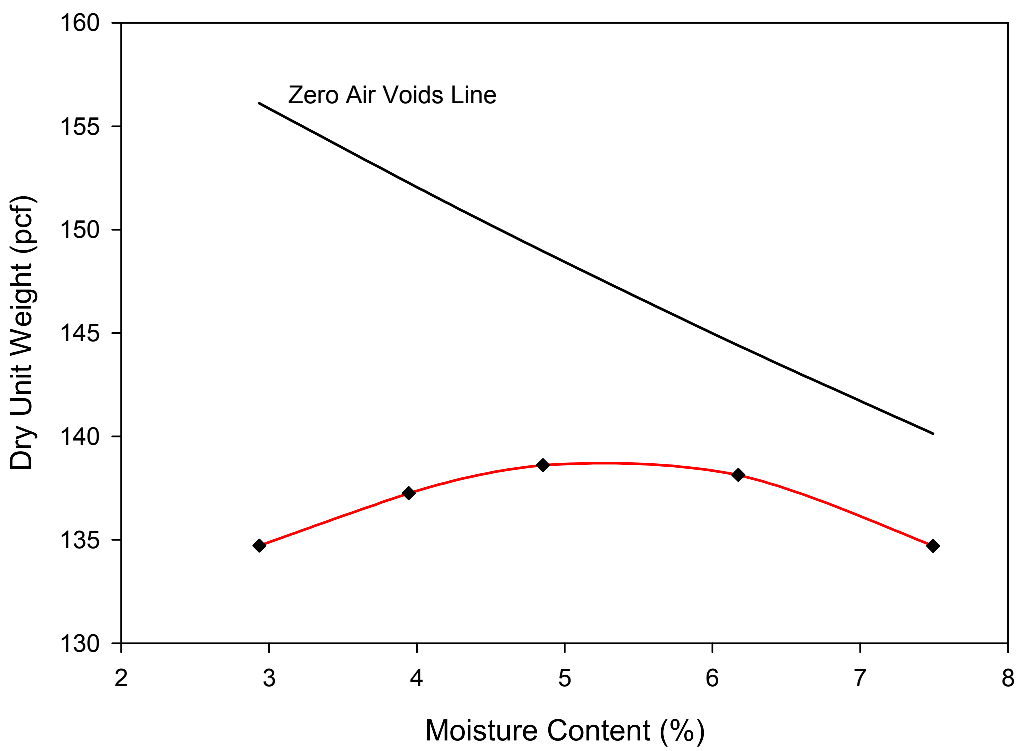



**Figure C-12: Modified Proctor results for Source F Modified gradation.**

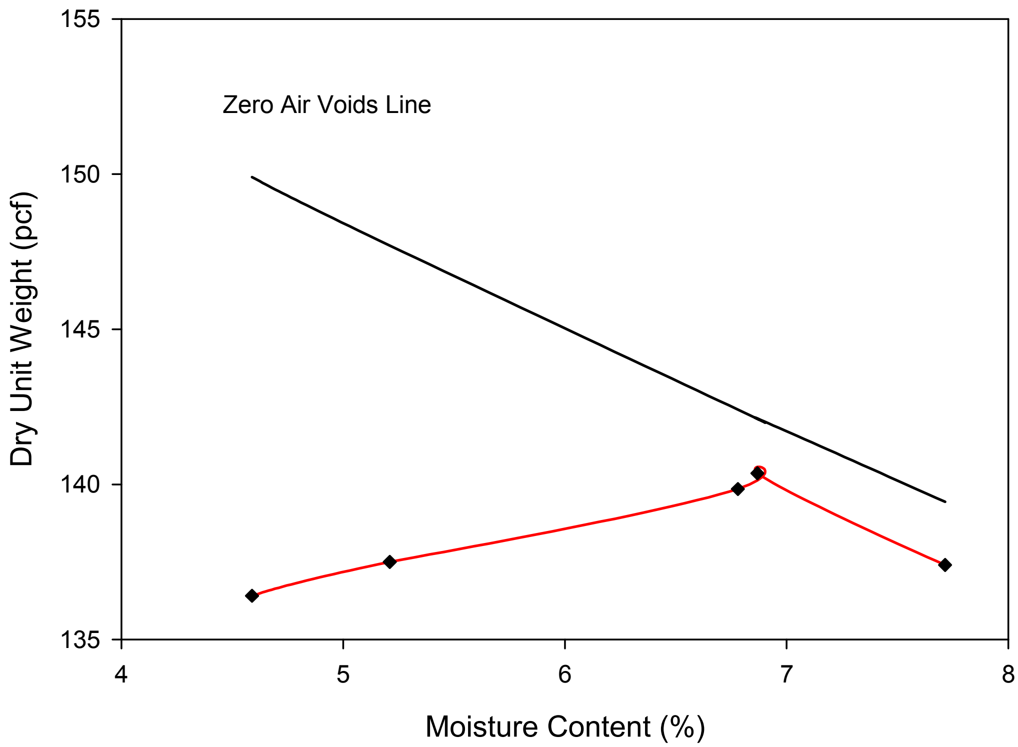



**Figure C-13: Modified Proctor results for Source G Prepared gradation.**

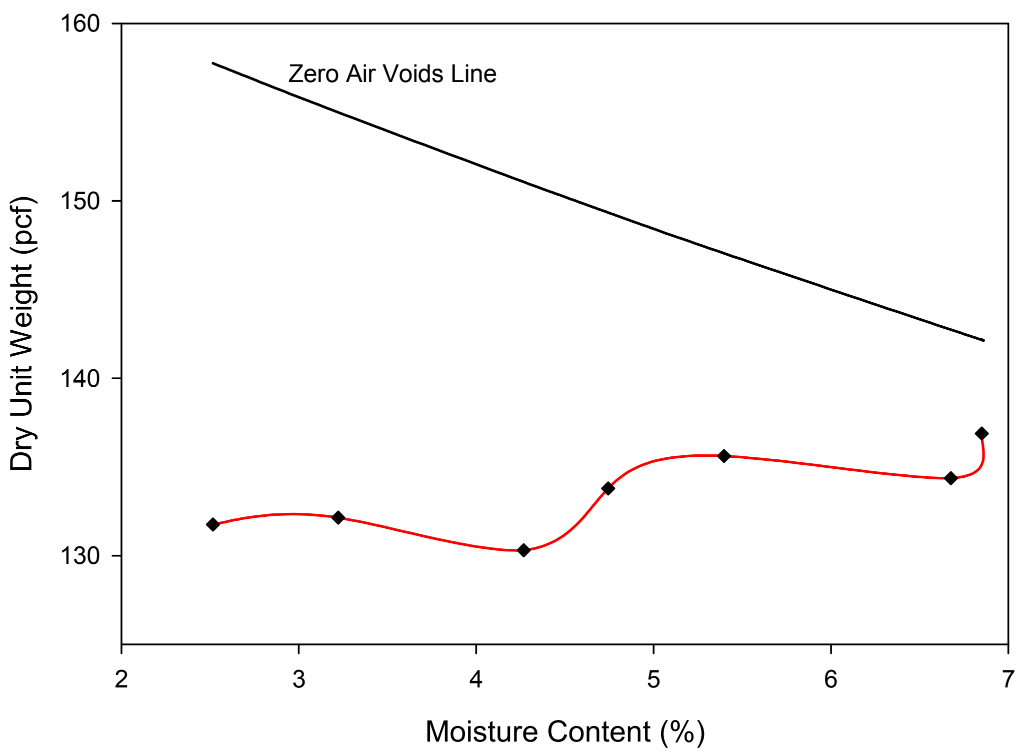



**Figure C-14: Modified Proctor results for Source G Modified gradation.**

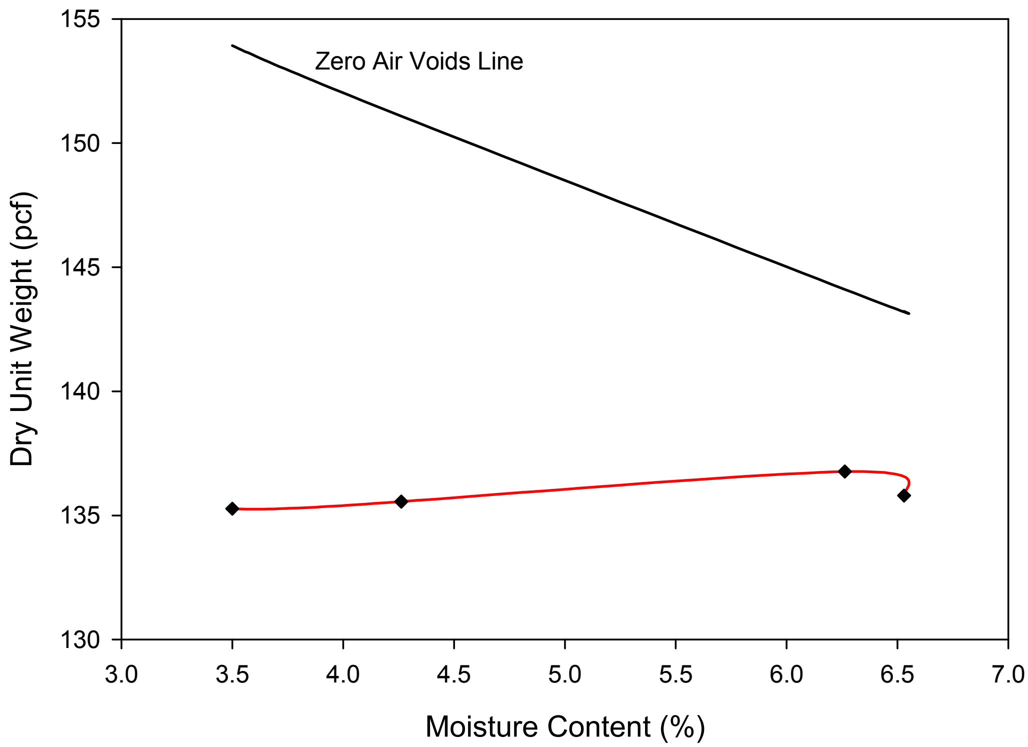



**Figure C-15: Modified Proctor results for Source H Prepared gradation.**

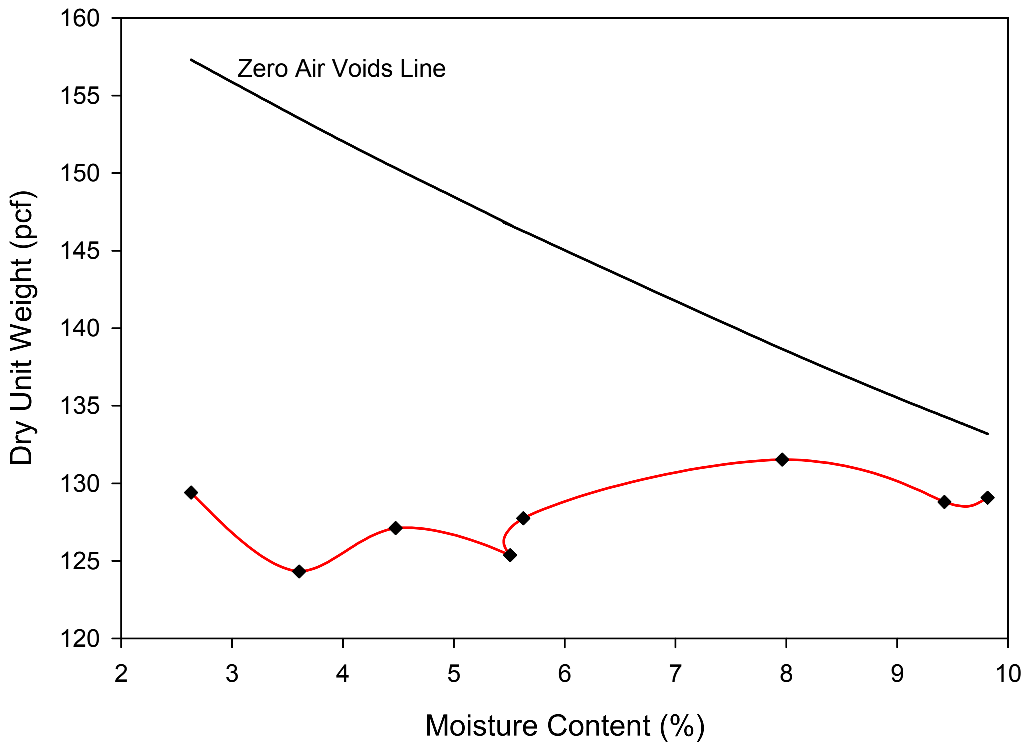
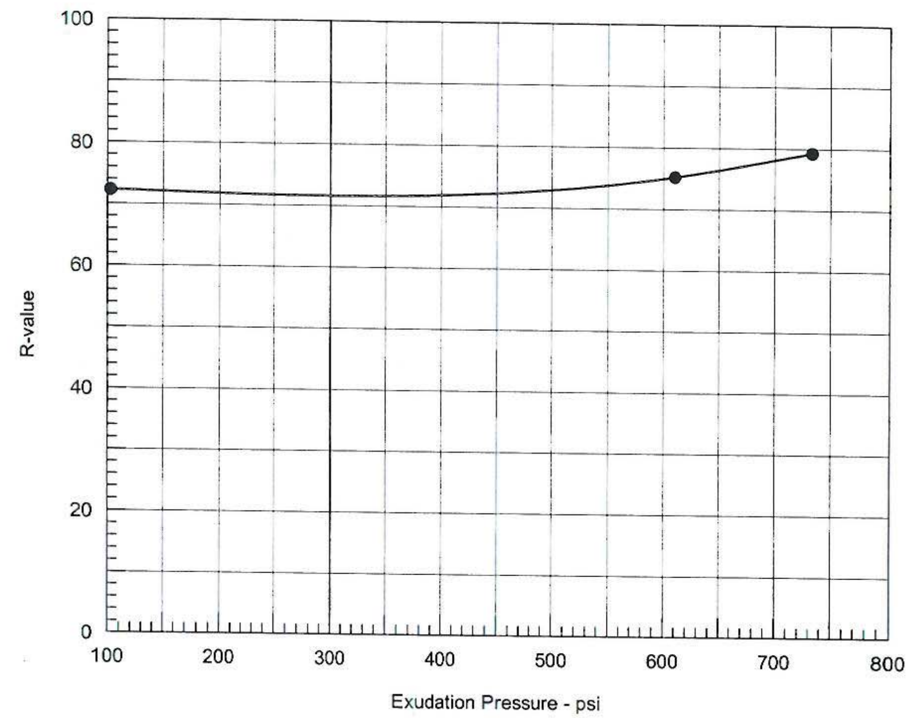



**Figure C-16: Modified Proctor results for Source H Modified gradation.**

# Appendix D – R-Value Test Reports and Results

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 19 | 2.59 | 733 | 77.9 | 79.3 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 19 | 2.51 | 610 | 75.2 | 75.2 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 25 | 2.50 | 102 | 72.3 | 72.3 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| R-value at 300 psi exudation pressure = 71.6 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** A PRE
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

Figure ______

**Figure D-1: R-value test report for Source A Prepared gradation.**

**RESISTANCE R-VALUE TESTING RESULTS**
**(ASTM D 2844)**

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** A PRE
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

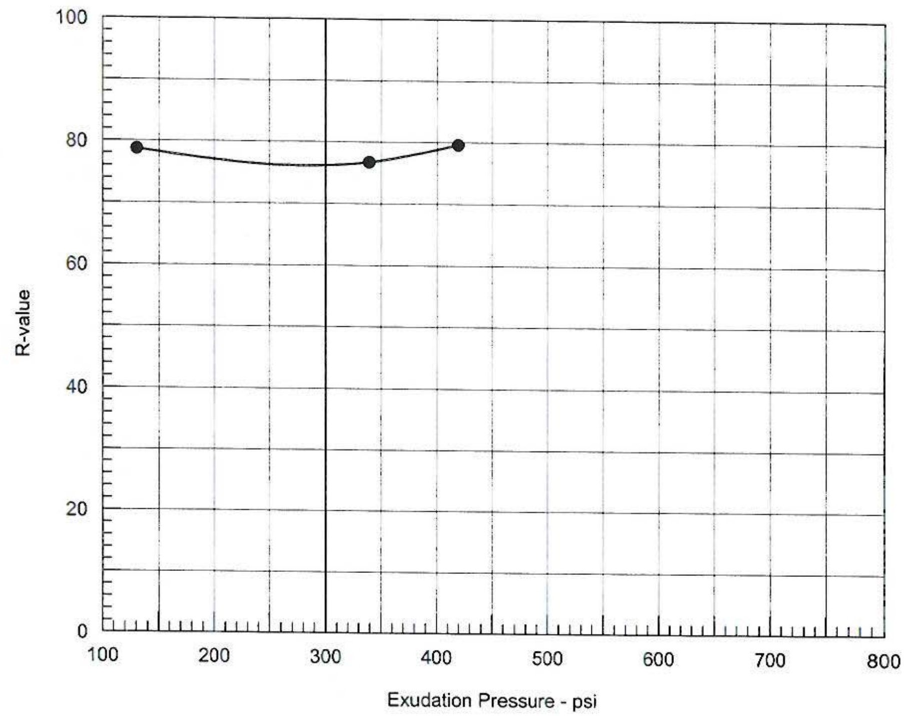
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 9215 | 7670 | 1287 |
| Exudation pressure (psi): | 733 | 610 | 102 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 19 | 19 | 25 |
| D turns: | 5.25 | 6.11 | 5.17 |
| R: | 77.9 | 75.2 | 72.3 |
| Height (in.): | 2.59 | 2.51 | 2.50 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 79.3 | 75.2 | 72.3 |

**R-Value at 300 psi exudation pressure =** 71.6
**Expansion pressure at 300 psi =** n/a psi

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure D-2: R-value test results for Source A Prepared gradation.**

## R-VALUE TEST REPORT




Resistance R-Value and Expansion Pressure - ASTM D 2844

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 18 | 2.49 | 339 | 76.7 | 76.7 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 14 | 2.50 | 419 | 79.6 | 79.6 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 19 | 2.45 | 130 | 78.7 | 78.7 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| R-value at 300 psi exudation pressure = 76.1 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** A MOD
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

Figure ______

**Figure D-3: R-value test report for Source A Modified gradation.**

RESISTANCE R-VALUE TESTING RESULTS
(ASTM D 2844)

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** A MOD
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

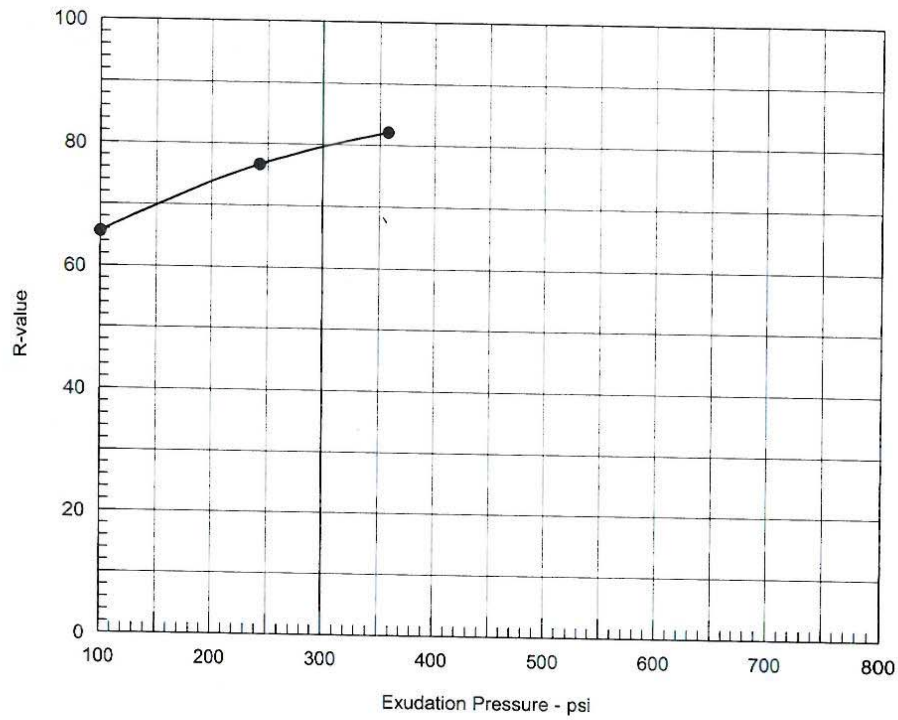
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 4266 | 5271 | 1636 |
| Exudation pressure (psi): | 339 | 419 | 130 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 18 | 14 | 19 |
| D turns: | 5.98 | 6.67 | 5.02 |
| R: | 76.7 | 79.6 | 78.7 |
| Height (in.): | 2.49 | 2.50 | 2.45 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 76.7 | 79.6 | 78.7 |

**R-Value at 300 psi exudation pressure =** 76.1
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-4: R-value test results for Source A Modified gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 18 | 2.50 | 243 | 76.6 | 76.6 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 12 | 2.49 | 358 | 82.1 | 82.1 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 28 | 2.45 | 100 | 65.6 | 65.6 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 79.6 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** B PRE
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

**R-VALUE TEST REPORT**

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-5: R-value test report for Source B Prepared gradation.**

RESISTANCE R-VALUE TESTING RESULTS
(ASTM D 2844)

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** B PRE
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

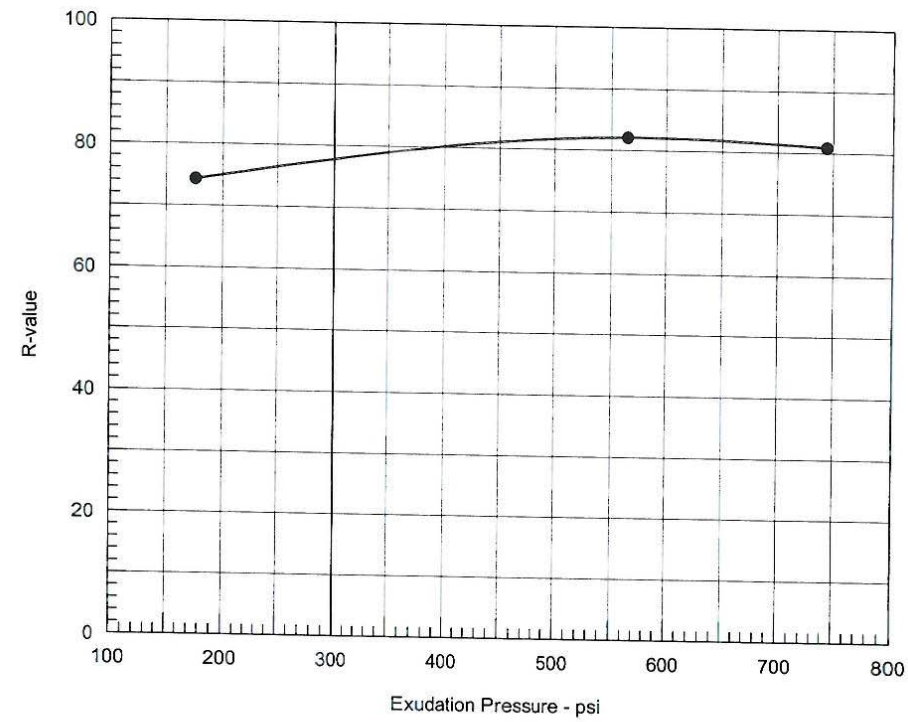
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 3053 | 4494 | 1258 |
| Exudation pressure (psi): | 243 | 358 | 100 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 18 | 12 | 28 |
| D turns: | 6.02 | 6.72 | 6.17 |
| R: | 76.6 | 82.1 | 65.6 |
| Height (in.): | 2.50 | 2.49 | 2.45 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 76.6 | 82.1 | 65.6 |

**R-Value at 300 psi exudation pressure =** 79.6
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-6: R-value test results for Source B Prepared gradation.**

# R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 16 | 2.55 | 744 | 80.9 | 80.9 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 18 | 2.55 | 176 | 74.3 | 74.3 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 12 | 2.41 | 565 | 83.1 | 82.1 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 77.8 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** B MOD
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT
**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** _____

**Figure D-7: R-value test report for Source B Modified gradation.**

**RESISTANCE R-VALUE TESTING RESULTS**
**(ASTM D 2844)**

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** B MOD
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

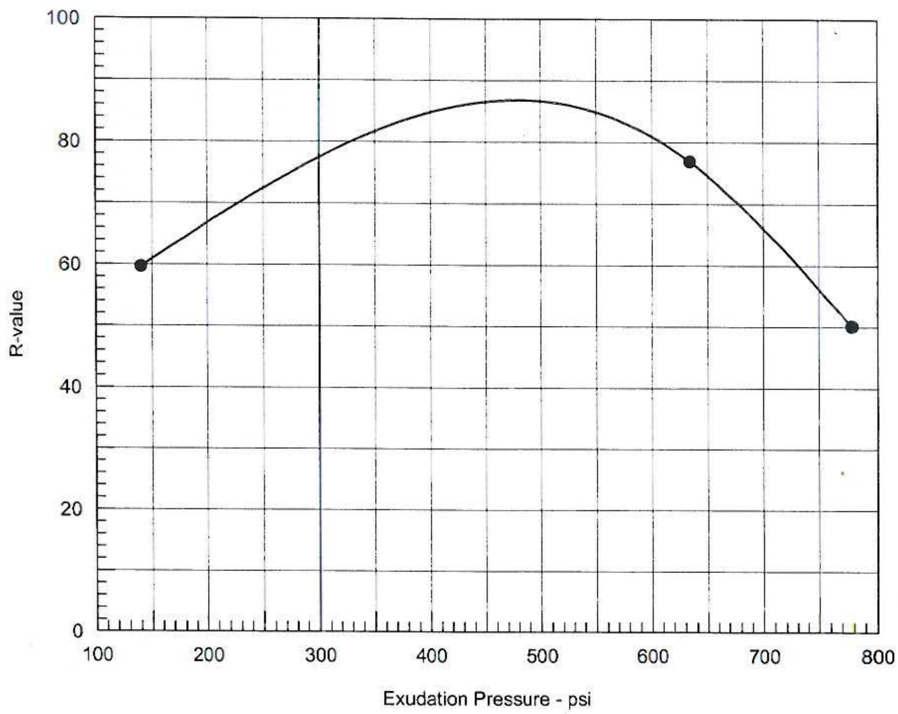
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 9352 | 2215 | 7098 |
| Exudation pressure (psi): | 744 | 176 | 565 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 16 | 18 | 12 |
| D turns: | 5.32 | 6.83 | 6.28 |
| R: | 80.9 | 74.3 | 83.1 |
| Height (in.): | 2.55 | 2.55 | 2.41 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 80.9 | 74.3 | 82.1 |

**R-Value at 300 psi exudation pressure =** 77.8
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-8: R-value test results for Source B Modified gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 29 | 2.65 | 140 | 55.8 | 59.7 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 30 | 2.35 | 779 | 54.1 | 50.1 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 12 | 2.51 | 634 | 77.0 | 77.0 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| R-value at 300 psi exudation pressure = 77.4 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** C PRE
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

Figure ______

**Figure D-9: R-value test report for Source C Prepared gradation.**

RESISTANCE R-VALUE TESTING RESULTS
(ASTM D 2844)

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** C PRE
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

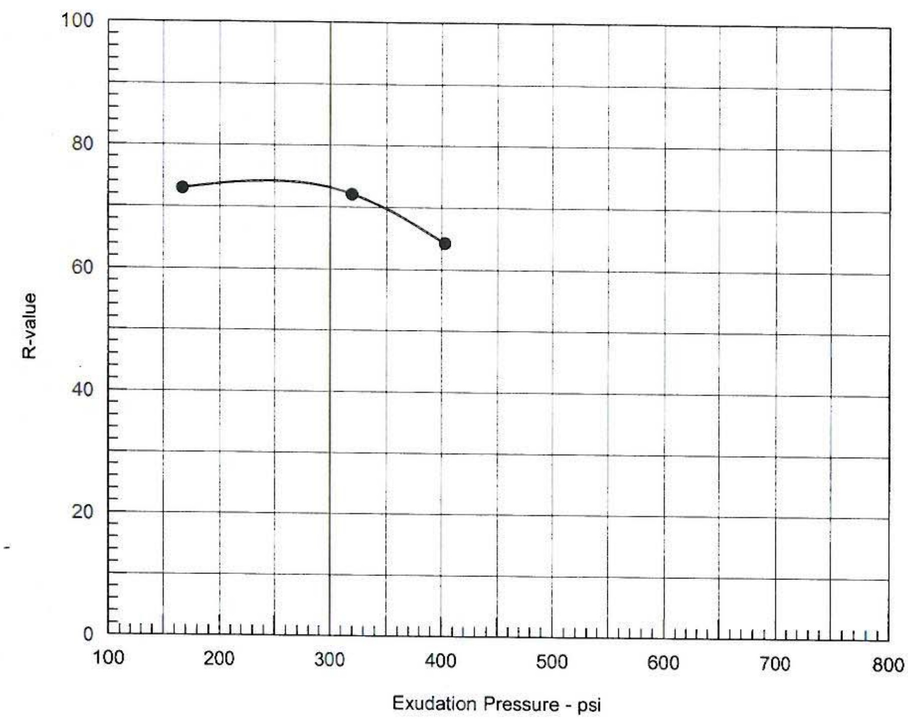
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 1762 | 9786 | 7966 |
| Exudation pressure (psi): | 140 | 779 | 634 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 29 | 30 | 12 |
| D turns: | 8.95 | 9.20 | 9.23 |
| R: | 55.8 | 54.1 | 77.0 |
| Height (in.): | 2.65 | 2.35 | 2.51 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 59.7 | 50.1 | 77.0 |

**R-Value at 300 psi exudation pressure =** 77.4
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-10: R-value test results for Source C Prepared gradation.**

# R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 24 | 2.65 | 167 | 69.9 | 72.9 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 23 | 2.61 | 403 | 61.7 | 64.3 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 19 | 2.50 | 320 | 72.1 | 72.1 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 73.1 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** C MOD
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-11: R-value test report for Source C Modified gradation.**

RESISTANCE R-VALUE TESTING RESULTS
(ASTM D 2844)

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** C MOD
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

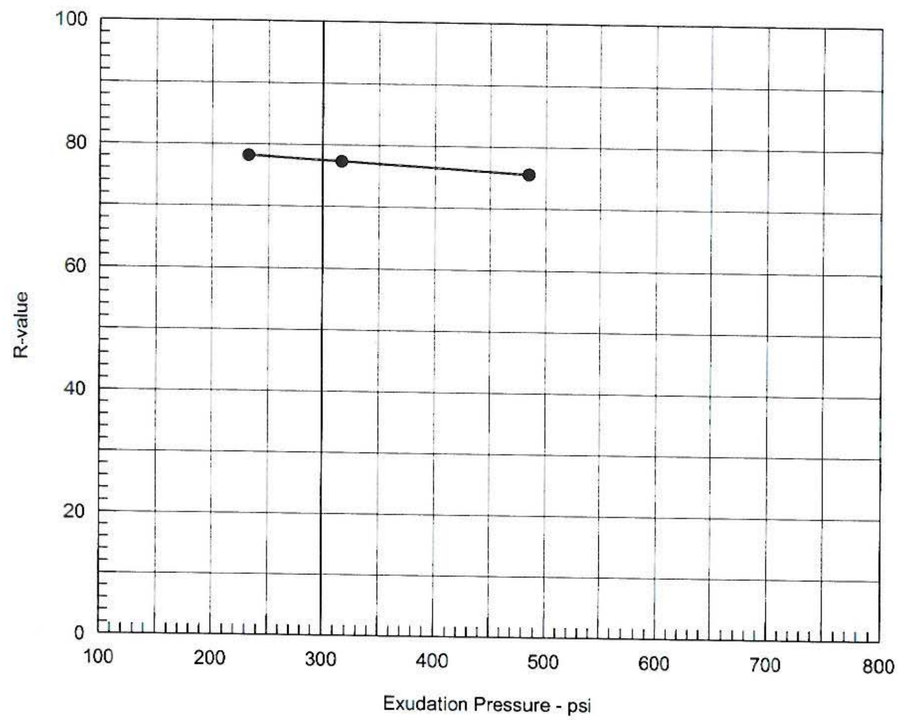
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 2098 | 5064 | 4017 |
| Exudation pressure (psi): | 167 | 403 | 320 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 24 | 23 | 19 |
| D turns: | 6.10 | 9.26 | 7.18 |
| R: | 69.9 | 61.7 | 72.1 |
| Height (in.): | 2.65 | 2.61 | 2.50 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 72.9 | 64.3 | 72.1 |

**R-Value at 300 psi exudation pressure =** 73.1
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-12: R-value test results for Source C Modified gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 22 | 2.60 | 485 | 73.8 | 75.5 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 19 | 2.60 | 316 | 75.7 | 77.3 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 18 | 2.49 | 232 | 78.2 | 78.2 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 77.5 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** D PRE
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

**R-VALUE TEST REPORT**

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-13: R-value test report for Source D Prepared gradation.**

RESISTANCE R-VALUE TESTING RESULTS
(ASTM D 2844)

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** D PRE
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

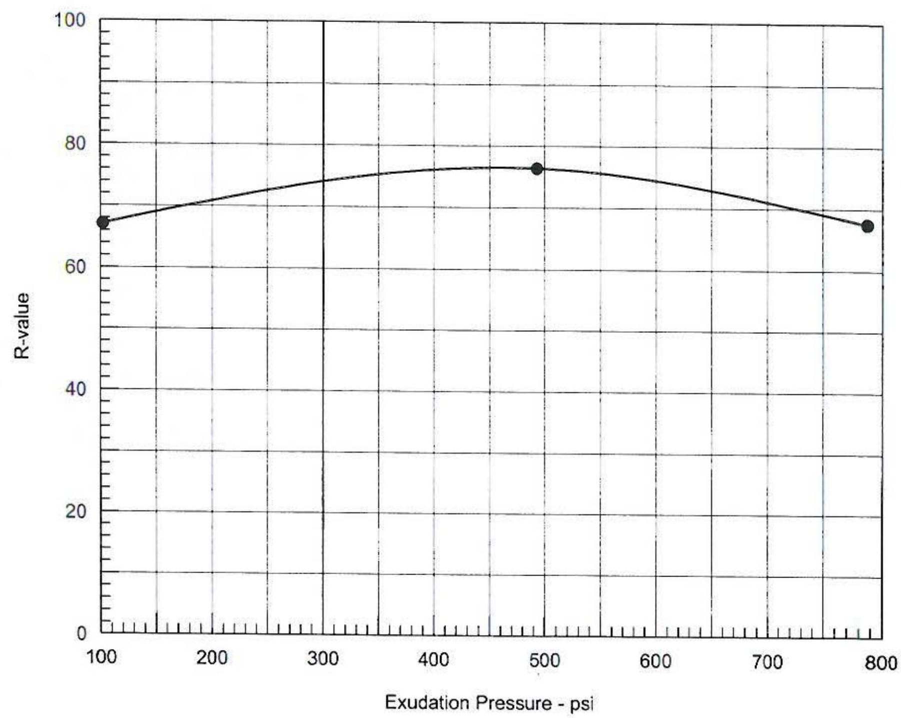
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 6092 | 3975 | 2912 |
| Exudation pressure (psi): | 485 | 316 | 232 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 22 | 19 | 18 |
| D turns: | 5.58 | 5.97 | 5.50 |
| R: | 73.8 | 75.7 | 78.2 |
| Height (in.): | 2.60 | 2.60 | 2.49 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 75.5 | 77.3 | 78.2 |

**R-Value at 300 psi exudation pressure =** 77.5
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-14: R-value test results for Source D Prepared gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 19 | 2.50 | 788 | 67.6 | 67.6 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 18 | 2.50 | 493 | 76.4 | 76.4 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 24 | 2.50 | 102 | 67.1 | 67.1 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| R-value at 300 psi exudation pressure = 74.1 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** D MOD
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

Figure ______

**Figure D-15: R-value test report for Source D Modified gradation.**

**RESISTANCE R-VALUE TESTING RESULTS**
**(ASTM D 2844)**

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** D MOD
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

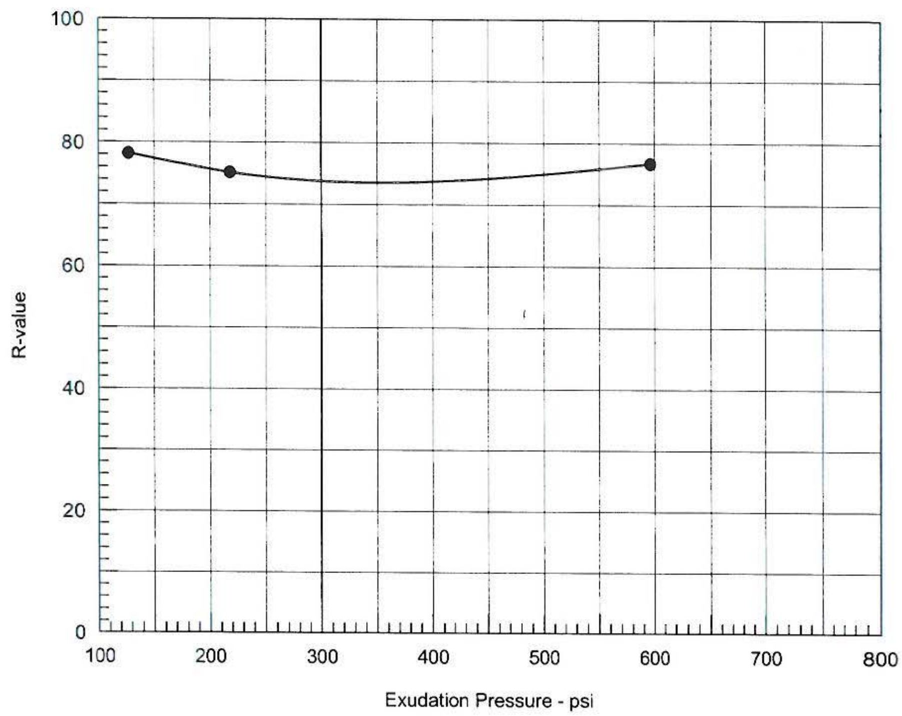
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 9899 | 6197 | 1283 |
| Exudation pressure (psi): | 788 | 493 | 102 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 19 | 18 | 24 |
| D turns: | 8.91 | 6.10 | 6.94 |
| R: | 67.6 | 76.4 | 67.1 |
| Height (in.): | 2.50 | 2.50 | 2.50 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 67.6 | 76.4 | 67.1 |

**R-Value at 300 psi exudation pressure =** 74.1
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-16: R-value test results for Source D Modified gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 15 | 2.50 | 596 | 76.8 | 76.8 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 18 | 2.49 | 127 | 78.2 | 78.2 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 17 | 2.50 | 218 | 75.1 | 75.1 |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 73.7 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** E PRE
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-17: R-value test report for Source E Prepared gradation.**

**RESISTANCE R-VALUE TESTING RESULTS**
**(ASTM D 2844)**

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** E PRE
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

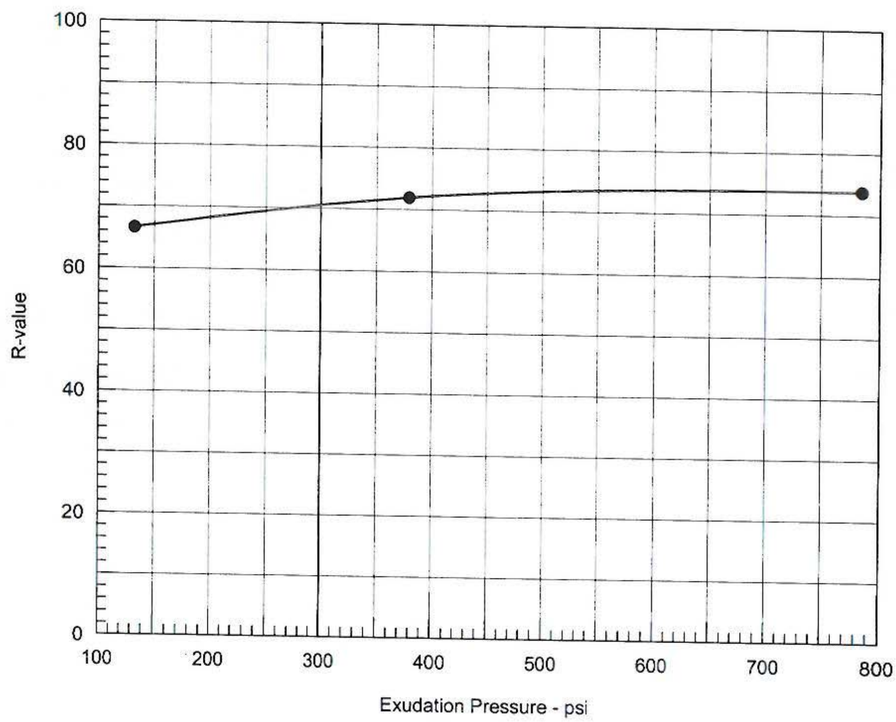
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 7494 | 1597 | 2741 |
| Exudation pressure (psi): | 596 | 127 | 218 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 15 | 18 | 17 |
| D turns: | 7.32 | 5.50 | 6.96 |
| R: | 76.8 | 78.2 | 75.1 |
| Height (in.): | 2.50 | 2.49 | 2.50 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 76.8 | 78.2 | 75.1 |

**R-Value at 300 psi exudation pressure =** 73.7
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-18: R-value test results for Source E Prepared gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 16 | 2.60 | 379 | 69.9 | 71.9 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 16 | 2.50 | 785 | 73.8 | 73.8 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 24 | 2.58 | 133 | 64.8 | 66.6 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 70.5 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** E MOD
**Date:** 4/22/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-19: R-value test report for Source E Modified gradation.**

RESISTANCE R-VALUE TESTING RESULTS
(ASTM D 2844)

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** E MOD
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

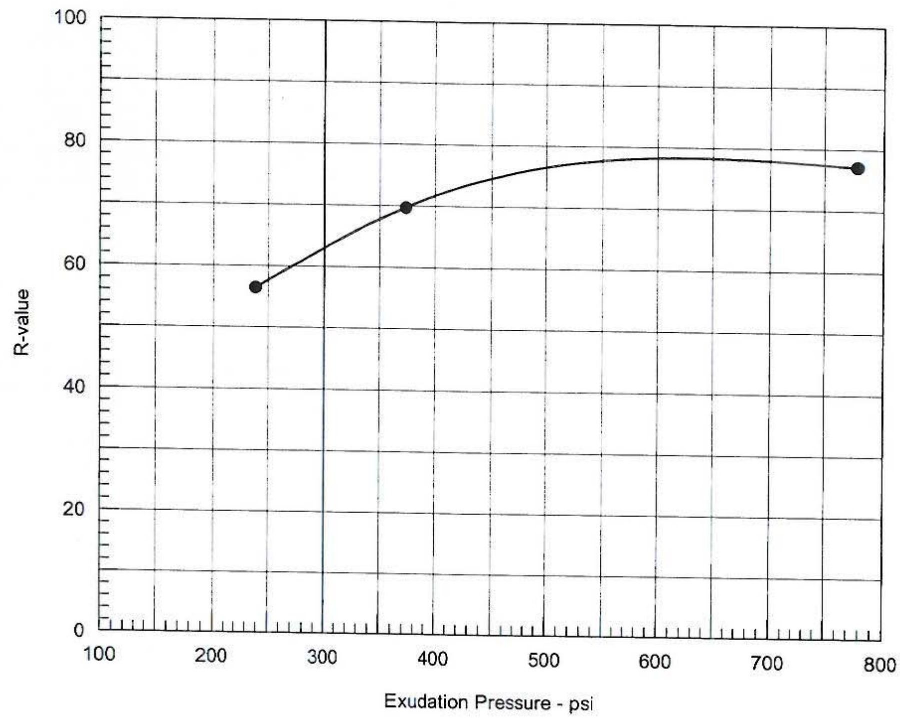
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 4766 | 9865 | 1673 |
| Exudation pressure (psi): | 379 | 785 | 133 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 16 | 16 | 24 |
| D turns: | 9.70 | 7.99 | 7.70 |
| R: | 69.9 | 73.8 | 64.8 |
| Height (in.): | 2.60 | 2.50 | 2.58 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 71.9 | 73.8 | 66.6 |

**R-Value at 300 psi exudation pressure =** 70.5
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-20: R-value test results for Source E Modified gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 23 | 2.50 | 373 | 69.7 | 69.7 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 14 | 2.35 | 779 | 79.2 | 77.1 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 38 | 2.50 | 239 | 56.4 | 56.4 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 63.0 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** F PRE
**Date:** 4/26/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-21: R-value test report for Source F Prepared gradation.**

**RESISTANCE R-VALUE TESTING RESULTS**
**(ASTM D 2844)**

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** F PRE
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

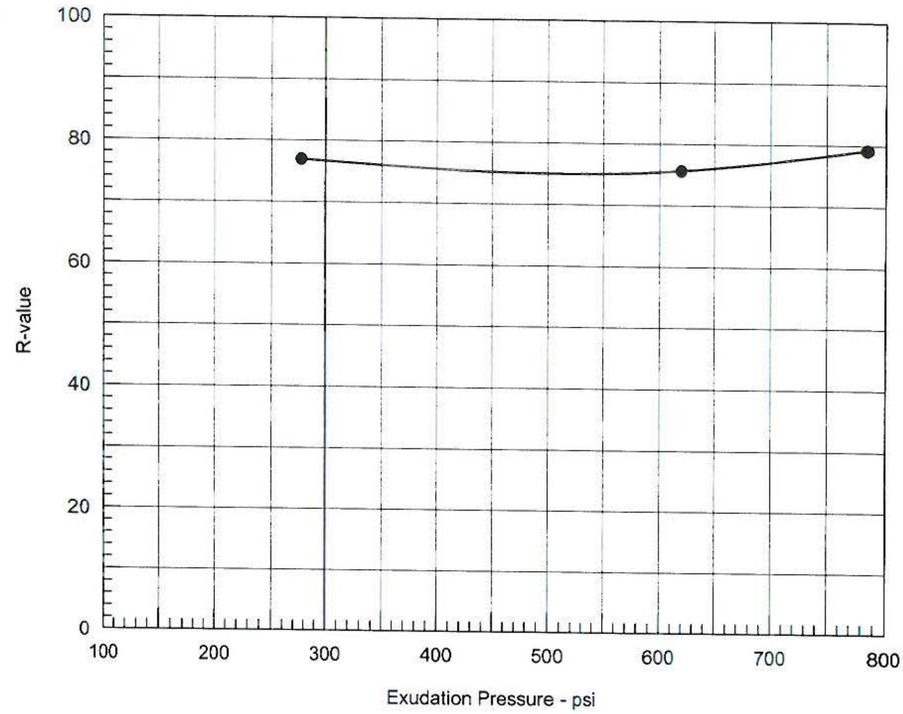
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 4683 | 9786 | 3001 |
| Exudation pressure (psi): | 373 | 779 | 239 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 23 | 14 | 38 |
| D turns: | 6.47 | 6.84 | 6.20 |
| R: | 69.7 | 79.2 | 56.4 |
| Height (in.): | 2.50 | 2.35 | 2.50 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 69.7 | 77.1 | 56.4 |

**R-Value at 300 psi exudation pressure =** 63.0
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-22: R-value test results for Source F Prepared gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 16 | 2.65 | 277 | 74.3 | 76.9 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 18 | 2.50 | 620 | 75.6 | 75.6 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 14 | 2.40 | 785 | 80.5 | 79.2 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 76.7 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** F MOD
**Date:** 4/26/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-23: R-value test report for Source F Modified gradation.**

**RESISTANCE R-VALUE TESTING RESULTS**
**(ASTM D 2844)**

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** F MOD
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

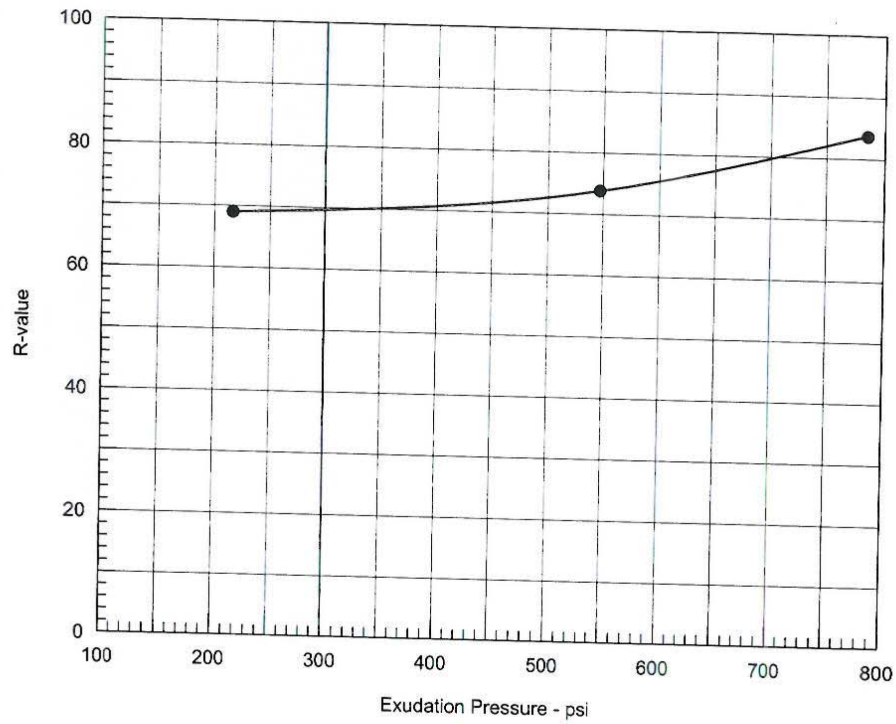
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 3486 | 7787 | 9867 |
| Exudation pressure (psi): | 277 | 620 | 785 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 16 | 18 | 14 |
| D turns: | 7.78 | 6.36 | 6.32 |
| R: | 74.3 | 75.6 | 80.5 |
| Height (in.): | 2.65 | 2.50 | 2.40 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 76.9 | 75.6 | 79.2 |

**R-Value at 300 psi exudation pressure =** 76.7
**Expansion pressure at 300 psi =** n/a psi

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure D-24: R-value test results for Source F Modified gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 24 | 2.50 | 217 | 69.0 | 69.0 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 11 | 2.50 | 785 | 83.7 | 83.7 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 14 | 2.40 | 547 | 75.5 | 73.8 |
| | | | | | | | | | |

**Test Results**

**R-value at 300 psi exudation pressure =** 69.6

**Material Description**

WTI Research

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** G PRE
**Date:** 4/26/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ____

**Figure D-25: R-value test report for Source G Prepared gradation.**

**RESISTANCE R-VALUE TESTING RESULTS**
**(ASTM D 2844)**

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** G PRE
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

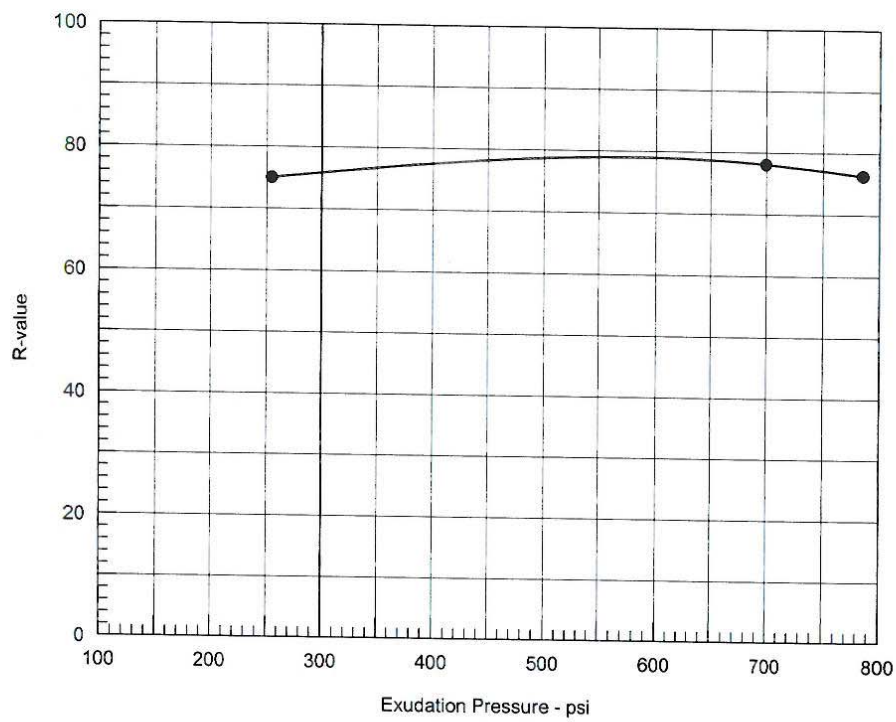
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 2722 | 9869 | 6874 |
| Exudation pressure (psi): | 217 | 785 | 547 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 24 | 11 | 14 |
| D turns: | 6.36 | 6.59 | 8.46 |
| R: | 69.0 | 83.7 | 75.5 |
| Height (in.): | 2.50 | 2.50 | 2.40 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 69.0 | 83.7 | 73.8 |

**R-Value at 300 psi exudation pressure =** 69.6
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-26: R-value test results for Source G Prepared gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 15 | 2.35 | 786 | 78.5 | 76.3 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 14 | 2.50 | 700 | 78.1 | 78.1 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 16 | 2.40 | 254 | 76.6 | 75.0 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 75.8 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** G MOD
**Date:** 4/26/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-27: R-value test report for Source G Modified gradation.**

**RESISTANCE R-VALUE TESTING RESULTS**
**(ASTM D 2844)**

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** G MOD
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

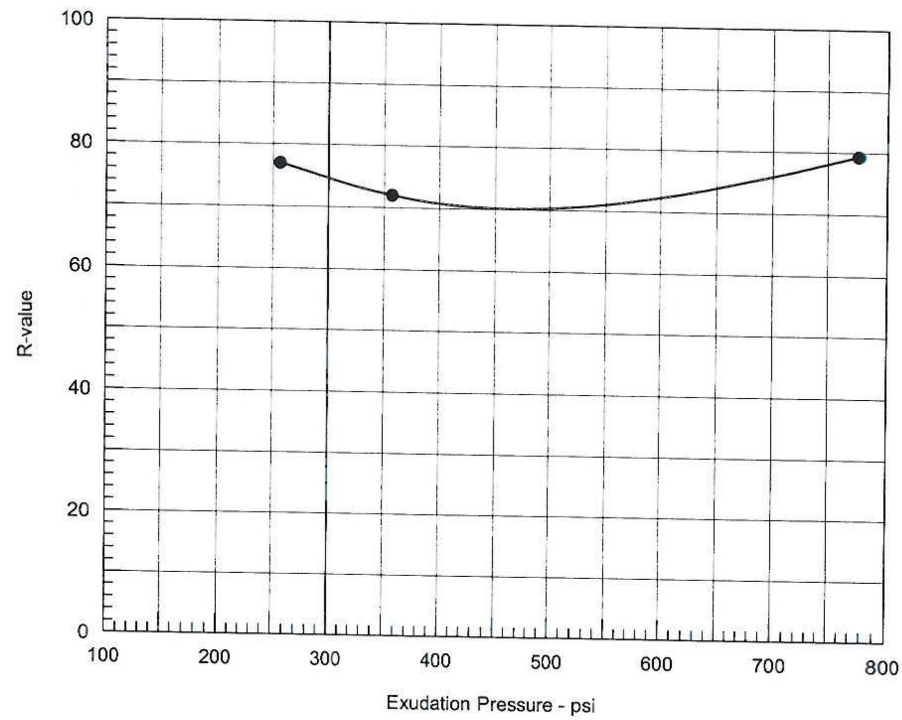
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 9872 | 8792 | 3198 |
| Exudation pressure (psi): | 786 | 700 | 254 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 15 | 14 | 16 |
| D turns: | 6.62 | 7.32 | 6.87 |
| R: | 78.5 | 78.1 | 76.6 |
| Height (in.): | 2.35 | 2.50 | 2.40 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 76.3 | 78.1 | 75.0 |

**R-Value at 300 psi exudation pressure =** 75.8
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-28: R-value test results for Source G Modified gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 18 | 2.50 | 777 | 79.3 | 79.3 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 21 | 2.50 | 357 | 72.0 | 72.0 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 19 | 2.61 | 256 | 75.1 | 77.0 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 74.6 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** H PRE
**Date:** 4/27/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ____

**Figure D-29: R-value test report for Source H Prepared gradation.**

## RESISTANCE R-VALUE TESTING RESULTS
## (ASTM D 2844)

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** H PRE
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

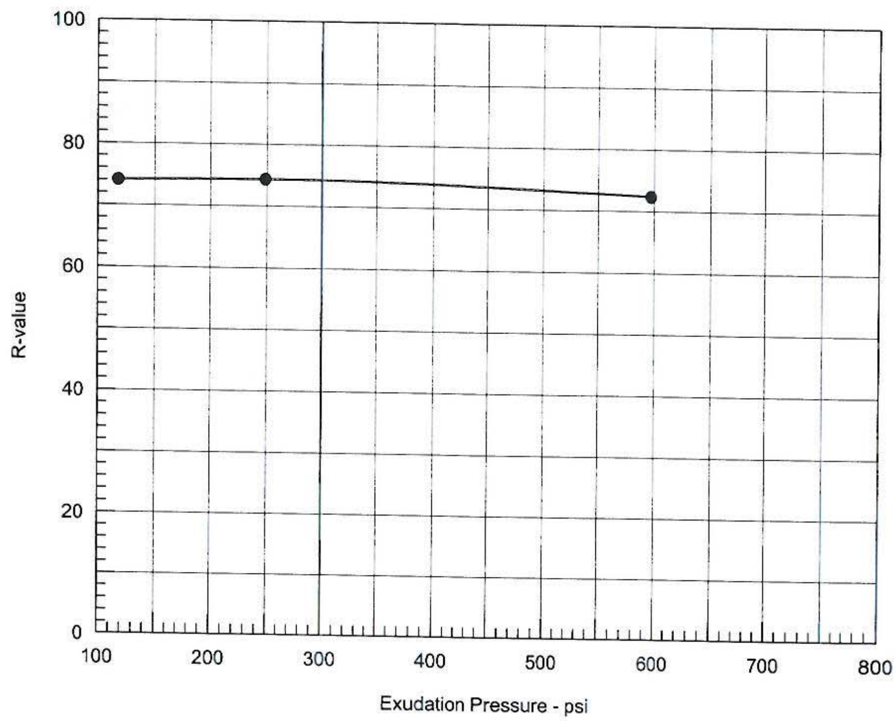
| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 9768 | 4485 | 3221 |
| Exudation pressure (psi): | 777 | 357 | 256 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 18 | 21 | 19 |
| D turns: | 5.14 | 6.43 | 6.14 |
| R: | 79.3 | 72.0 | 75.1 |
| Height (in.): | 2.50 | 2.50 | 2.61 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 79.3 | 72.0 | 77.0 |

**R-Value at 300 psi exudation pressure =** 74.6
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-30: R-value test results for Source H Prepared gradation.**

## R-VALUE TEST REPORT




**Resistance R-Value and Expansion Pressure - ASTM D 2844**

| No. | Compact. Pressure psi | Density pcf | Moist. % | Expansion Pressure psi | Horizontal Press. psi @ 160 psi | Sample Height in. | Exud. Pressure psi | R Value | R Value Corr. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 0.0 | 0.0 | 0.00 | 27 | 2.70 | 597 | 68.1 | 72.4 |
| 2 | 350 | 0.0 | 0.0 | 0.00 | 22 | 2.60 | 249 | 72.5 | 74.3 |
| 3 | 350 | 0.0 | 0.0 | 0.00 | 23 | 2.60 | 118 | 72.2 | 74.1 |
| | | | | | | | | | |

| Test Results | Material Description |
|---|---|
| **R-value at 300 psi exudation pressure =** 74.3 | WTI Research |

**Project No.:** WTI Research
**Project:** WTI Research
**Location:** U0260163B084115
**Sample Number:** H MOD
**Date:** 4/27/2016

**Tested by:** Desiree Moffett
**Checked by:**
**Remarks:**

R-VALUE TEST REPORT

**MONTANA DEPARTMENT OF TRANSPORTATION**

**Figure** ______

**Figure D-31: R-value test report for Source H Modified gradation.**

## RESISTANCE R-VALUE TESTING RESULTS
## (ASTM D 2844)

**Project:** WTI Research
**Project Number:** WTI Research
**Location:** U0260163B084115
**Sample Number:** H MOD
**Material Description:** WTI Research
**Tested by::** Desiree Moffett

| Test specimen number | 1 | 2 | 3 |
|---|---|---|---|
| Compaction pressure (psi): | 350 | 350 | 350 |
| Wet weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Dry weight (gms): | 1200.0 | 1200.0 | 1200.0 |
| Tare weight (gms): | 0.0 | 0.0 | 0.0 |
| % Moisture: | 0.0 | 0.0 | 0.0 |
| Exudation load (lbs.): | 7503 | 3125 | 1479 |
| Exudation pressure (psi): | 597 | 249 | 118 |
| Total weight (gms.): | 0.1 | 0.1 | 0.1 |
| Mold weight (gms.): | 0.0 | 0.0 | 0.0 |
| Sample weight (gms.): | 0.1 | 0.1 | 0.1 |
| Initial expansion (x10,000): | 0 | 0 | 0 |
| Final expansion (x10,000): | 0 | 0 | 0 |
| Expansion pressure (psi): | 0.00 | 0.00 | 0.00 |
| Ph at 2000 lbs.: | 27 | 22 | 23 |
| D turns: | 5.76 | 5.96 | 5.74 |
| R: | 68.1 | 72.5 | 72.2 |
| Height (in.): | 2.70 | 2.60 | 2.60 |
| Dry density (pcf): | 0.0 | 0.0 | 0.0 |
| Corrected R: | 72.4 | 74.3 | 74.1 |

**R-Value at 300 psi exudation pressure =** 74.3
**Expansion pressure at 300 psi =** n/a psi

MONTANA DEPARTMENT OF TRANSPORTATION

**Figure D-32: R-value test results for Source H Modified gradation.**

# Appendix E – Direct Shear Load-Displacement Plots

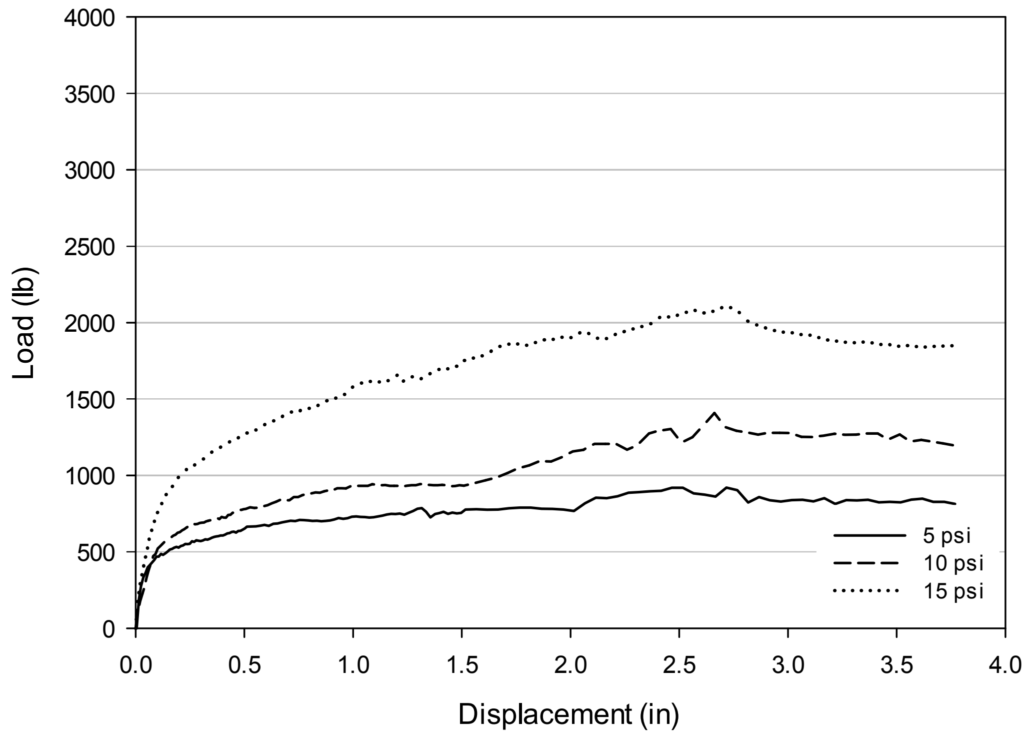



**Figure E-1: Load-displacement plots from direct shear tests on Source A Prepared gradation.**

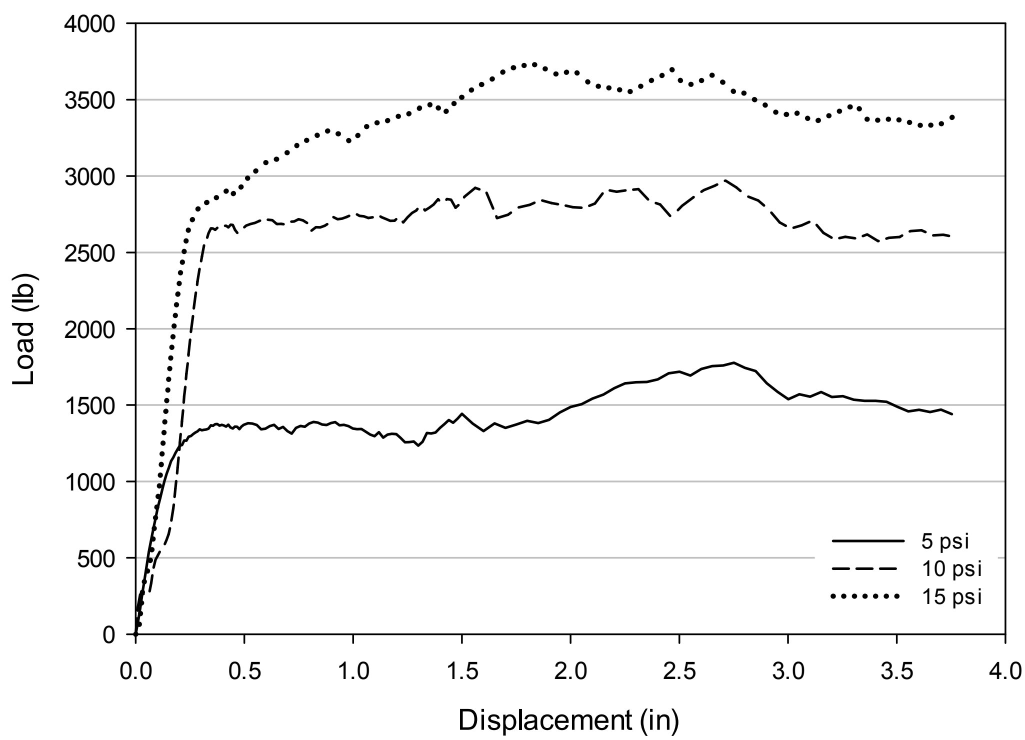



**Figure E-2: Load-displacement plots from direct shear tests on Source A Modified gradation.**

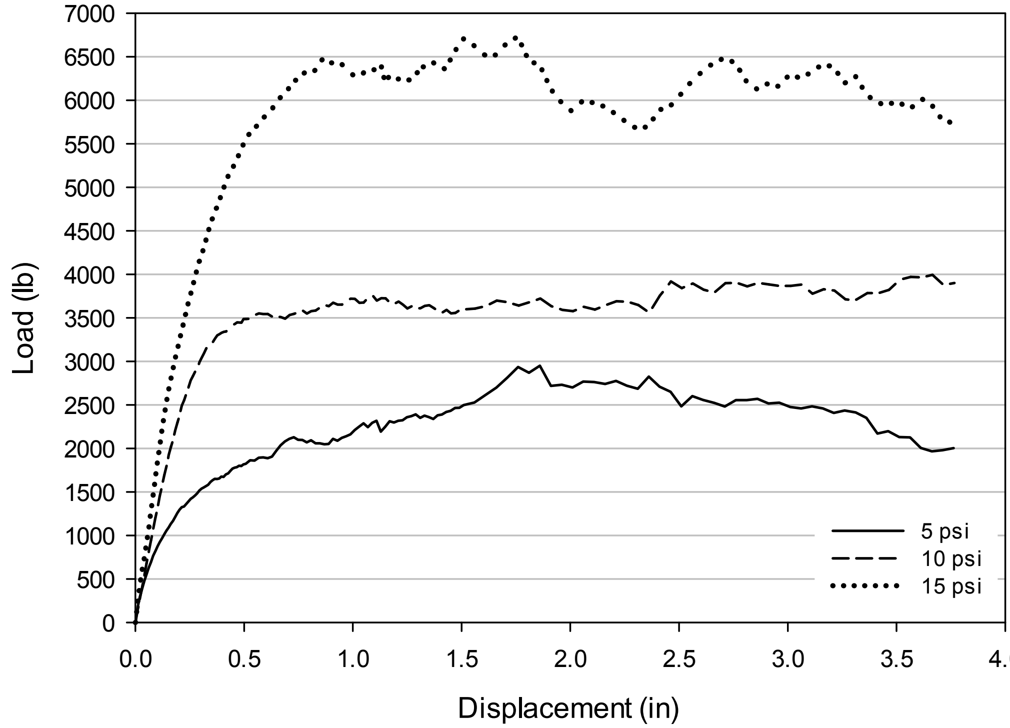



**Figure E-3: Load-displacement plots from direct shear tests on Source B Prepared gradation.**

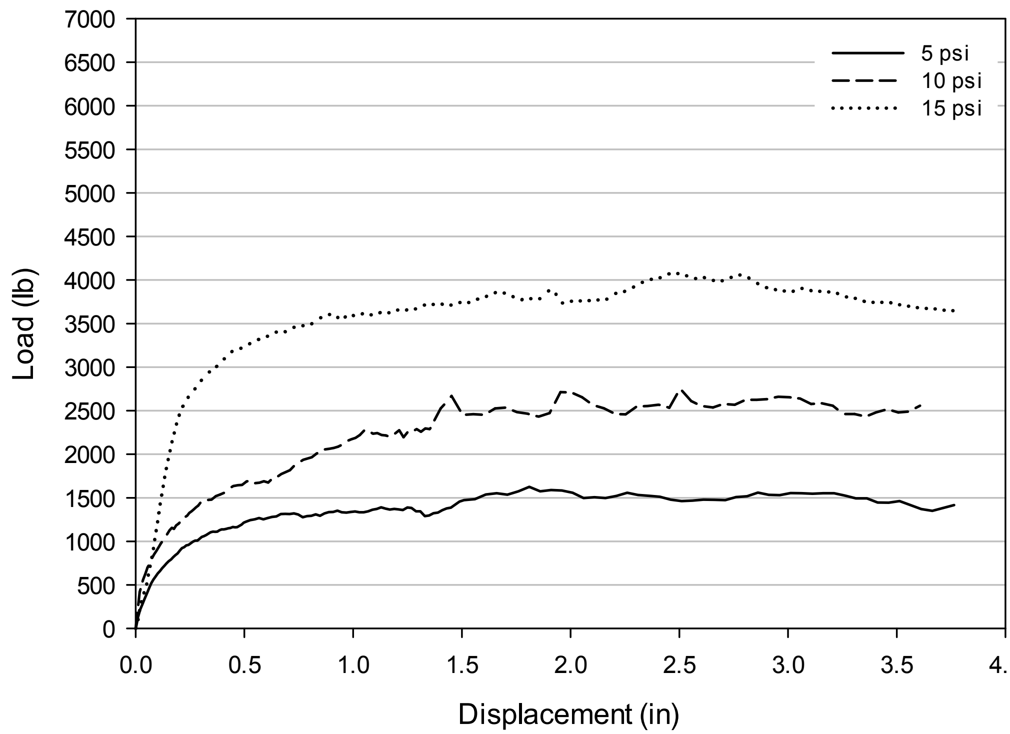



**Figure E-4: Load-displacement plots from direct shear tests on Source B Modified gradation.**

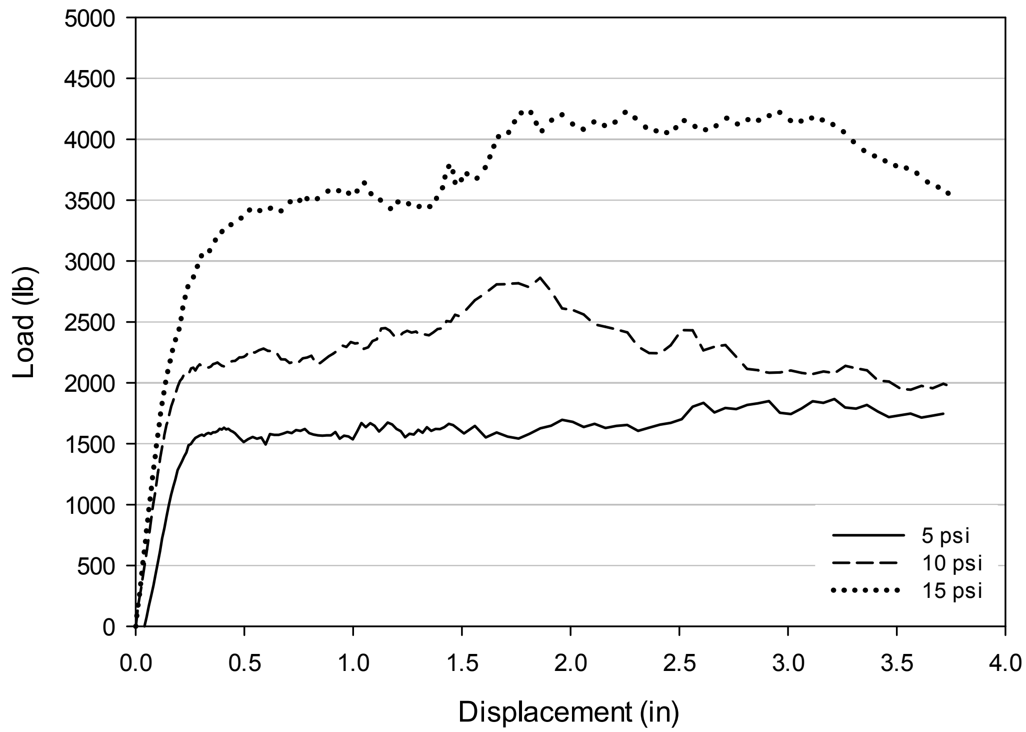



**Figure E-5: Load-displacement plots from direct shear tests on Source C Prepared gradation.**

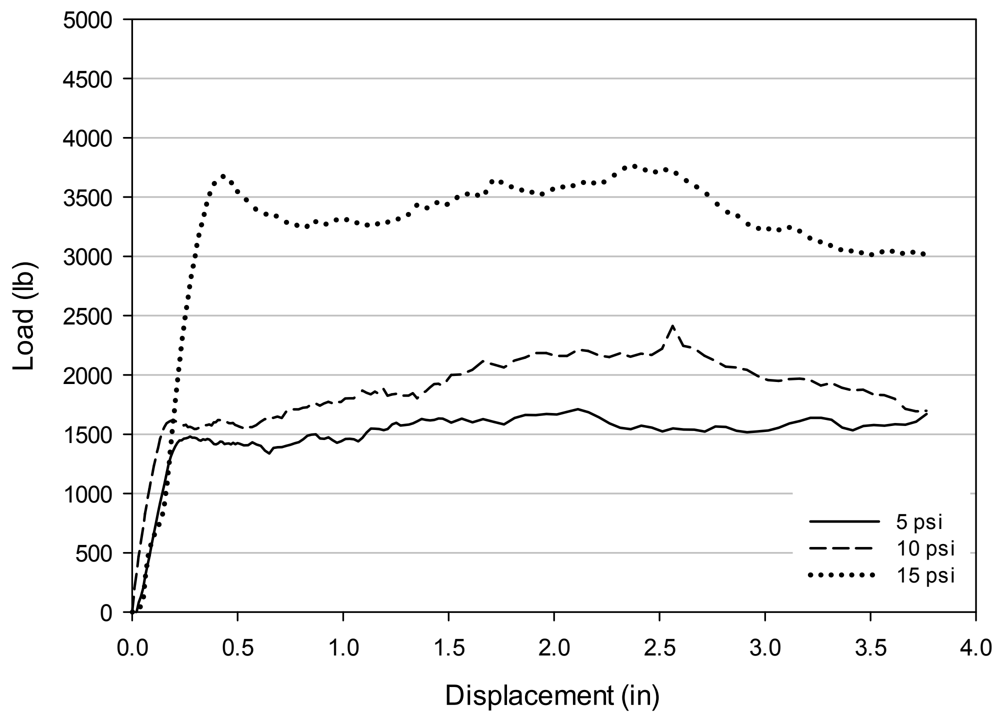



**Figure E-6: Load-displacement plots from direct shear tests on Source C Modified gradation.**

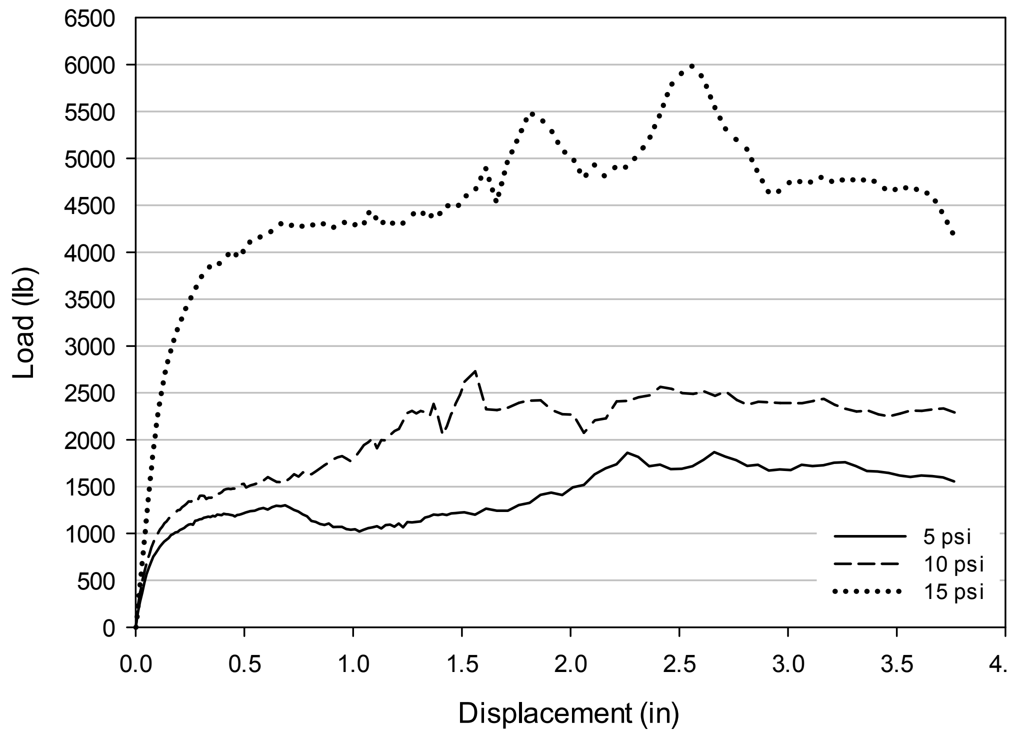



**Figure E-7: Load-displacement plots from direct shear tests on Source D Prepared gradation.**

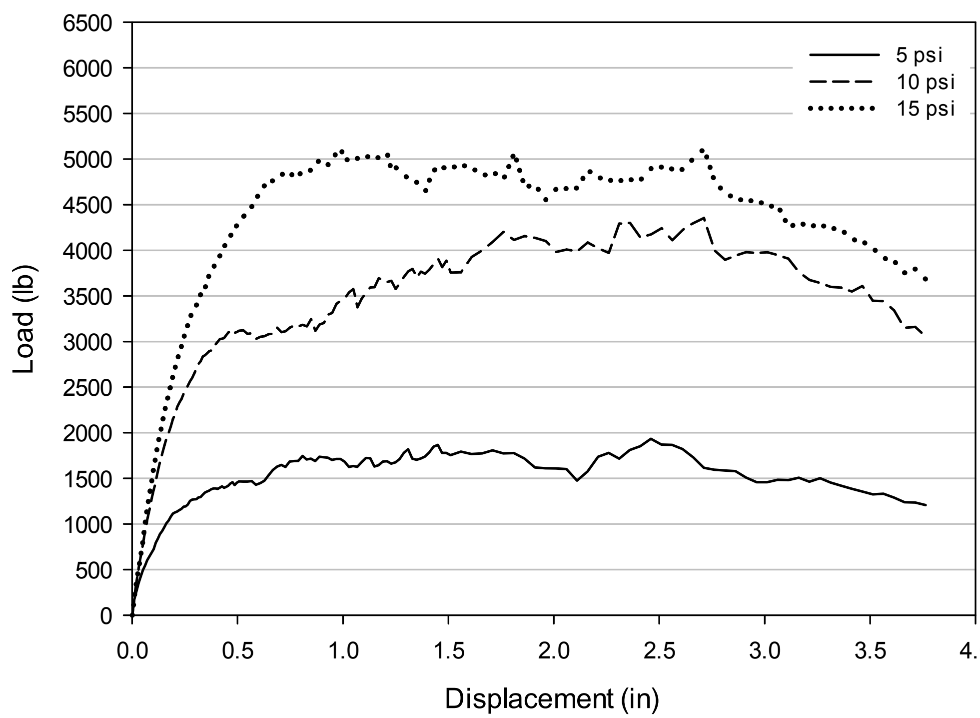



**Figure E-8: Load-displacement plots from direct shear tests on Source D Modified gradation.**

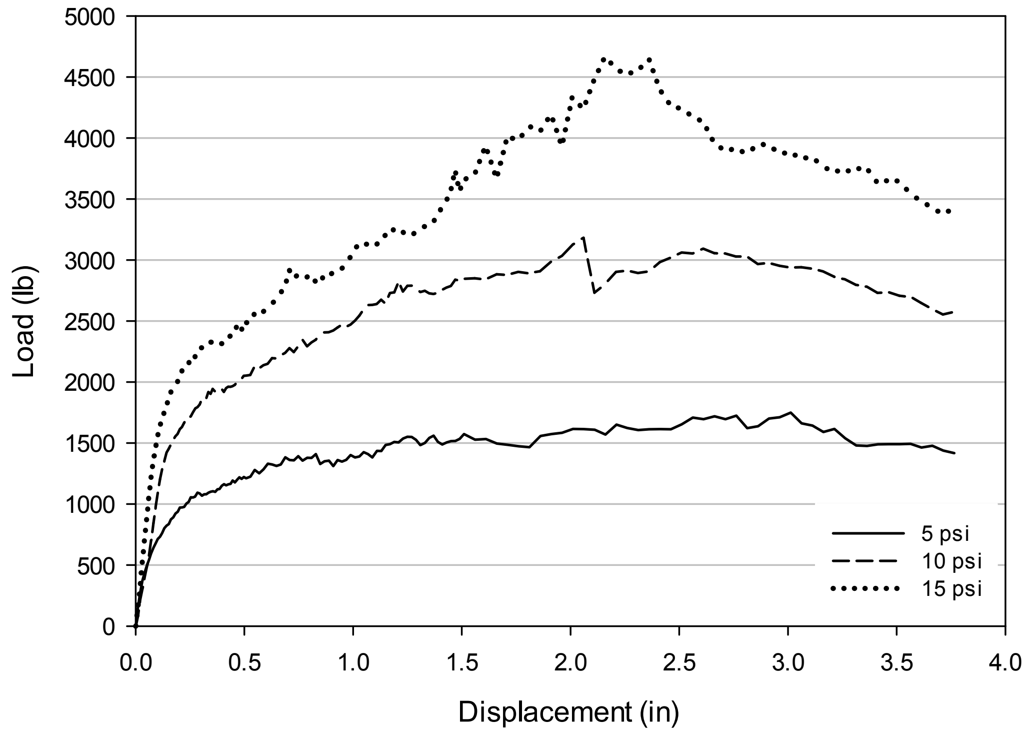



**Figure E-9: Load-displacement plots from direct shear tests on Source E Prepared gradation.**

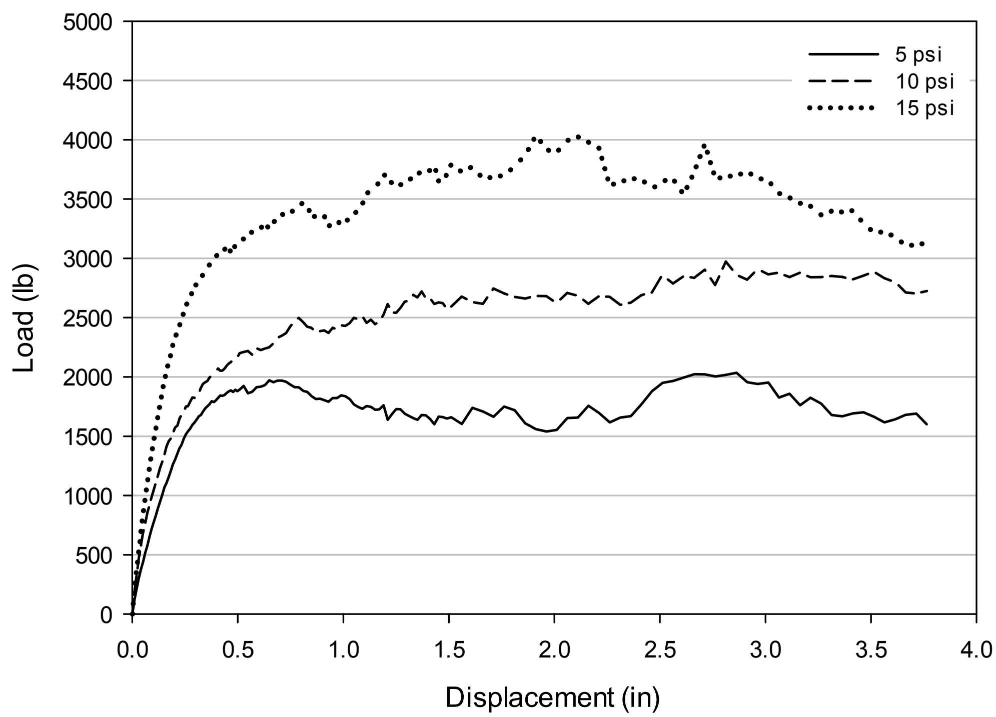



**Figure E-10: Load-displacement plots from direct shear tests on Source E Modified gradation.**

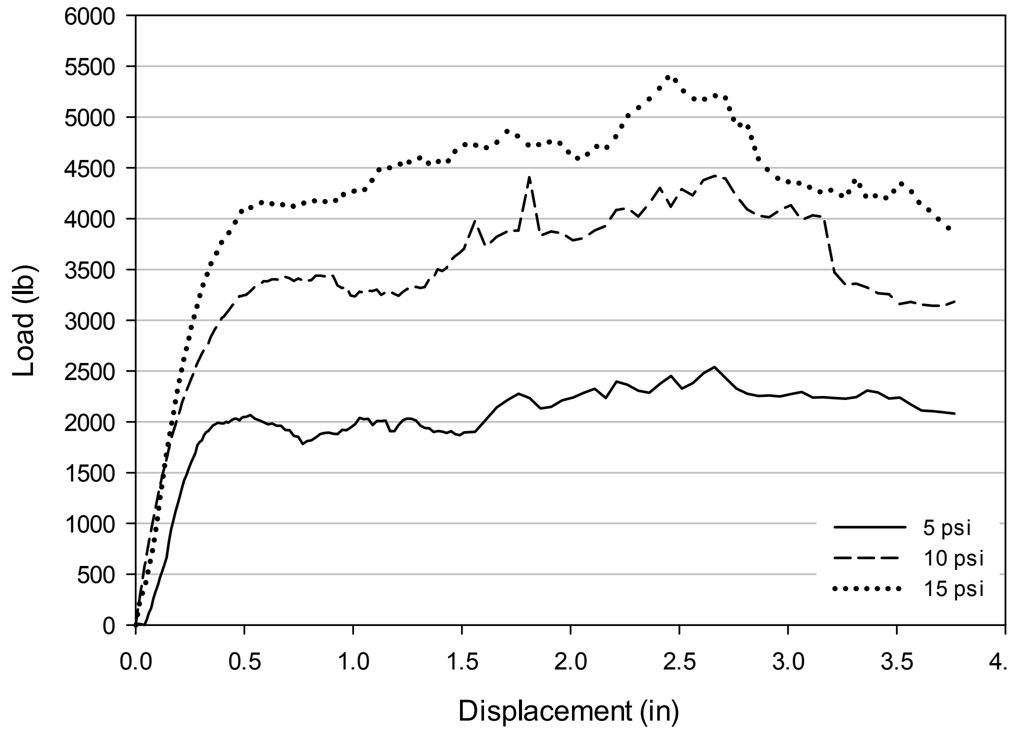



**Figure E-11: Load-displacement plots from direct shear tests on Source F Prepared gradation.**

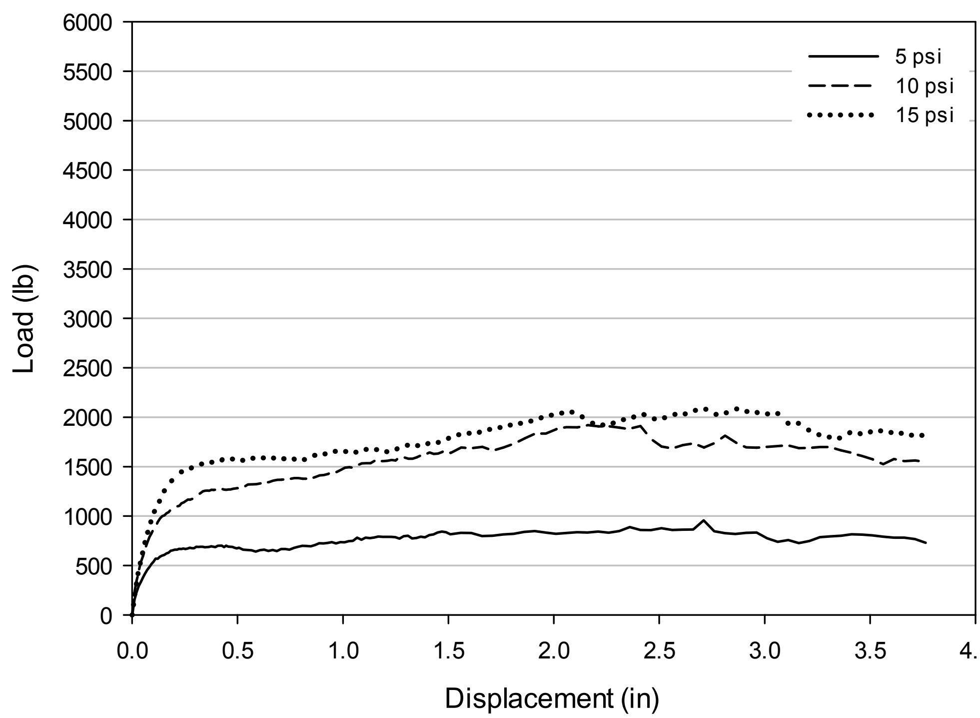



**Figure E-12: Load-displacement plots from direct shear tests on Source F Modified gradation.**

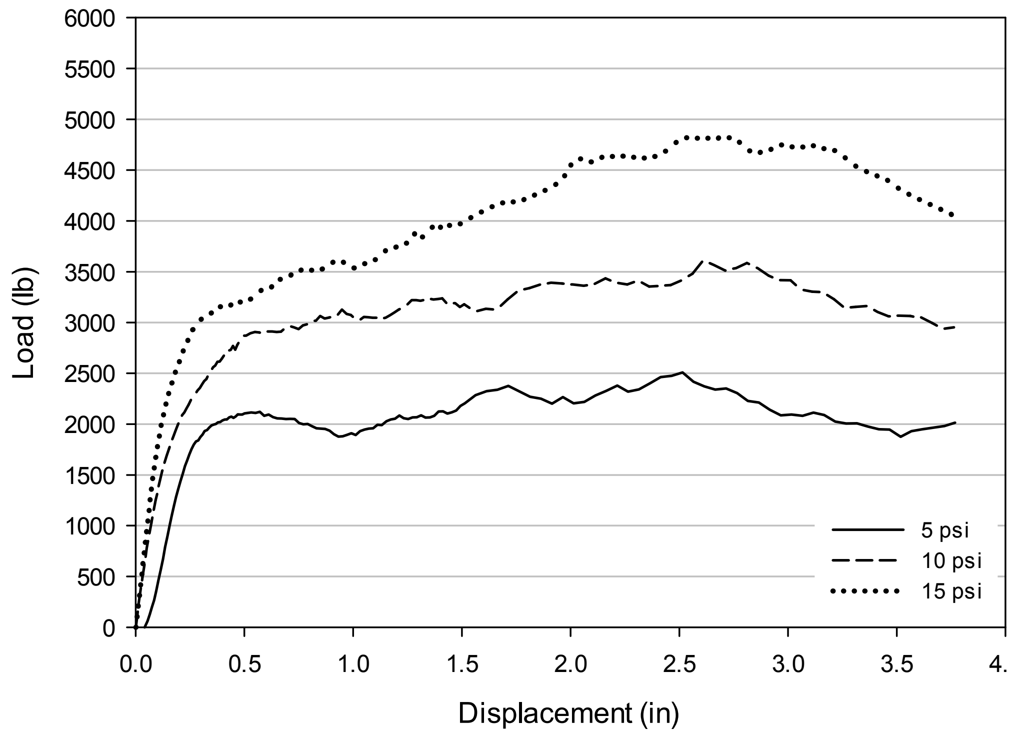



**Figure E-13: Load-displacement plots from direct shear tests on Source G Prepared gradation.**

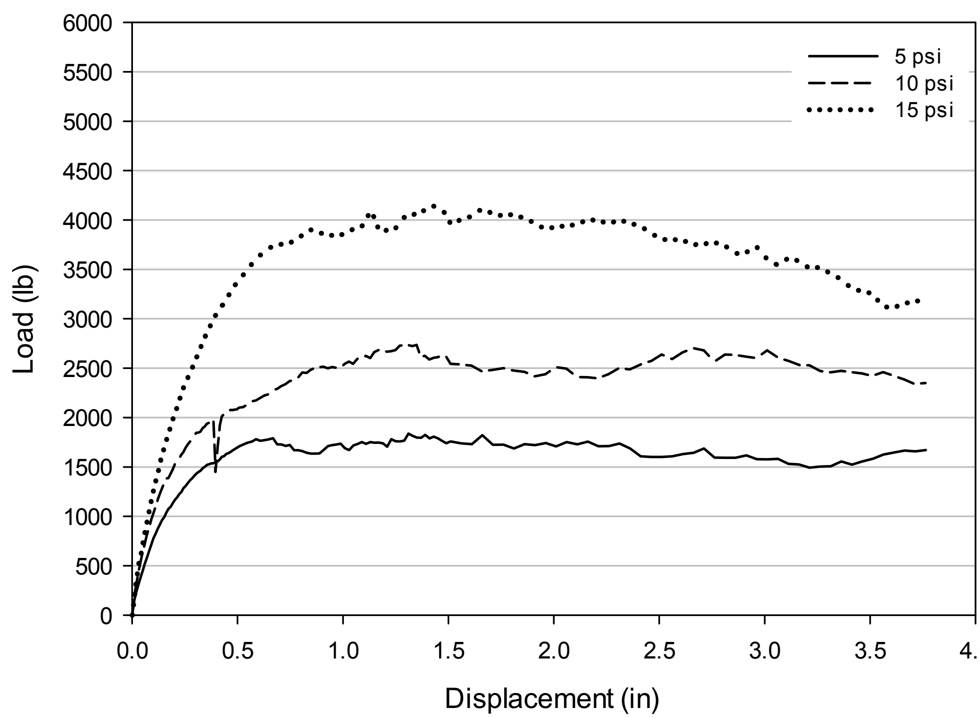



**Figure E-14: Load-displacement plots from direct shear tests on Source G Modified gradation.**

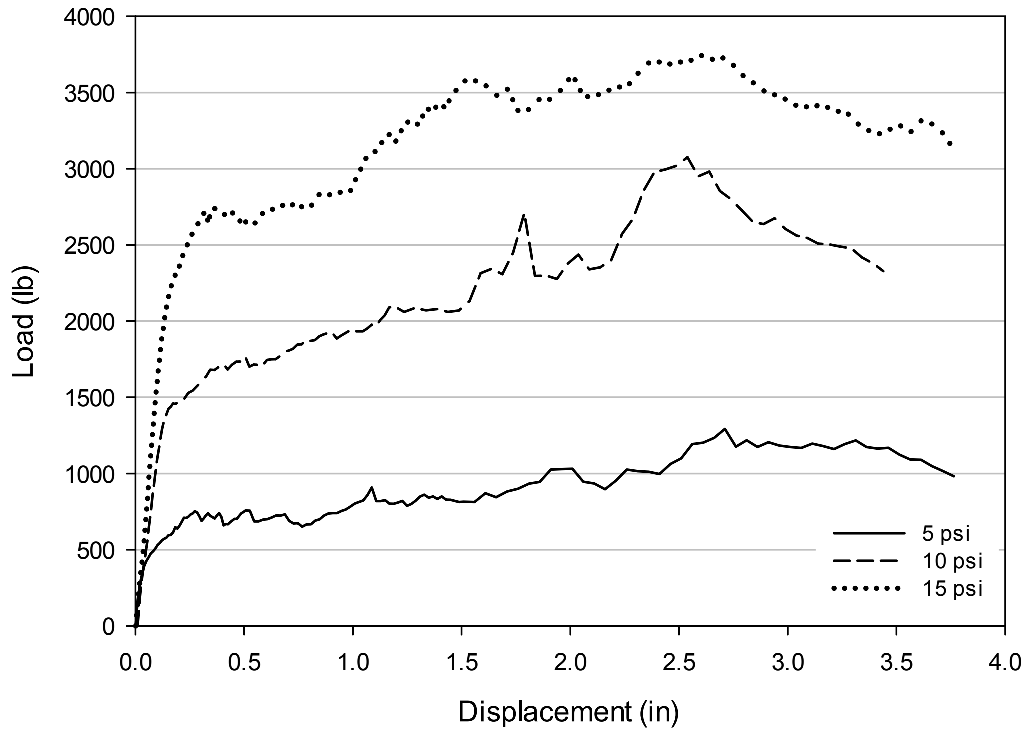



**Figure E-15: Load-displacement plots from direct shear tests on Source H Prepared gradation.**

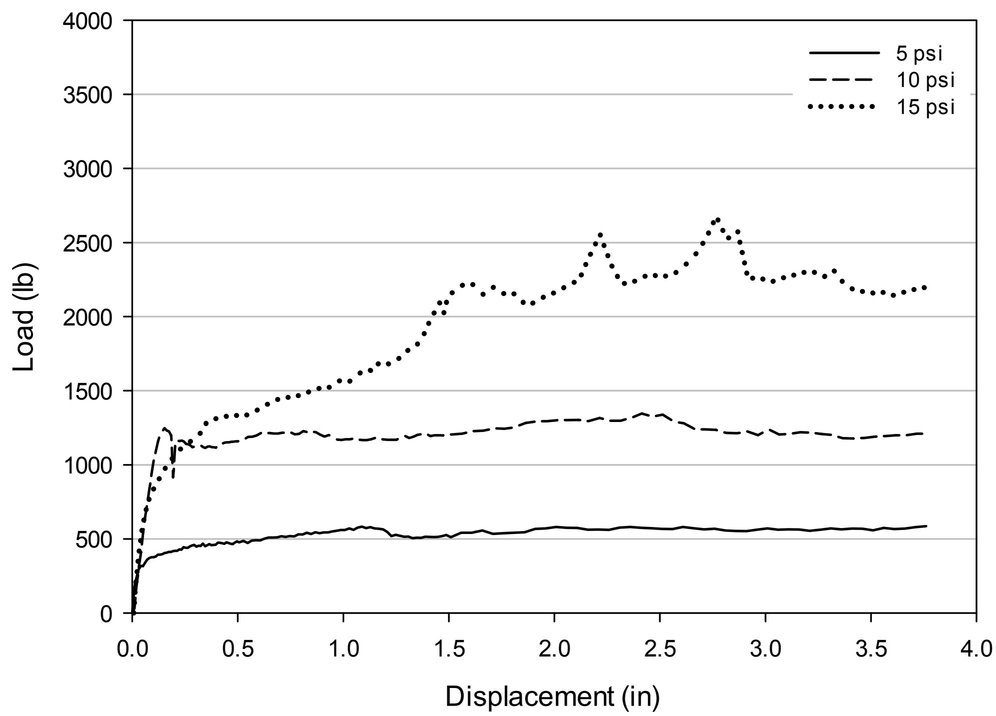



**Figure E-16: Load-displacement plots from direct shear tests on Source H Modified gradation.**

# Appendix F – Direct Shear Friction Angle Plots

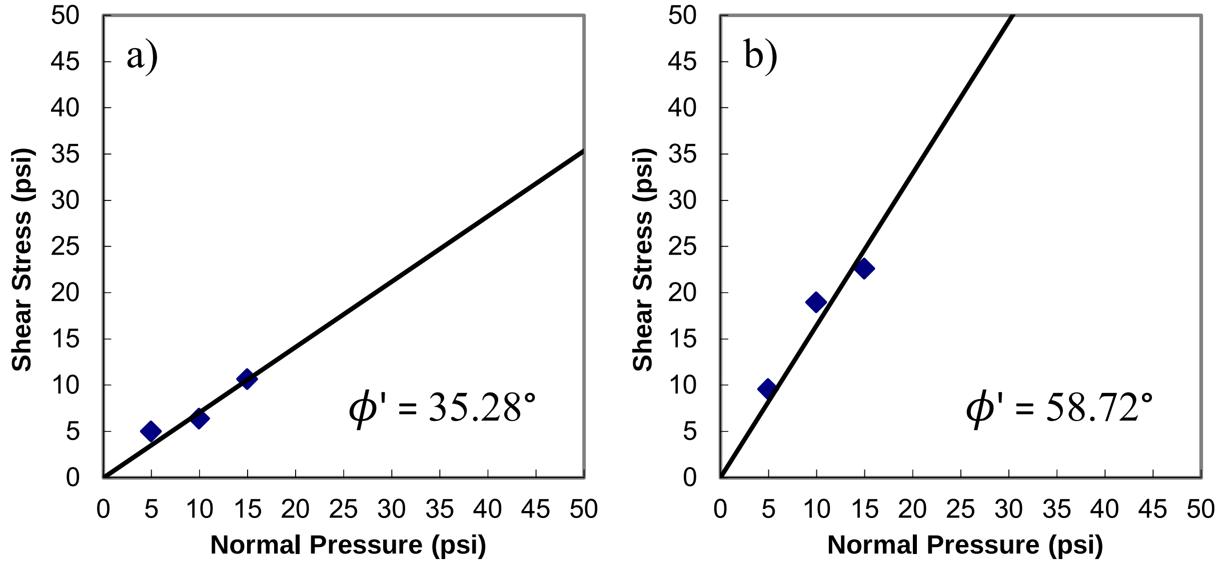



**Figure F-1: Friction angle plots for Source A a) Prepared gradation and b) Modified gradation.**

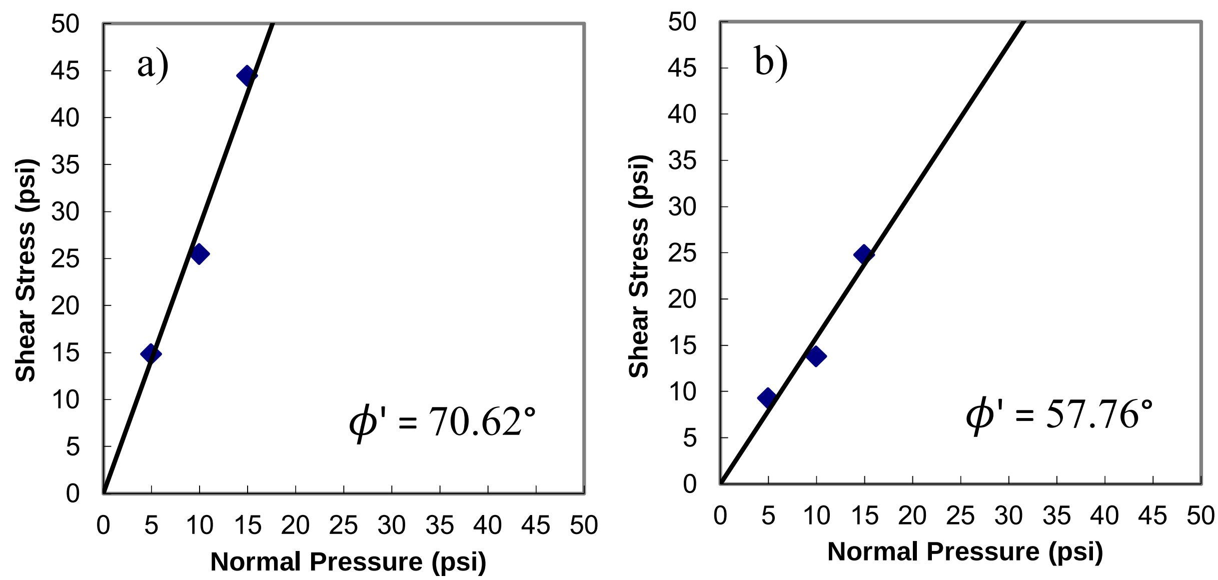



**Figure F-2: Friction angle plots for Source B a) Prepared gradation and b) Modified gradation.**

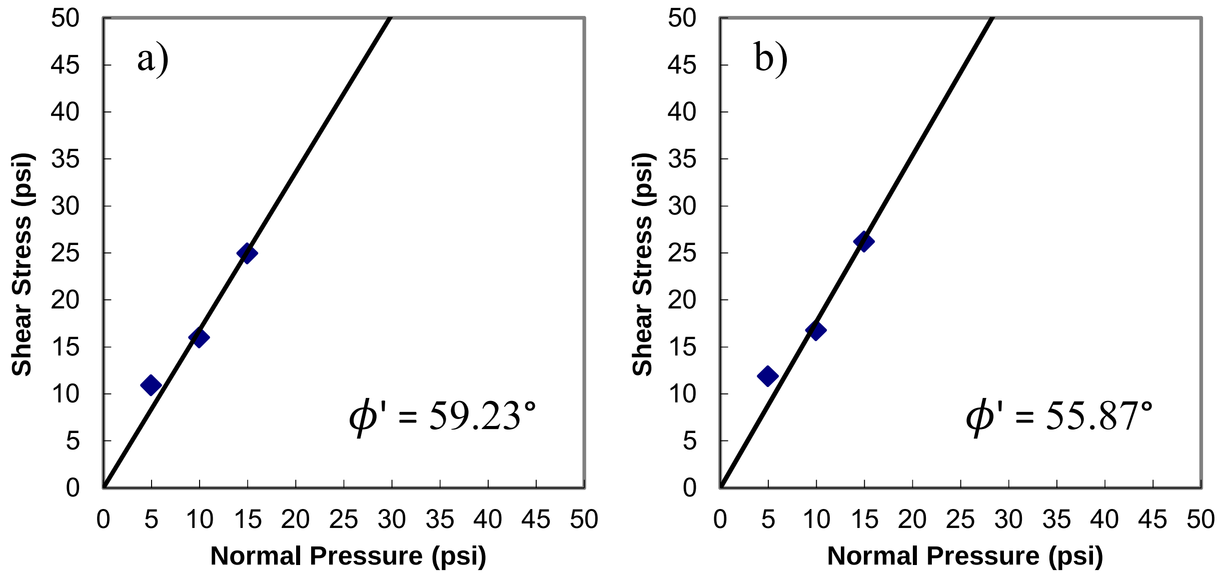



**Figure F-3: Friction angle plots for Source C a) Prepared gradation and b) Modified gradation.**

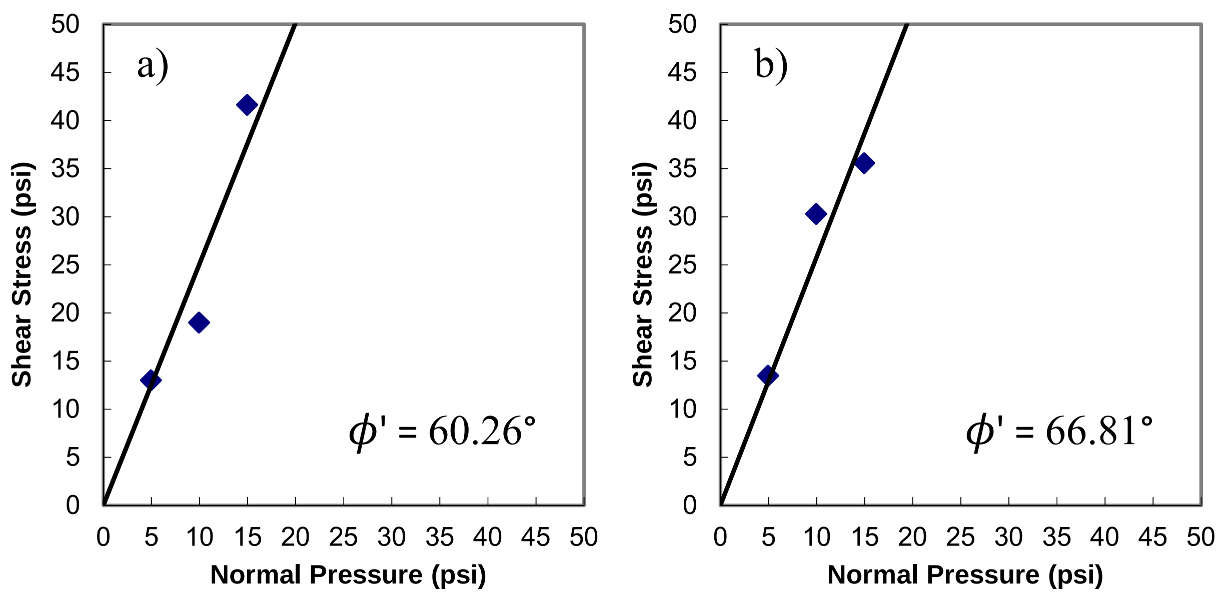



**Figure F-4: Friction angle plots for Source D a) Prepared gradation and b) Modified gradation.**

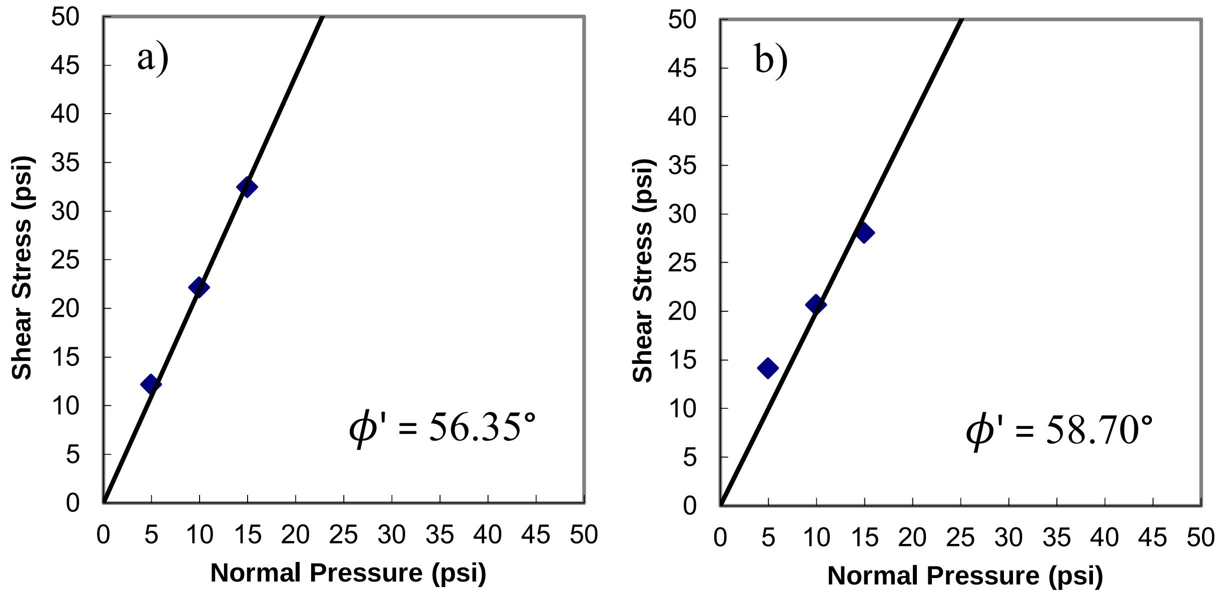



**Figure F-5: Friction angle plots for Source E a) Prepared gradation and b) Modified gradation.**

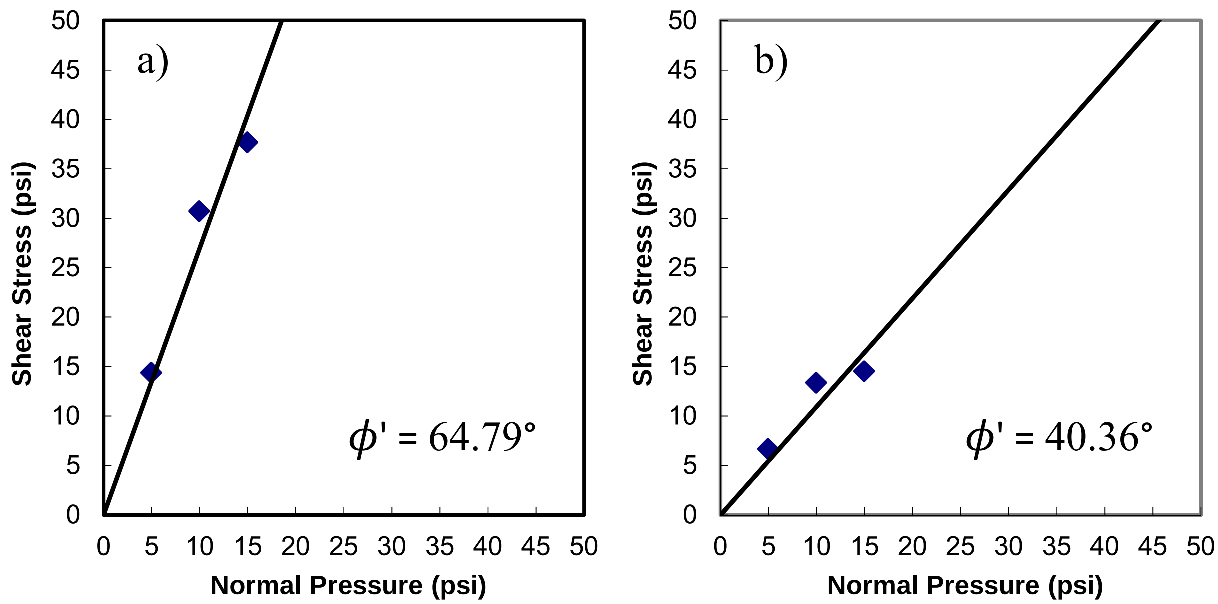



**Figure F-6: Friction angle plots for Source F a) Prepared gradation and b) Modified gradation.**

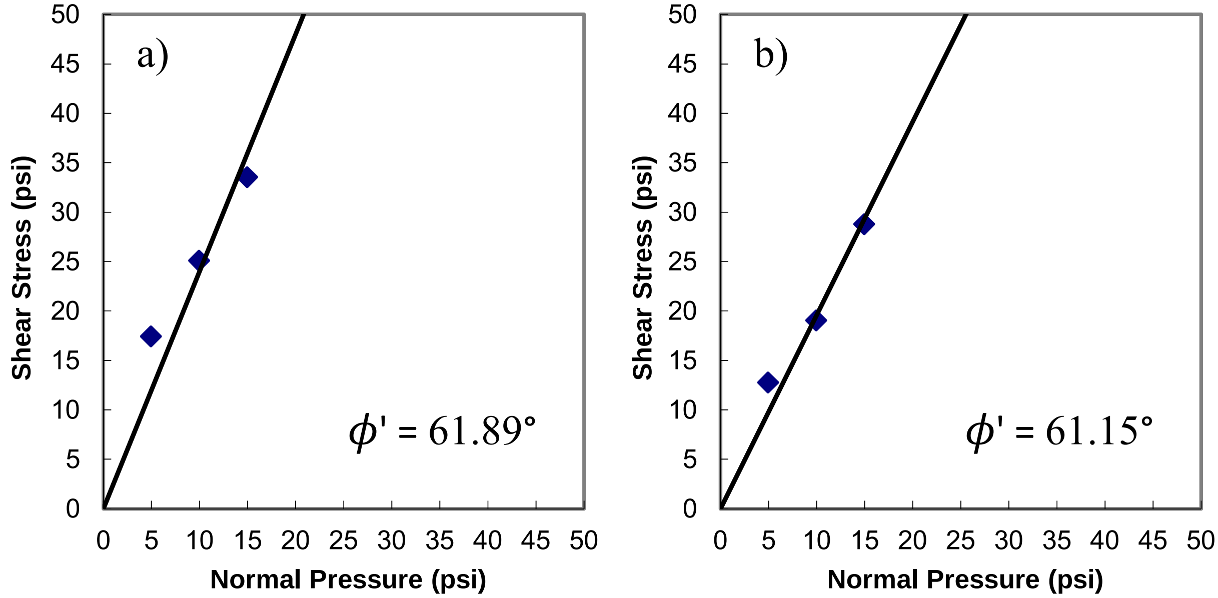



**Figure F-7: Friction angle plots for Source G a) Prepared gradation and b) Modified gradation.**

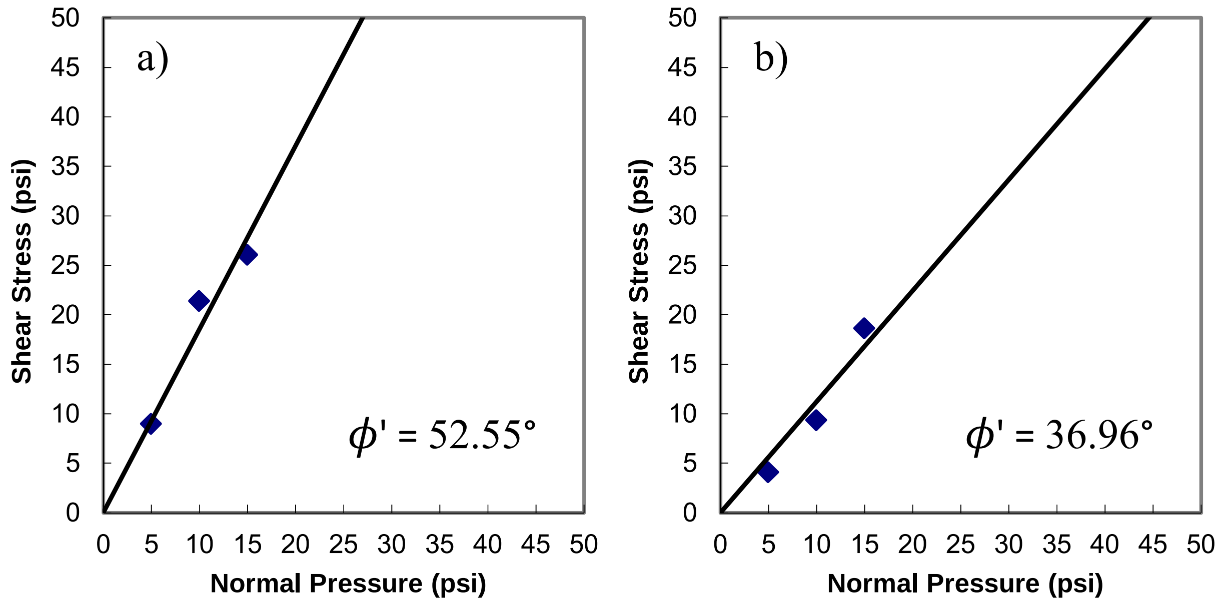



**Figure F-8: Friction angle plots for Source H a) Prepared gradation and b) Modified gradation.**