RESILIENT MODULUS TESTING OF OPEN GRADED DRAINAGE LAYER AGGREGATES FOR INTERLOCKING CONCRETE BLOCK PAVEMENTS

David Hein, P. Eng., Principal Engineer
Applied Research Associates, Inc.
5401 Eglinton Avenue West, Suite # 204
Toronto, Ontario, Canada M9C 5K6
Tel: 416-621-9555, Fax: 416-621-4917 E-mail: dhein@ara.com

SUMMARY

This paper outlines the results of a series of resilient modulus and hydraulic conductivity testing completed for untreated open graded drainage layer aggregates in accordance with the protocols outlined in AASHTO T-307-99. The testing was completed for aggregate gradations corresponding to American Standards for Testing Materials (ASTM) #2, #8 and #57 grading limits as well as several combinations of materials in combination. The purpose of the combined materials testing was to assess the impact of multi-layer aggregate combinations on resilient modulus and layer permeability. The results are compared with those of a conventional dense graded base.

The following conclusions can be drawn from the results of the laboratory testing and analysis program:

- **Deviatoric stress has little influence of resilient modulus of ASTM stones and their combinations tested.**
- **Well graded coarse aggregates (e.g., ASTM #57 stone) tend to have higher resilient modulus.**
- **The measured modulus using "scalped" ASTM #2 stone may not reflect the true characteristics of the material.**
- **When mixing or using combinations, finer aggregate fills up voids between larger particles in a zone at the interface, which may slightly increase resilient modulus and slightly decrease permeability.**
- **The resilient modulus of tests ASTM stones is likely at the higher end of most dense graded aggregate base materials.**

1. INTRODUCTION

Storm water management is a key component of urban infrastructure design. If properly designed and constructed, porous pavements can help rainwater infiltrate soil, decrease urban heating, replenish groundwater and reduce overall water runoff. The construction of permeable pavement systems that can accommodate surface water runoff is gaining increasing attention through the Leadership in Energy and Environmental Design (LEED) program.

The U.S. Environmental Protection Agency (EPA) has indicated that porous pavements traditionally have a failure rate of over 75 percent [US EPA, 2000]. Failure was generally attributed to poor design, inadequate construction quality, improper treatment of the subgrade soils and overloading of under-designed pavements. Recent studies in the United States, United Kingdom and Australia have shown the benefits of porous pavement designs [Shackel, 2002].

A typical interlocking concrete block pavement includes concrete pavers placed on top of a succession of layers including; bedding sand, base and subbase. The base layer can be constructed using untreated aggregate, asphalt treated base or cement treated base. If either asphalt or cement treated base or a permeable base material is used a dense graded granular subbase layer is typically placed underneath the treated base layer.

The factors that are typically taken into account by pavement design methodologies can be grouped into five main categories: environment, traffic type and composition, subgrade soil strength, and pavement layer material properties. Moisture and temperature levels and variations can have a significant influence on the performance of a pavement. Excessive moisture can decrease the load bearing capacity of the subgrade or base materials, while high temperatures can contribute to a decreased load bearing capacity, particularly for asphalt stabilized layers. Moisture and freezing temperatures working together will lead to freeze-thaw cycles in the pavement structure, thus causing heaving of certain layers and reduced bearing capacity during thaw periods.

In order to develop some structural and permeability data on typical untreated drainage layer aggregates, a laboratory study was completed. The testing was completed for combinations of aggregate corresponding to American Standards for Testing Materials (ASTM) #2, #8 and #57 aggregate gradations in layer thicknesses as follows:

- 300 mm of ASTM #2 stone.
- 300 mm of ASTM #8 stone.
- 300 mm of ASTM #57 stone.
- 100 mm of ASTM #57 stone over 200 mm of ASTM #2 stone.
- 75 mm of ASTM #8 stone over 100 mm of ASTM # 57 stone over 125 mm of ASTM # 2 stone.
- 50 mm of ASTM #8 stone over 100 mm of ASTM #57 stone over 150 mm of ASTM #2 stone.
- 300 mm of dense graded aggregate base.

Hydraulic conductivity tests were also conducted on each aggregate and each aggregate combination. The AASHTO standards utilized for this study include:

- AASHTO T307-99, Determining the Resilient Modulus of Soils and Aggregate Materials.
- AASHTO D 2434-68, Standard Test Method for Permeability of Granular Soils.
- AASHTO Designation: T27-99, Sieve Analysis of Fine and Coarse Aggregates.

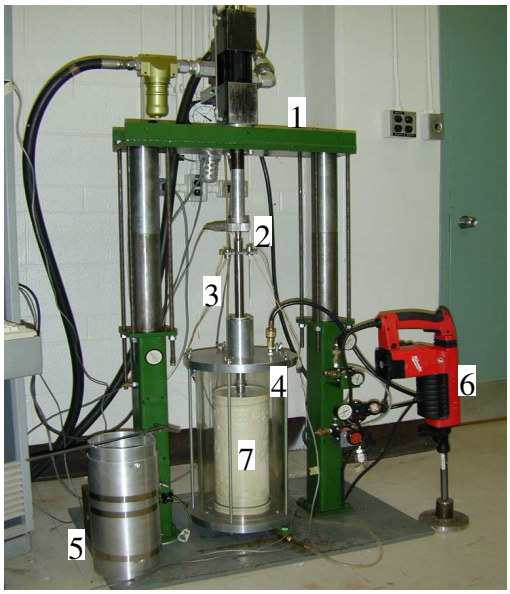
The following symbols, (as used in AASHTO designation T 307-99), are used in this paper:

e_r	–	The resilient axial deformation due to S_{cyclic}
M_r	–	Resilient modulus
S_1	–	Axial stress
S_3	–	Confining pressure
$S_{contact}$	–	Contact stress
S_{cyclic}	–	Cyclic axial stress
S_{max}	–	Maximum axial stress
p	–	Mean stress $p = (S_1 + 2S_3)/3$
Bulk stress	–	$\sigma = 3p = S_1 + 2S_3$;
σ	–	The resilient (recovered) axial strain due to S_{cyclic}.

2. TESTING SYSTEM FOR RESILIENT MODULUS

2.1 Apparatus

The loading device is a closed-loop, servo-controlled electro-hydraulic MTS testing machine with a function generator that is capable of applying repeated cycles of a haversine load pulse and of following a history supplied by the microcomputer control software. Photograph 1 shows the loading frame together with the triaxial cell that is capable of hosting the 150 mm x 300 mm specimen, the devices for specimen preparation as well as the transducers, including a load cell and two linear differential transducers (LVDT) used externally to measure the deformation of the specimen.



1–Load frame
2–Load cell
3–LVDT
4–Triaxial cell
5–Split mould
6–Vibratory compaction device
7–Test specimen

Photograph 1. Loading system

2.2 Load Pulse and Data Acquisition

Figure 1 provides an example of repetitive load pulses generated by the testing system. Each loading cycle consists of a loading duration of 0.1 second followed by a rest period of 0.9 second, as required by AASHTO T 307-99. Approximately 200 data points from the load cell and each LVDT are recorded per load cycle.

2.3 Sample Preparation Method and Testing Procedure

All samples were compacted using a vibration device (as shown in Figure 1, Item 6), which meets the requirement of AASHTO T307-99. Samples were prepared and tests following the sample preparation method and the standard procedure described in AASHTO T307-99.

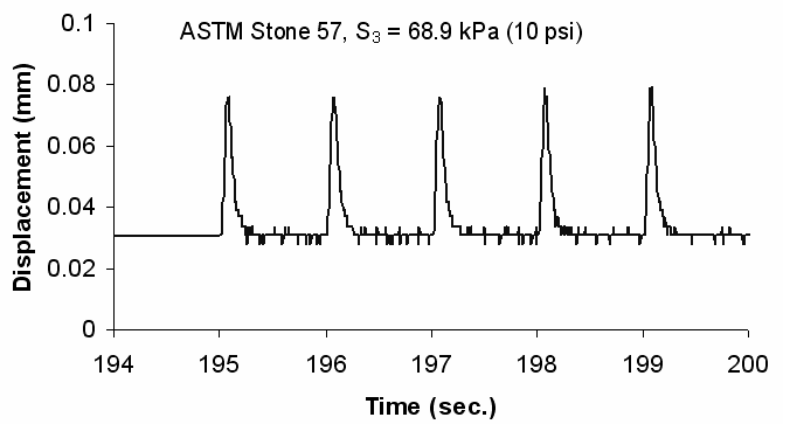


Figure 1. Cyclic axial load and induced displacements for ASTM # 57 Stone

3. AGGREGATE AND PROPERTIES

Limestone aggregates were obtained from a local Ontario quarry source for use in the testing. Sieve analyses were completed for each aggregate according to the requirements outlined in AASHTO T27-99. These materials as obtained directly from the quarry did not satisfy the gradation requirements for ASTM specifications for #2, #8 and #57 stones. In order to satisfy the ASTM gradations, particles of different sizes were separated and re-mixed in the laboratory. It should be noted that particles larger than 37.5 mm were removed "scalped" according to the requirements outlined in the test procedure. As a result, the modified ASTM #2 stone only had particles smaller than 37.5 mm. The ASTM gradations of the materials tested are shown in Figures 2, 3 and 4. Based on volume measurements of the compacted specimens, given the specific gravity of particles varies over a range of 2.63 to 2.70, the average void ratios of compacted ASTM gradations and different combinations are given in Table 1. With the exception of the modified ASTM #2 stone and the combination of 100 mm of ASTM #57 stone over 200 mm modified ASTM #2 stone, the average void ratio of all other materials varies over a range of 0.45 to 0.55, which corresponds to a porosity of approximately 31 to 35 percent.

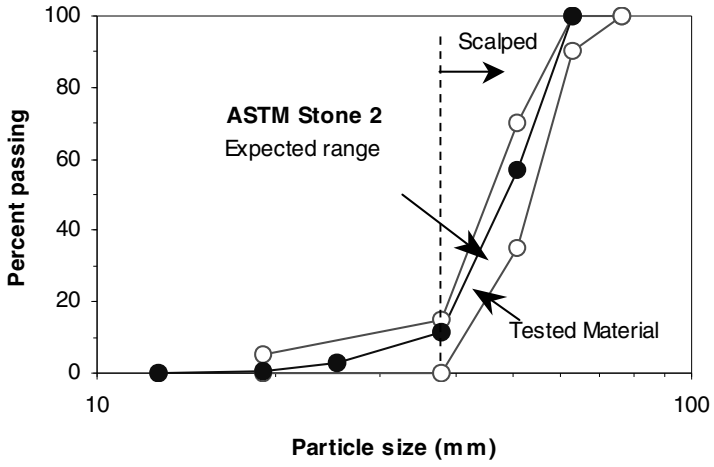


Figure 2. Gradation for ASTM #2 Stone

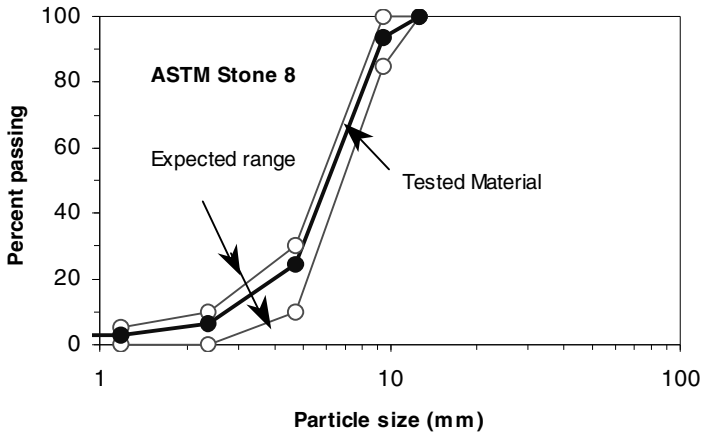


Figure 3. Gradation for ASTM #8 Stone

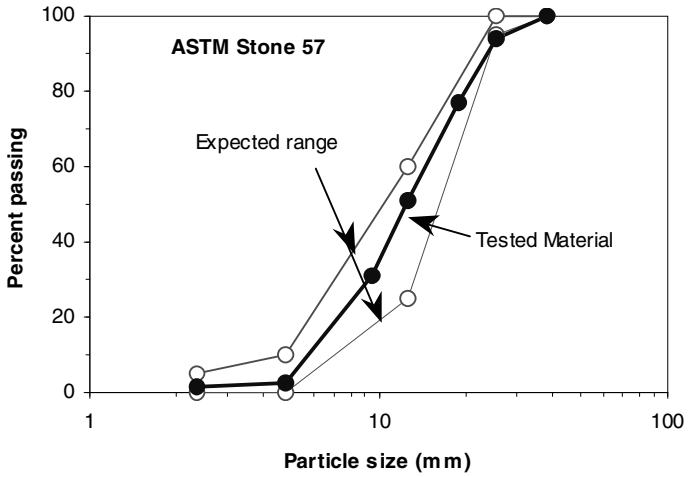


Figure 4. Gradation for ASTM #57 Stone

Table 1. Void space and permeability of various compacted materials

Material/Combination	Voids (%)	Permeability(x 10^{-5})m/s
ASTM #57 stone	33	30-35
ASTM #8 stone	31	30-35
ASTM #2 stone (modified)	48	35-40
100 mm #57 over 200 mm #2 stone (modified *)	39	25-30
75 mm #8 + 100 mm #57 + 125 mm #2 stone (modified)	35	25-30
50 mm #8 + 100 mm #57 + 150 mm #2 stone (modified)	35	25-30
Granular A Base	18	19-21
Harris Granular A Base	13	9-12.5
Aberfoyle Granular A Base	13	0.3-0.4

* Note: Modified refers to the fact that particles larger than 37.5 mm were "scalped" from the ASTM #2 stone gradation according to the requirements outlined in AASHTO T 307-99.

4. RESILIENT MODULUS TEST RESULTS

The results of the resilient modulus results for the 300 mm of ASTM #57 stone are shown in Figure 5. The variation of resilient modulus (M_r) with mean stress can be described by

ASTM #57 stone: $M_r = 416.5(p / p_a)^{0.589}$ (MPa) (1)

with p_a = 100 kPa being the atmospheric pressure and the unit of the mean stress p being kilopascals. Figure 6 summarizes the measured resilient moduli of the ASTM #2, #8 and #57 stone. The relation between M_r and mean stress p for the ASTM #8 and #2 stone can be described by

ASTM Stone #8: $M_r = 365.0(p / p_a)^{0.575}$ (MPa) (2)

ASTM Stone #2: $M_r = 334.5(p / p_a)^{0.561}$ (MPa) (3)

Dense graded base: $M_r = 420.0(p / p_a)^{0.445}$ (MPa) (4)

For a given mean stress p, the ASTM #57 stone has the highest resilient modulus and the ASTM #2 stone has the lowest resilient modulus. It should be noted that Eq. (3) may not reflect the true characteristics of ASTM #2 stone since particles larger than 37.5 mm (25 percent of the mould diameter) were scalped off as required in the AASHTO T 307-99 protocol.

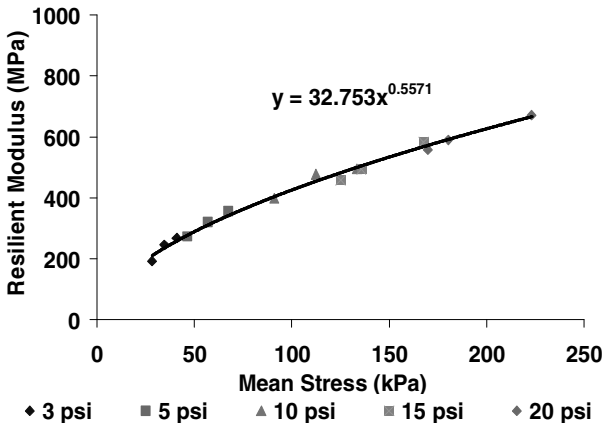


Figure 5: M_r of ASTM #57 Stone (300 mm) (10 psi – 68.9 kPa)

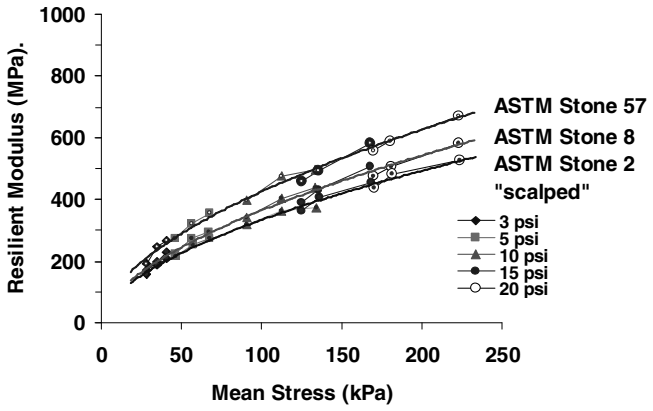


Figure 6: M_r of ASTM #2, #8, #57 Stone (10 psi – 68.9 kPa)

4.1 Resilient Moduli of ASTM Stone Combinations

Figure 7 presents the resilient moduli of various combinations of ASTM stones. The test results indicate that the combination of 100 mm of ASTM #57 stone over 200 mm of ASTM #2 stone has the same resilient modulus characteristics as those of the 75 mm of ASTM #8 over 100 mm of ASTM #57 over 125 mm of ASTM #2 stone. Figure 8 compares the resilient moduli of 100 mm of ASTM #57 over 200 mm of ASTM #2 stone with those of 300 mm of ASTM #57 stone. With combinations of various aggregates, the finer aggregate particles tend to fill the voids between larger particles at the material interface, as shown in Figure 9. As a result, one may expect locally denser zones at material interfaces, which may result in slightly higher resilient moduli, particularly for the combination of 50 mm of ASTM #8 over 100 mm of ASTM #57 over 150 mm of ASTM #2 stone (modified).

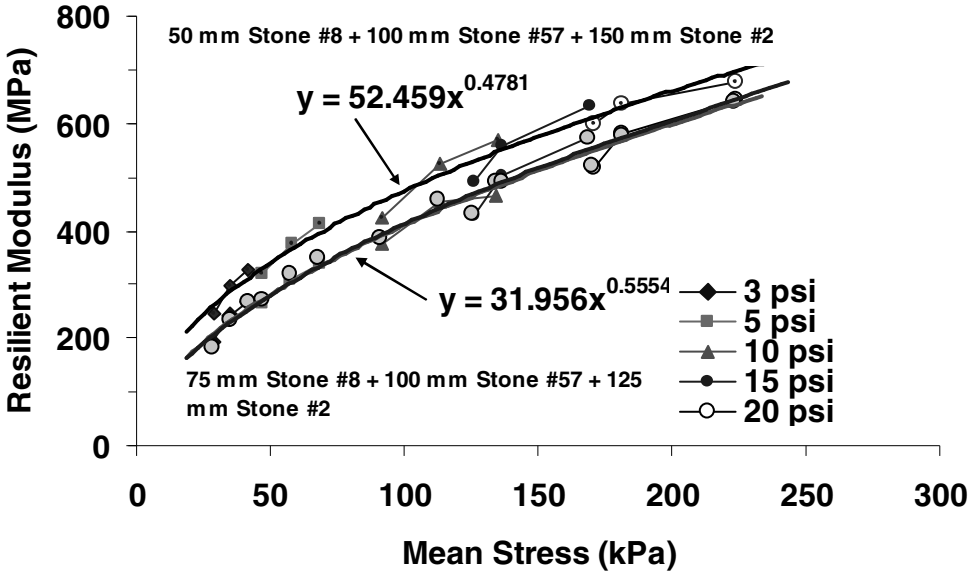


Figure 7. Resilient moduli of ASTM Stone Combinations (10 psi – 68.9 kPa)

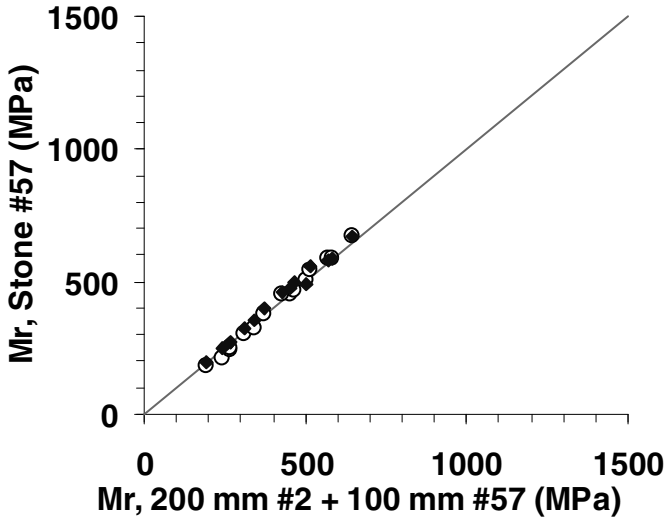


Figure 8. Comparison of ASTM #57 and 200 mm #2 over 100 mm #57 Combination

4.2 Resilient Modulus of Dense Graded Aggregate Base

Figures 10 and 11 present the resilient moduli of the tested aggregates in comparison to a typical Ontario dense graded base course material. The values of resilient modulus of these base materials vary over a wide range. For example, at the mean stress p = 27 kPa (or the bulk stress σ = 81 kPa), M_r varies between 120 MPa and 230 MPa. When p = 220 kPa (i.e., σ = 660 kPa), M_r can range between 470 to 650 MPa. From, it can be seen that the resilient modulus of compacted ASTM stones and stone

combinations is at the higher end of dense graded aggregate base materials.

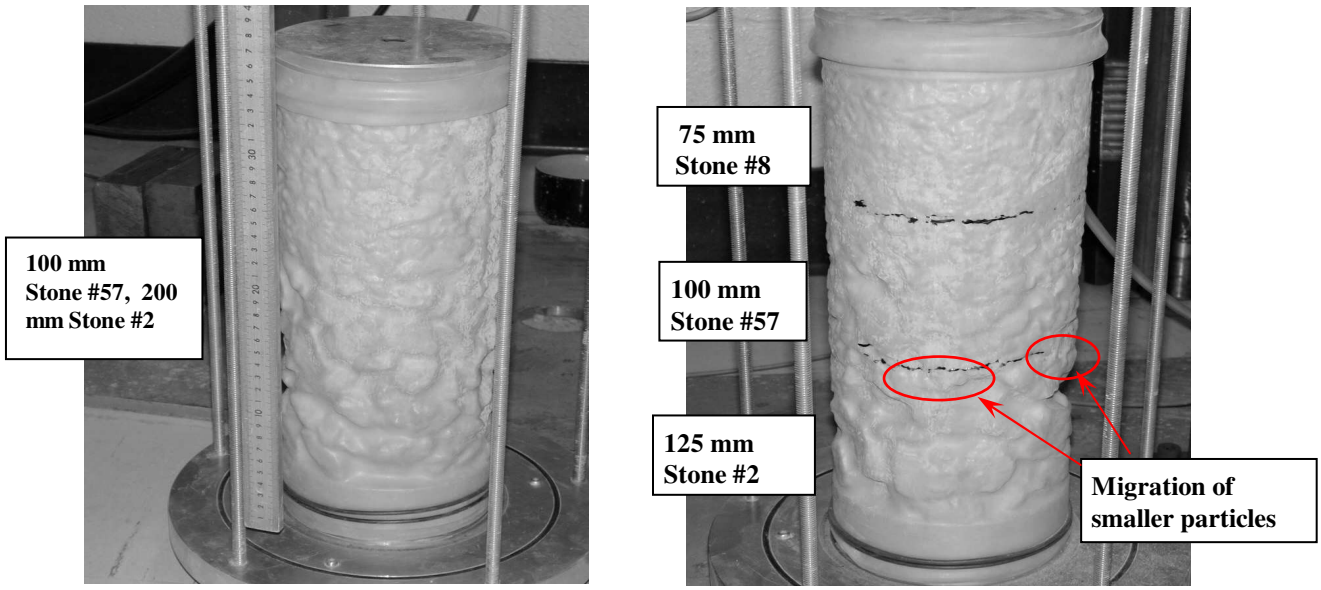


Figure 9. Specimens of ASTM Stone #2 and Different Combinations

4.3 Recommended Resilient Modulus Values for Pavement Design Purposes

The results of the resilient modulus testing for the three gradations of ASTM stone, combinations of ASTM stone and dense graded aggregate base is generally consistent with expectations for the aggregate types and gradations. Using a mean stress of 100 kPa, which would represent the stress condition of a typical concrete block paver pavement under the load of a heavy truck/bus, a design resilient modulus of about 400 MPa could conservatively be selected for input for elastic layer analyses.

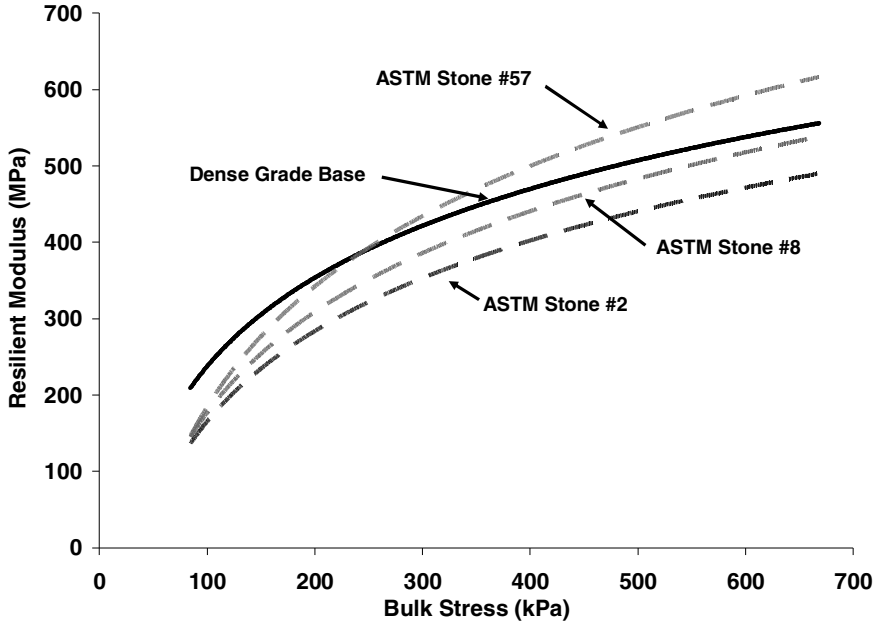


Figure 10. Modulus of tested aggregates (single sizes) vs. typical Ontario dense graded base

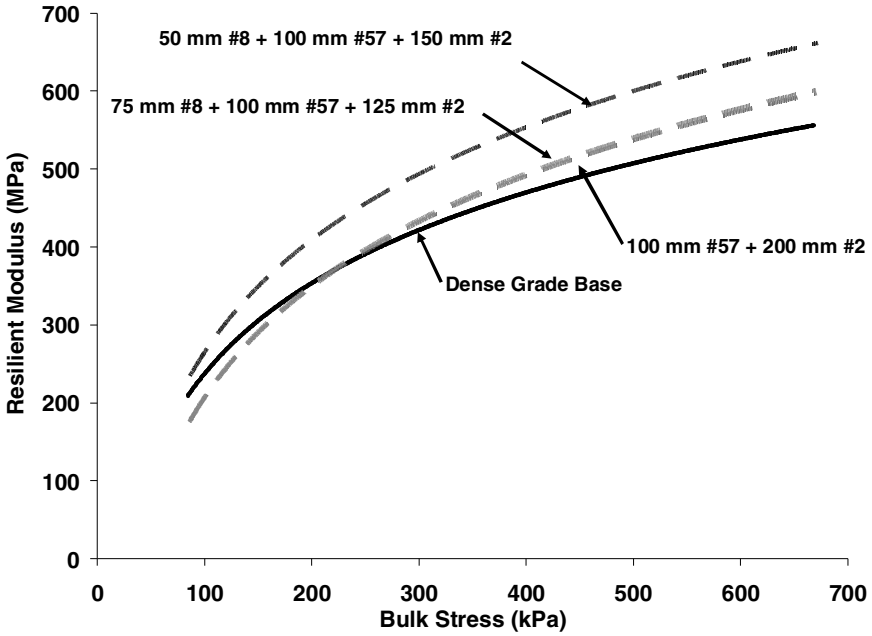


Figure 11 Modulus of tested aggregates (combined sizes) vs. typical Ontario dense graded base

5. HYDRAULIC CONDUCTIVITY TEST RESULTS

The coefficients of permeability of the ASTM #8 and #57 stones were measured using a mould of 156 mm in diameter in accordance with ASTM designation D 2434-68. All particles for the ASTM #57 stone larger than 19 mm were removed and not used for the permeability tests. The coefficient of permeability of both #8 and #57 stone is in the range of $(3.0 - 3.5) \times 10^{-4}$ m/sec. The coarser the aggregate material, the higher the permeability. The combination of various stones tended to slightly reduce the overall permeability of the combination compared to the individual aggregate gradations due to the "filling" of some of the larger void spaces by the smaller aggregate particles.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the observations presented in the previous sections, the following conclusions can be drawn:

- Deviatoric stress has little influence of resilient modulus of ASTM stones and their combinations tested in this project. It is possible that higher deviatoric stress levels, i.e approaching the Mohr-Coulomb failure curve would result in a decreasing modulus with increasing deviator stress.
- Well graded coarse aggregates (e.g., ASTM #57 stone) tend to have higher resilient modulus.
- The measured modulus using "scalped" ASTM #2 stone may not reflect the true characteristics of the material.
- When mixing or using combinations, finer aggregate fills up voids between larger particles in a zone at the interface, which may slightly increase resilient modulus.
- The resilient modulus of tests ASTM stones is likely at the higher end of most dense graded aggregate base materials.

7. REFERENCES

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