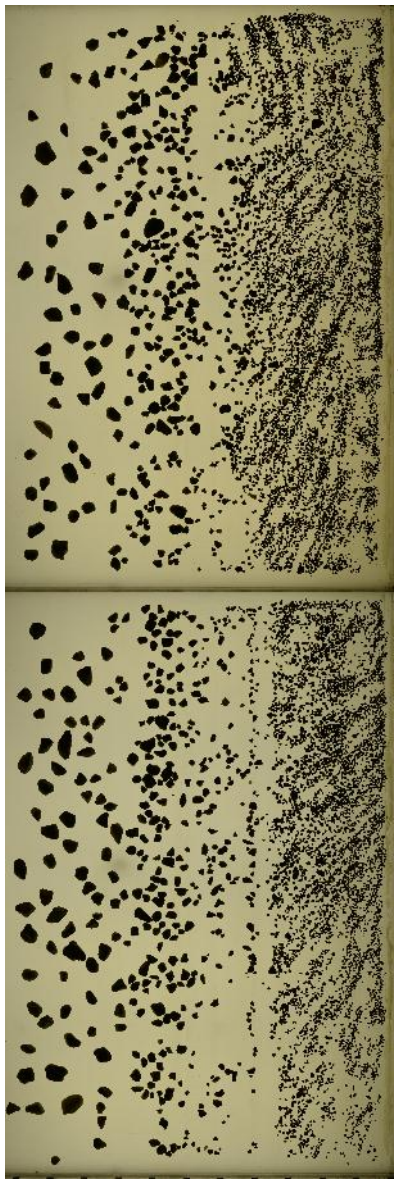


MATERIAL: TST 9 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

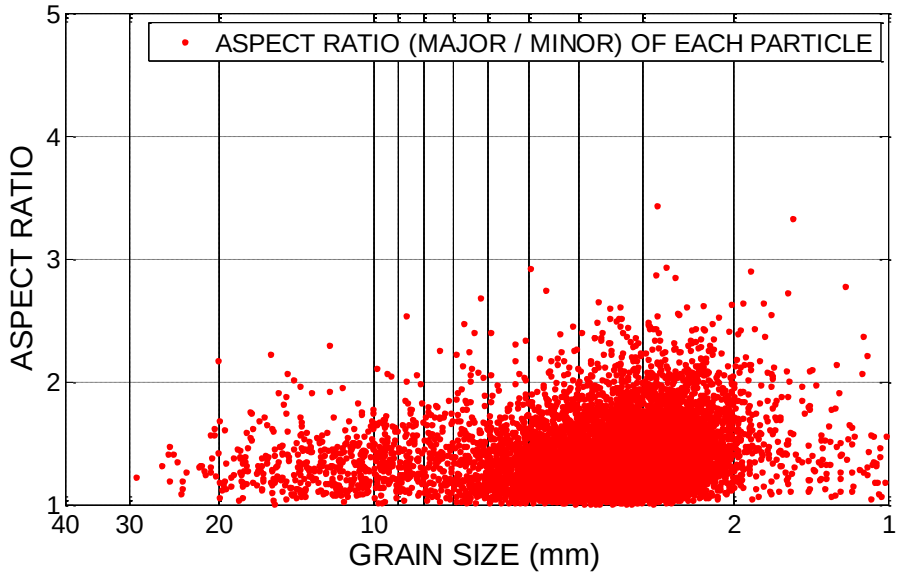
DATE TESTED: 09/19/11

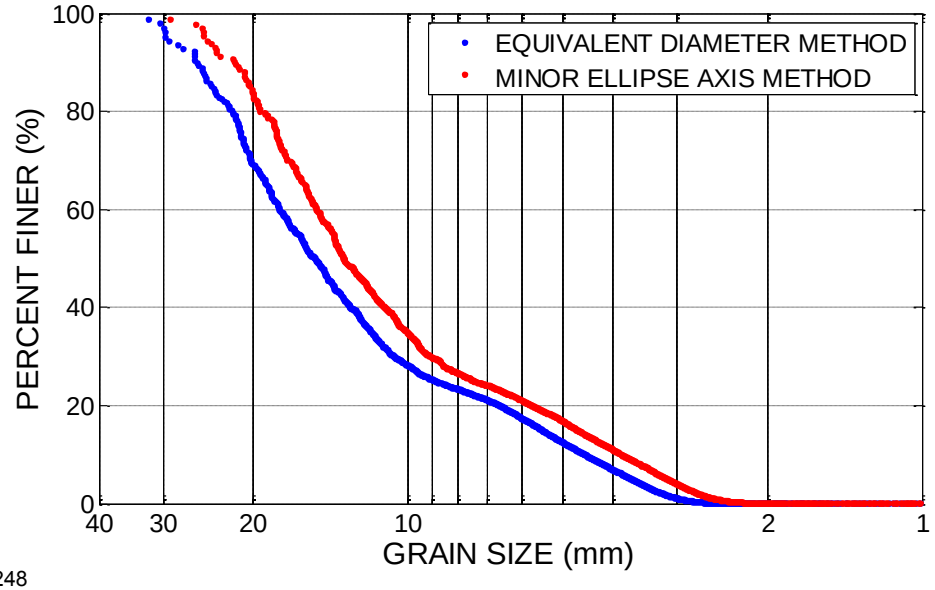
TESTED BY: HS

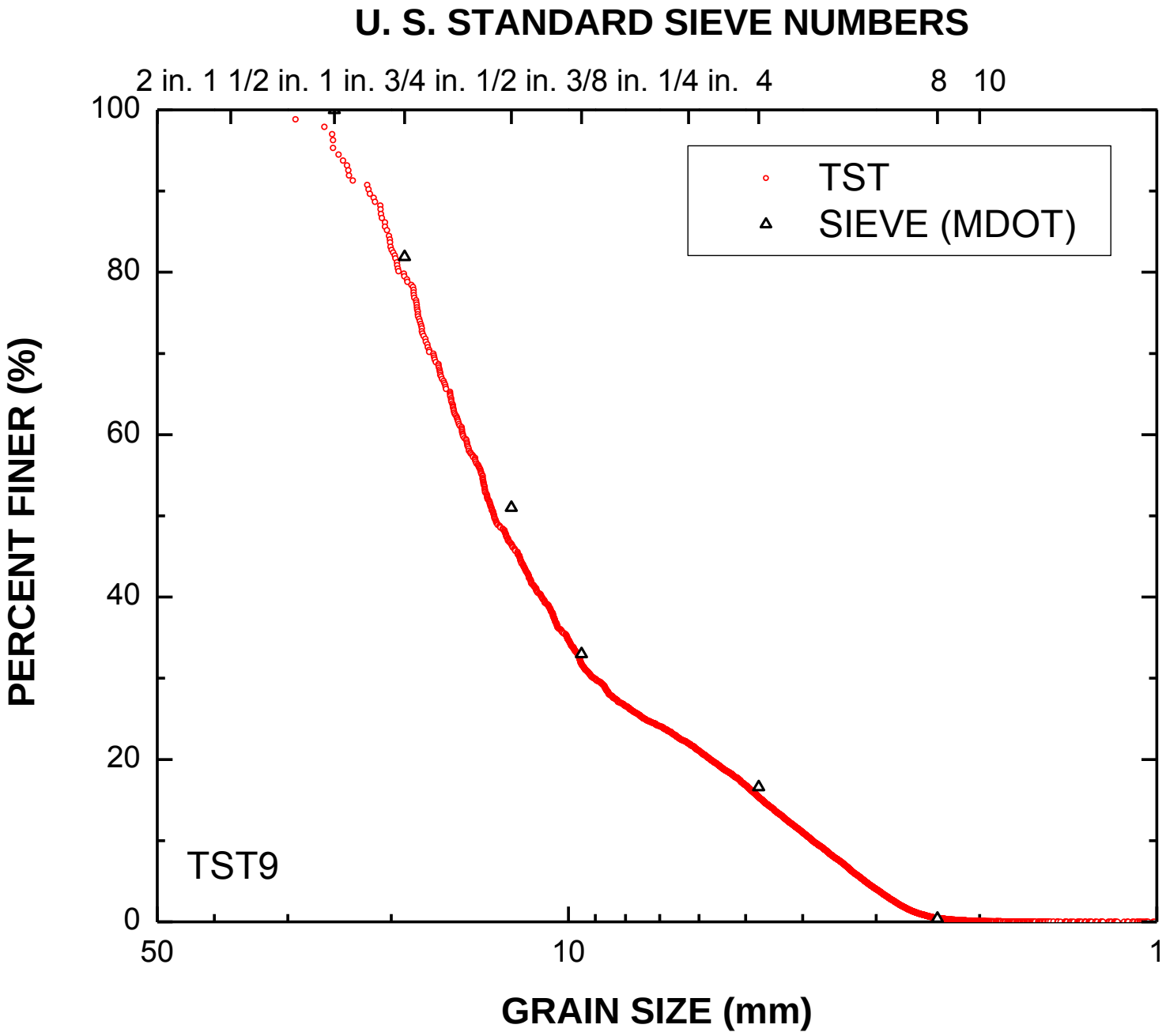
MAGNIFICATION (pix/mm): 5.6

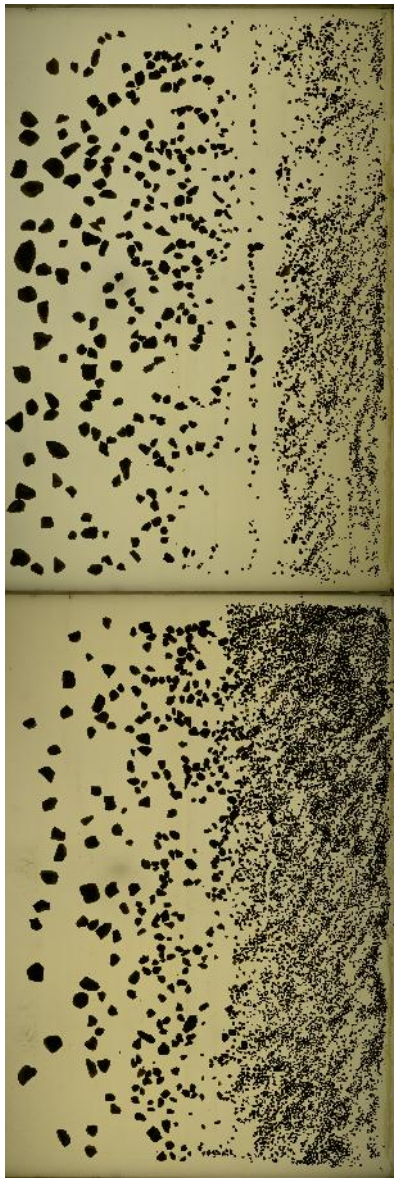
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST9



MATERIAL: TST 10 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

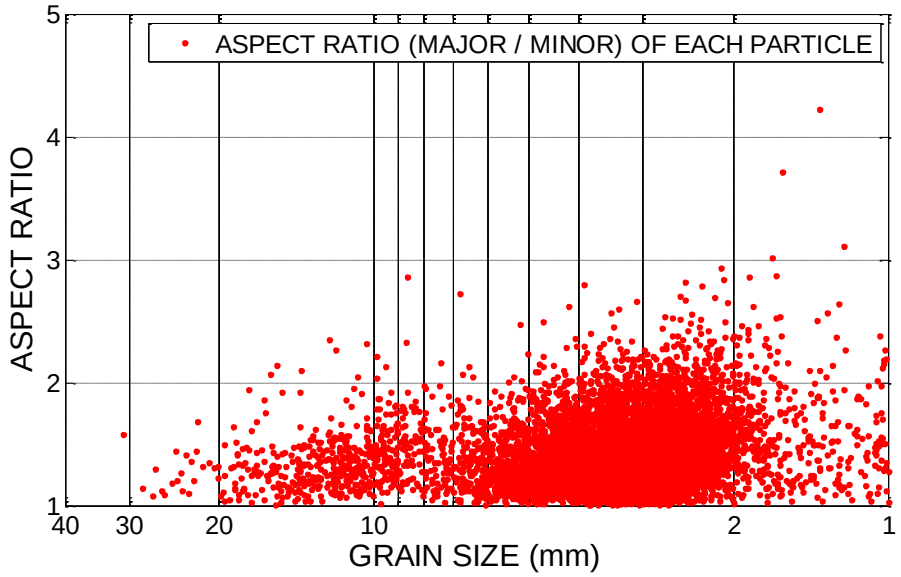
DATE TESTED: 09/19/11

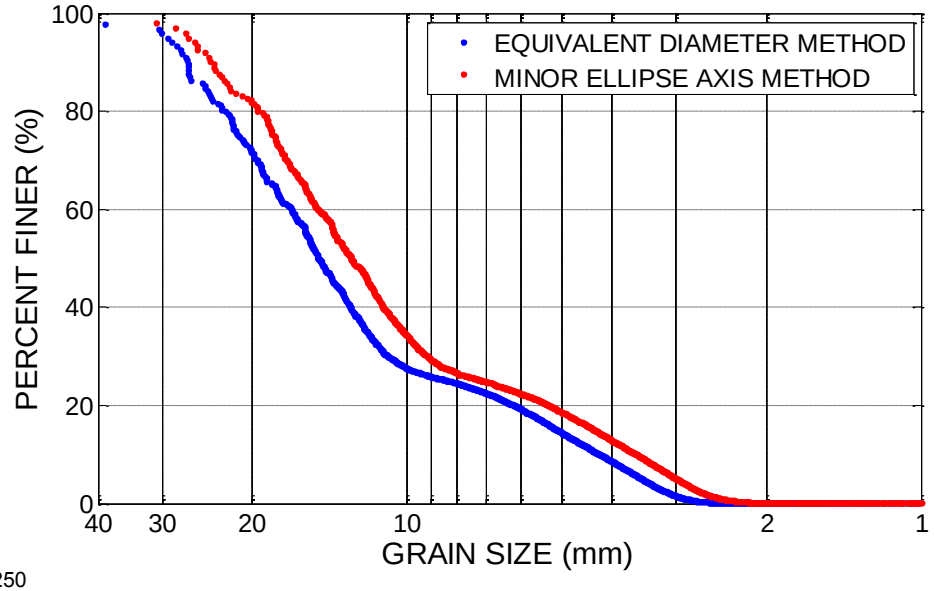
TESTED BY: HS

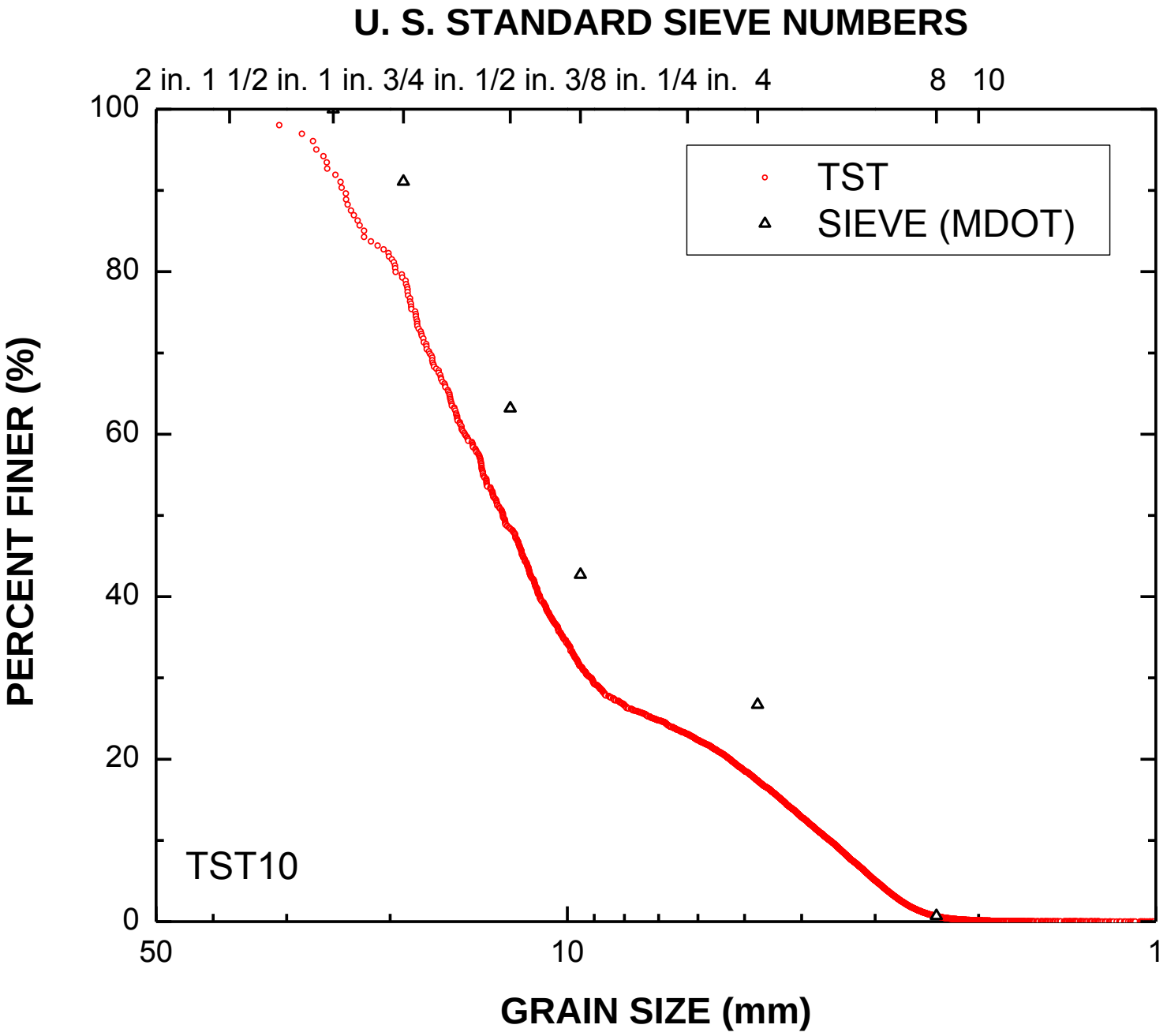
MAGNIFICATION (pix/mm): 5.6

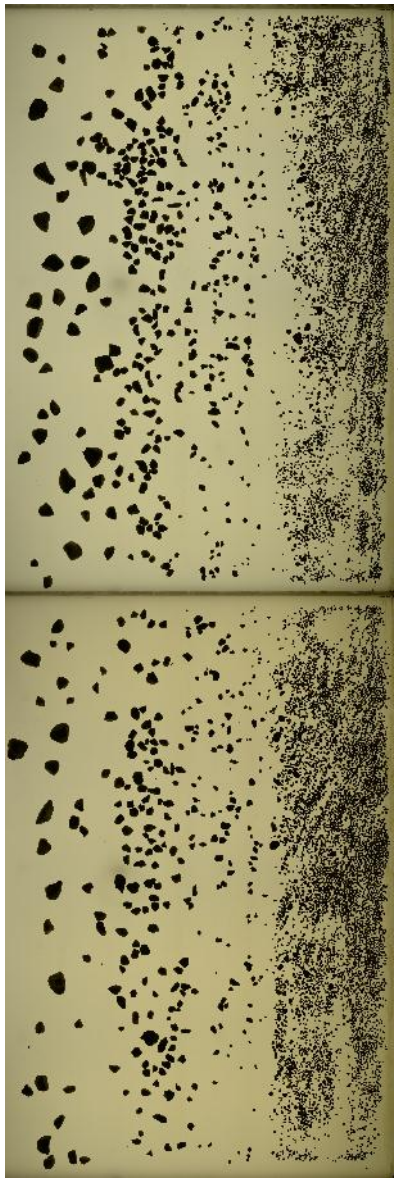
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
TST
SIEVE (MDOT)
TST10
50
10
1
GRAIN SIZE (mm)



MATERIAL: TST 11 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

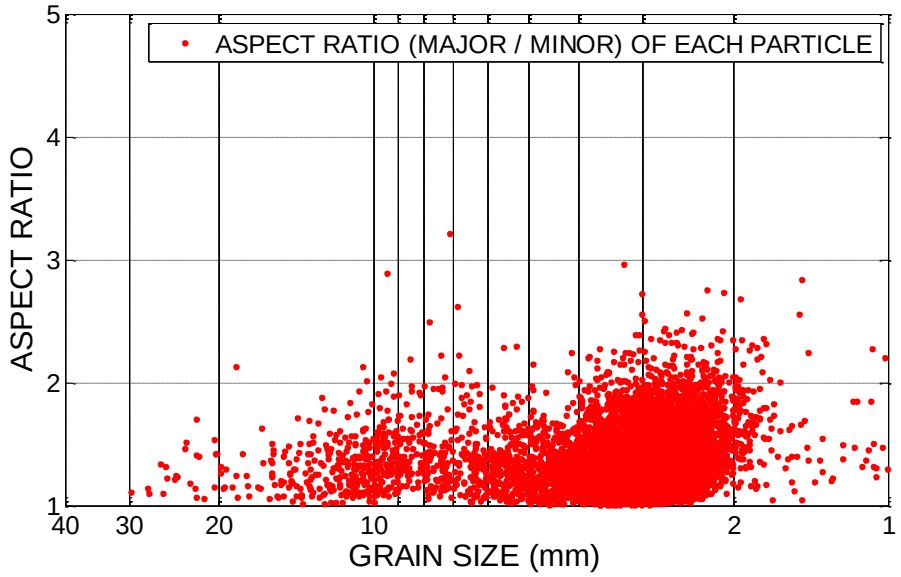
DATE TESTED: 09/19/11

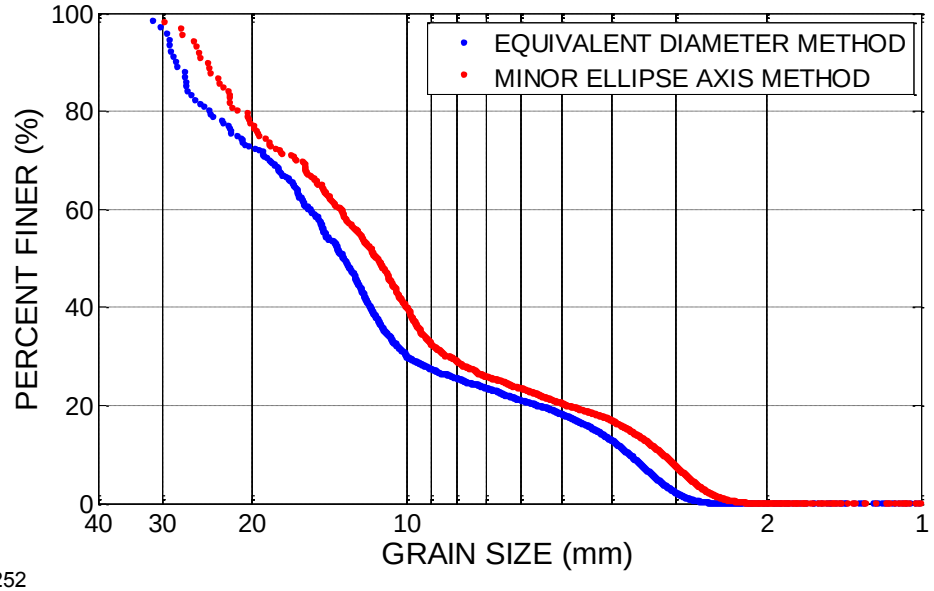
TESTED BY: HS

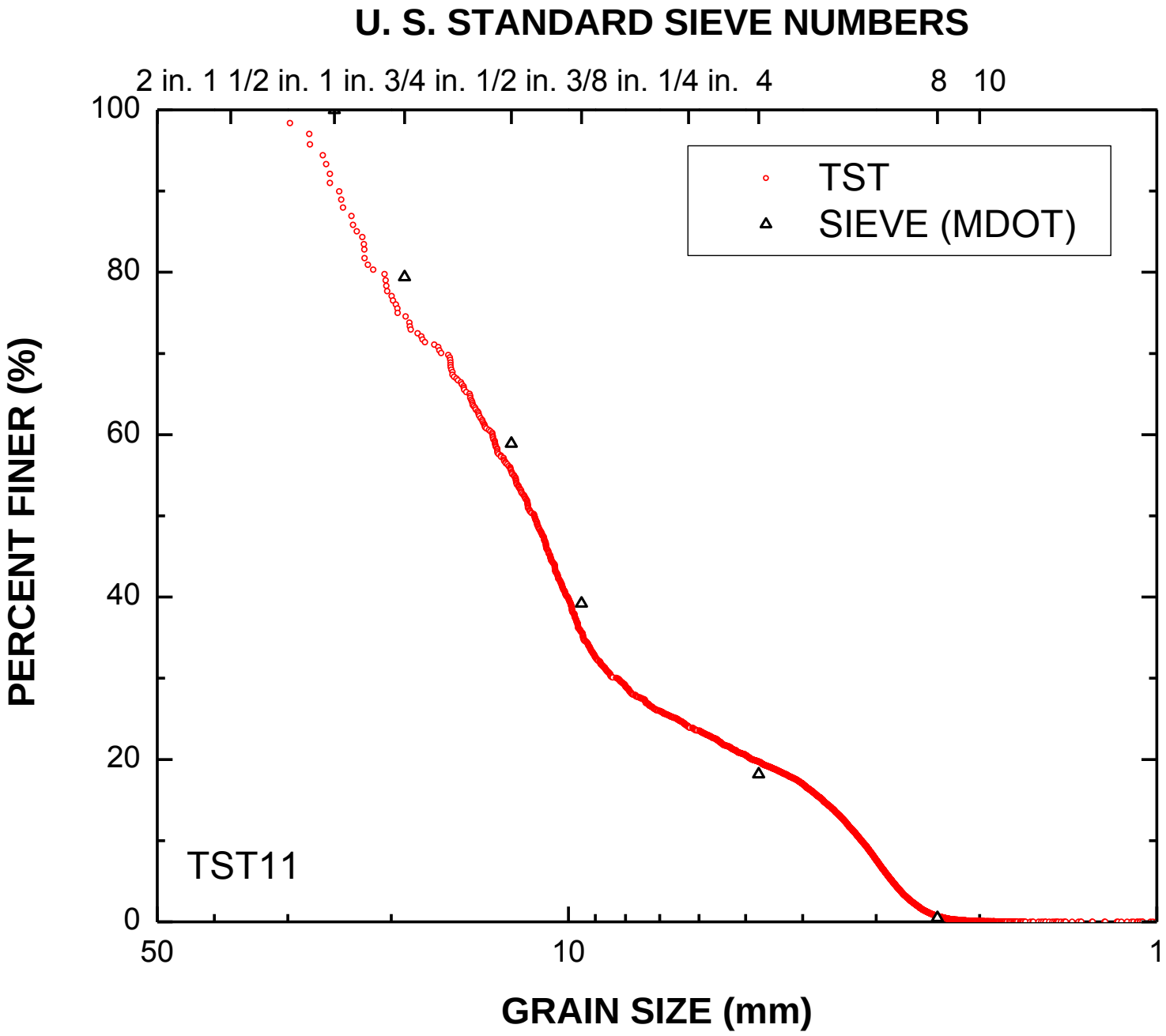
MAGNIFICATION (pix/mm): 5.6

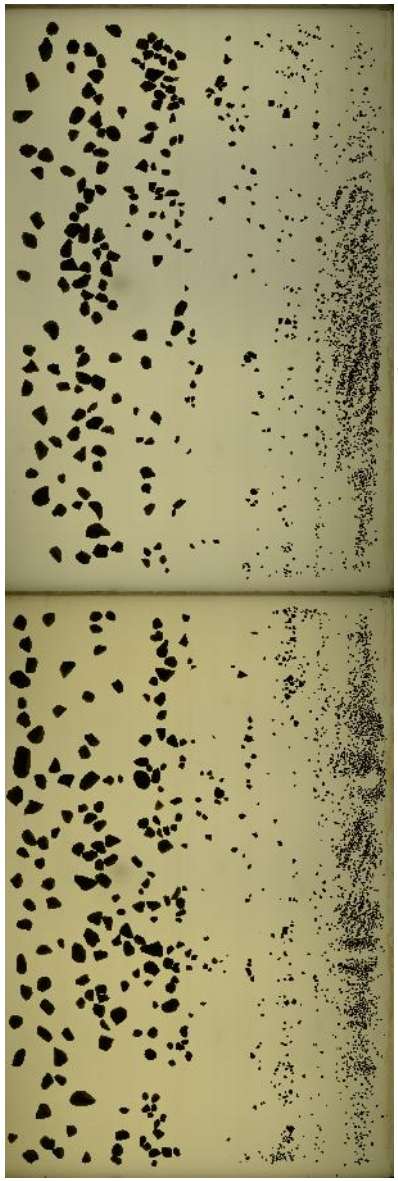
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
TST
SIEVE (MDOT)
TST11
50
10
1
GRAIN SIZE (mm)



MATERIAL: TST 12 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

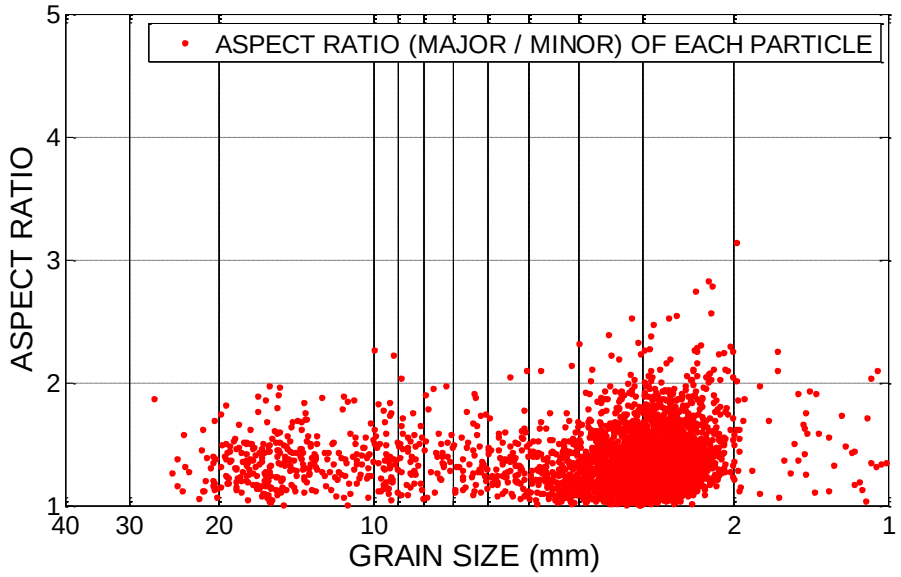
DATE TESTED: 09/19/11

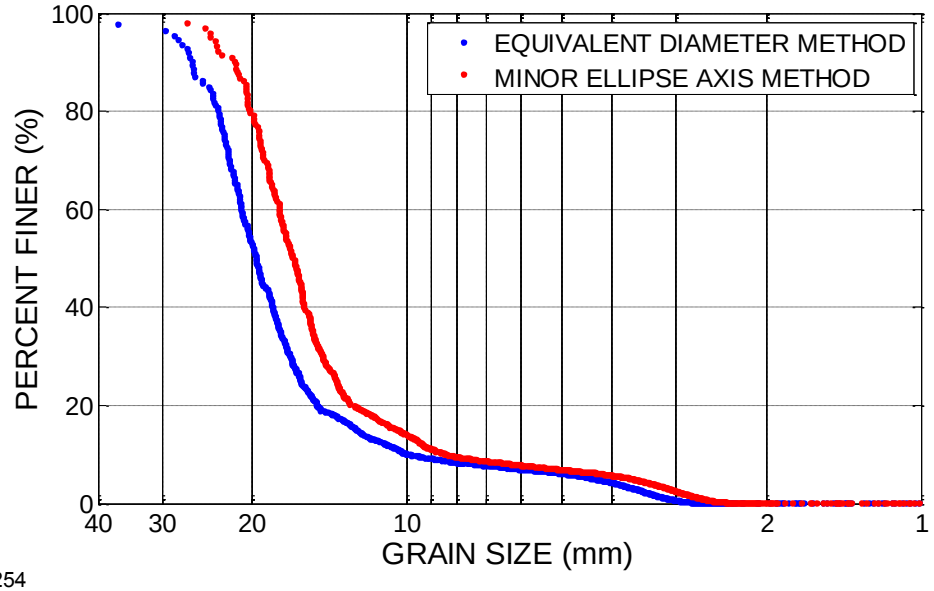
TESTED BY: HS

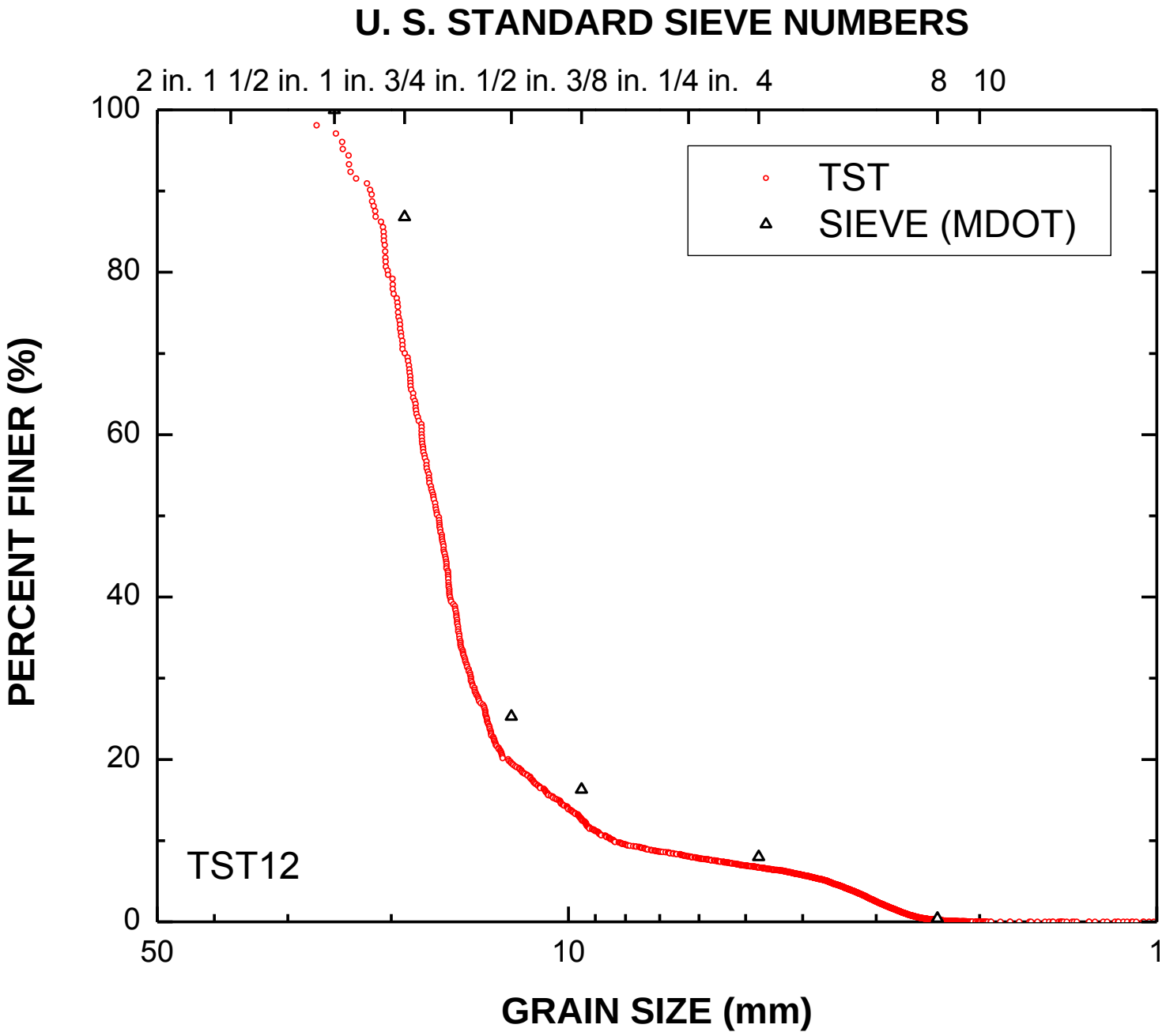
MAGNIFICATION (pix/mm): 5.6

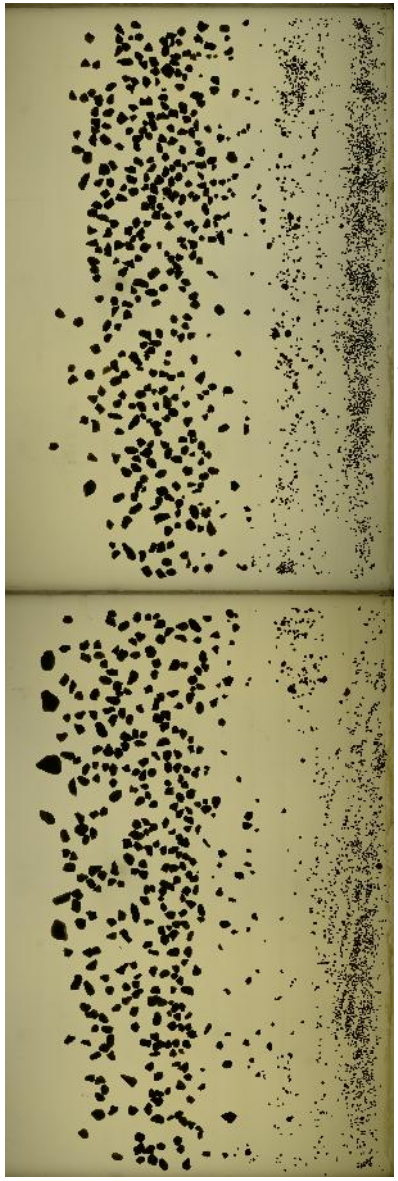
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST12



MATERIAL: TST 13 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

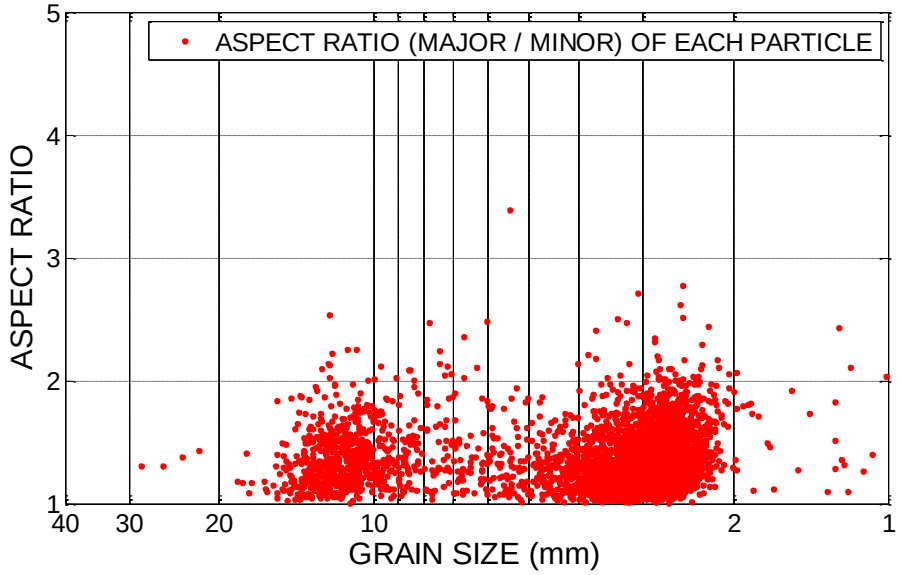
DATE TESTED: 09/19/11

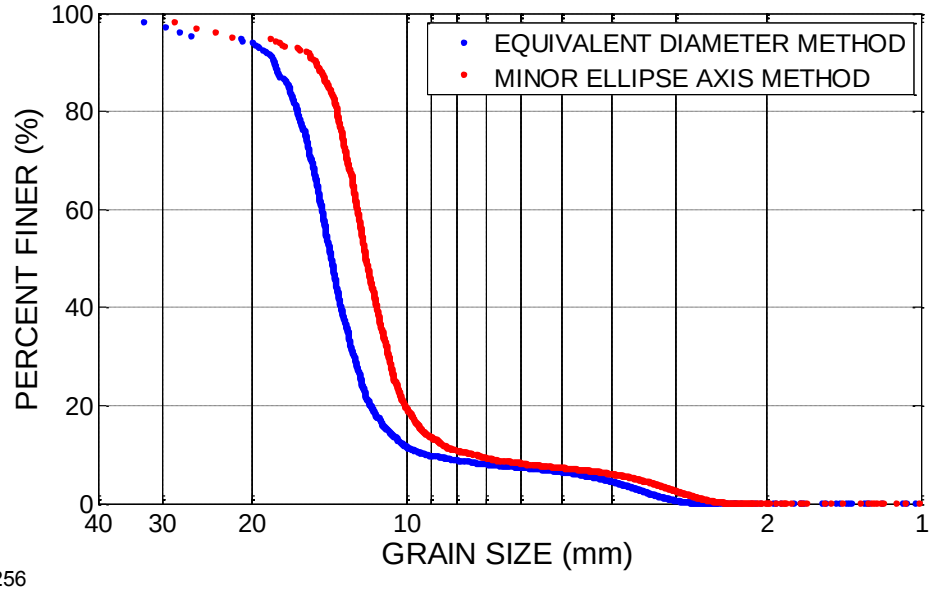
TESTED BY: HS

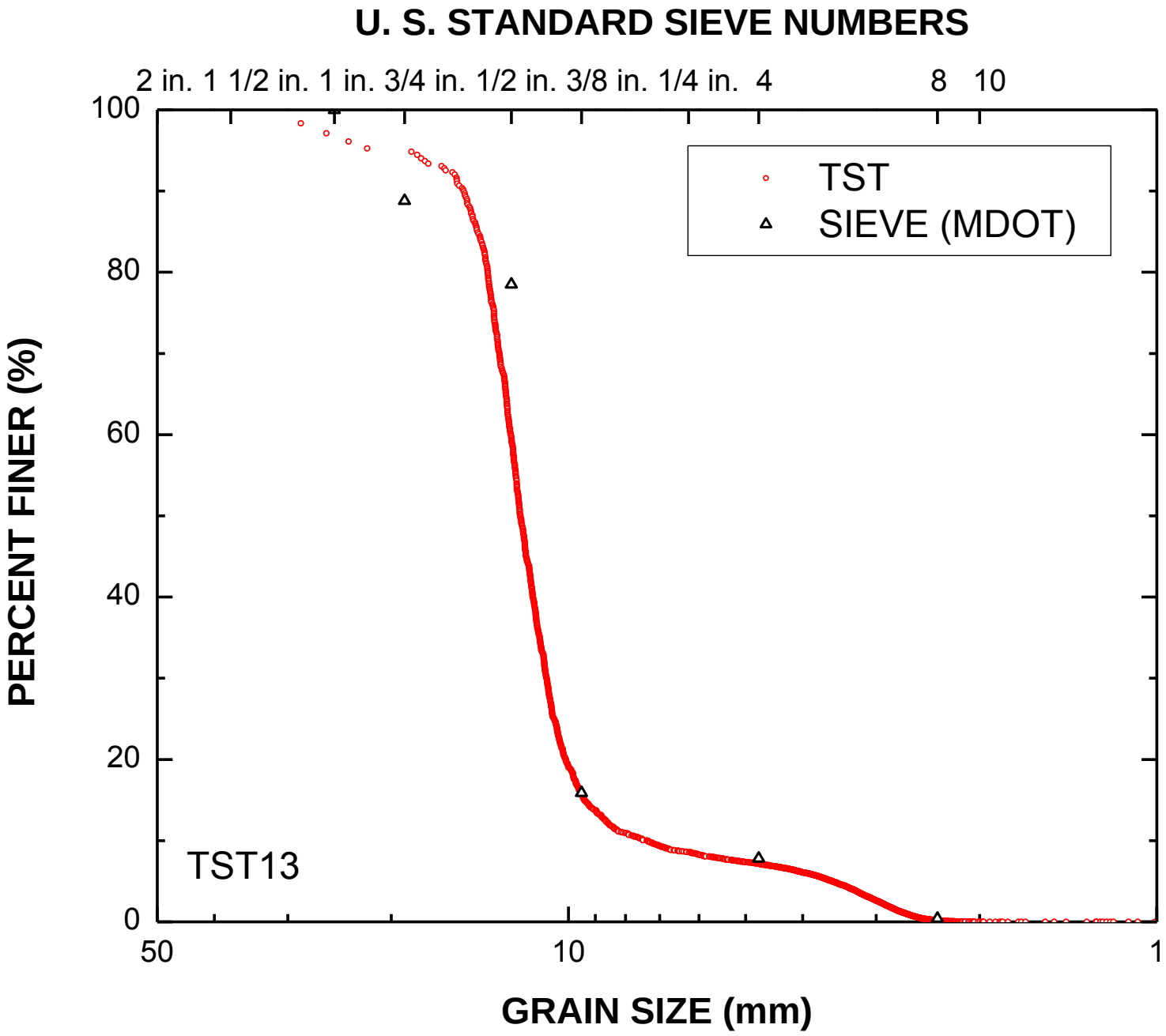
MAGNIFICATION (pix/mm): 5.6

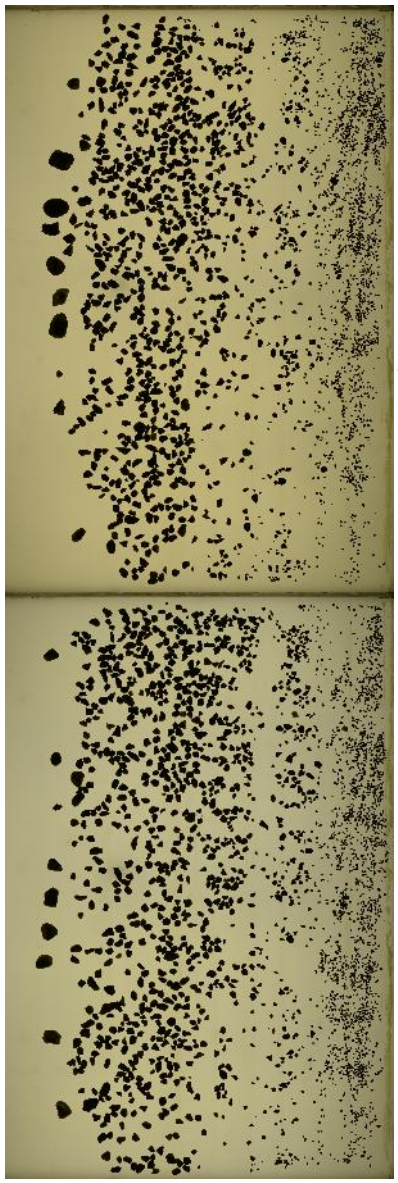
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST13



MATERIAL: TST 14 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

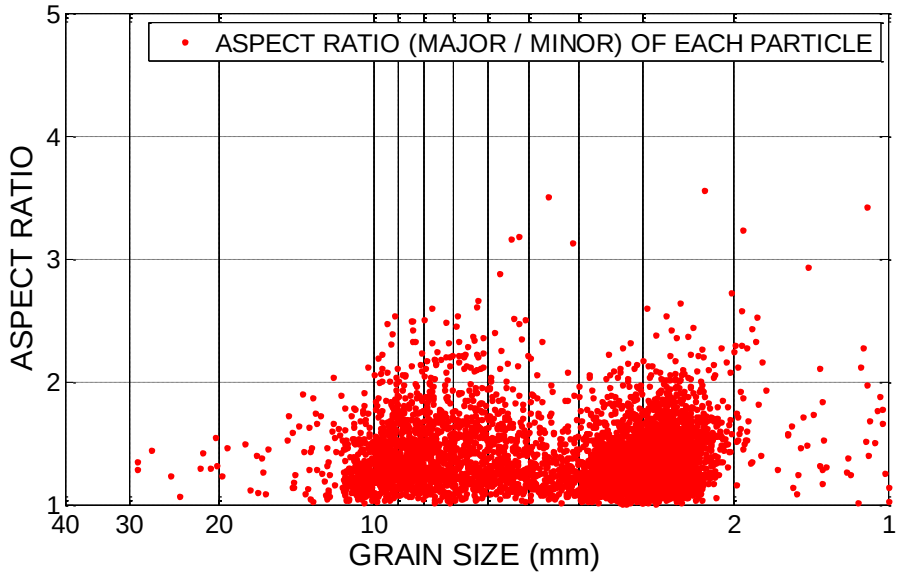
DATE TESTED: 09/19/11

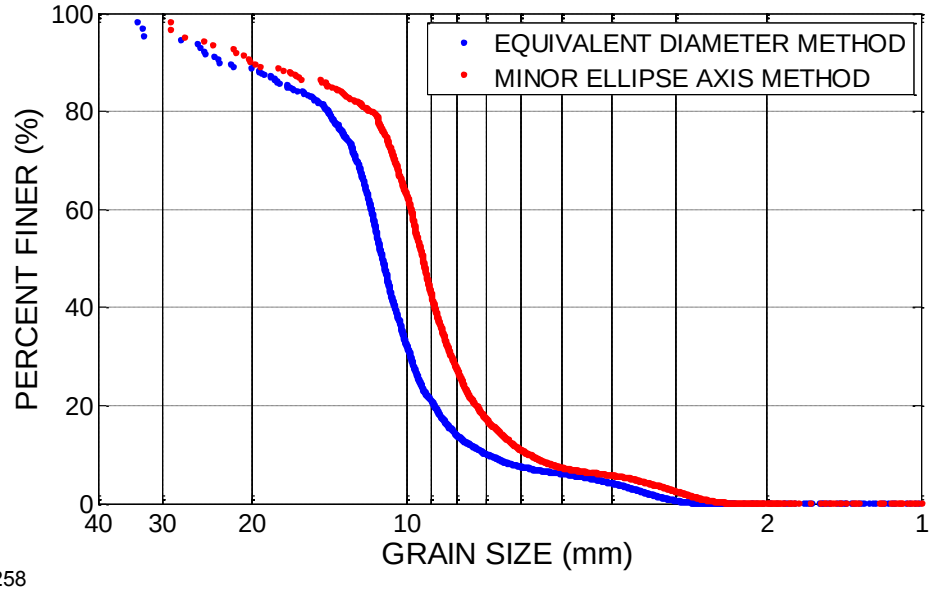
TESTED BY: HS

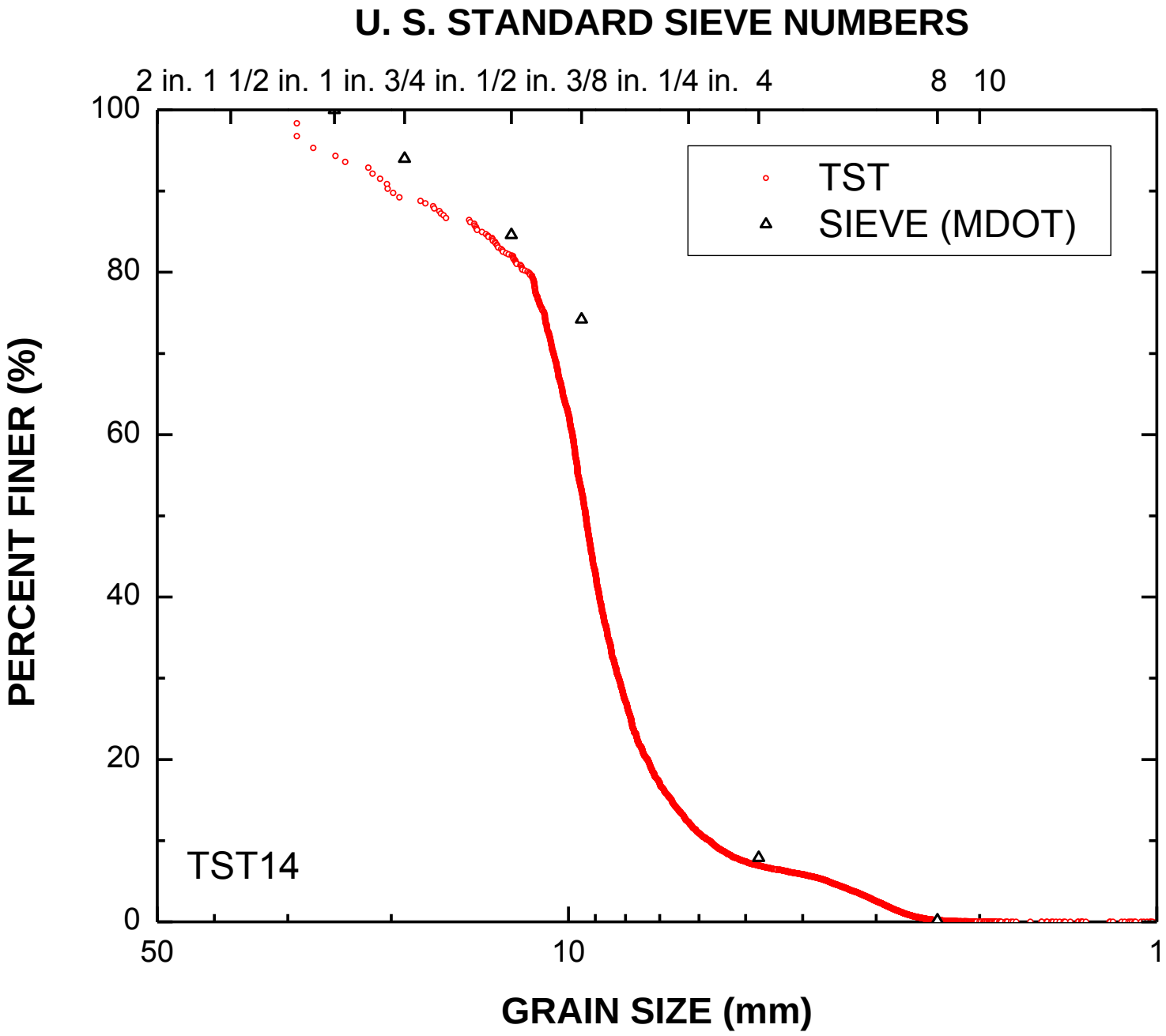
MAGNIFICATION (pix/mm): 5.6

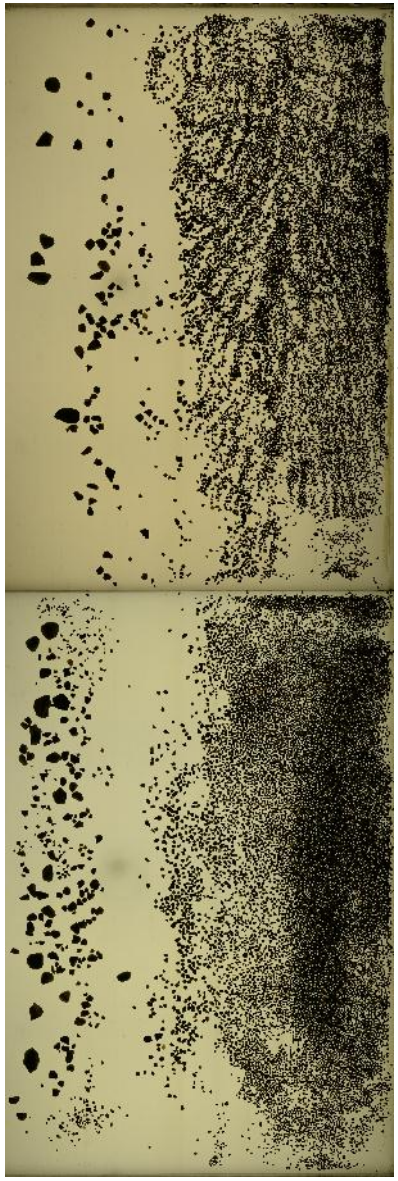
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST14



MATERIAL: TST 15 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

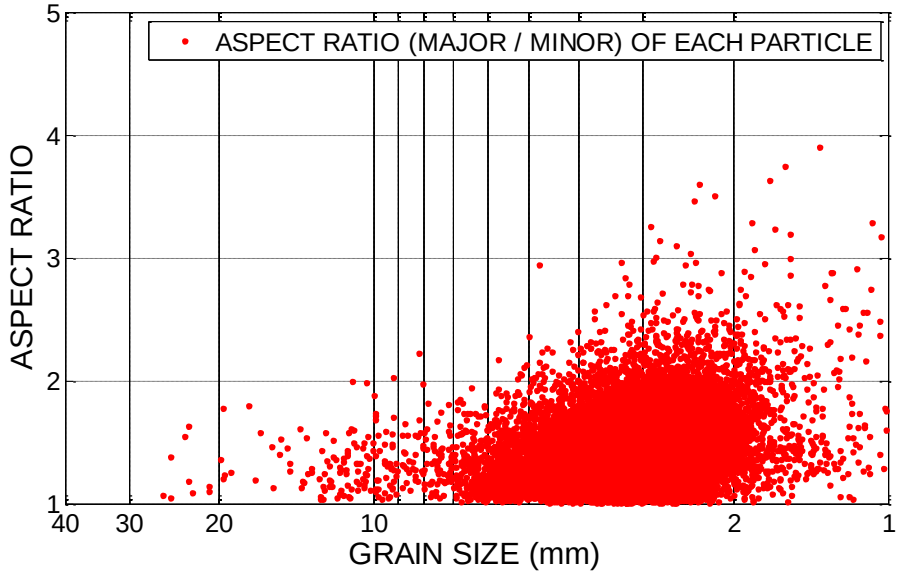
DATE TESTED: 09/19/11

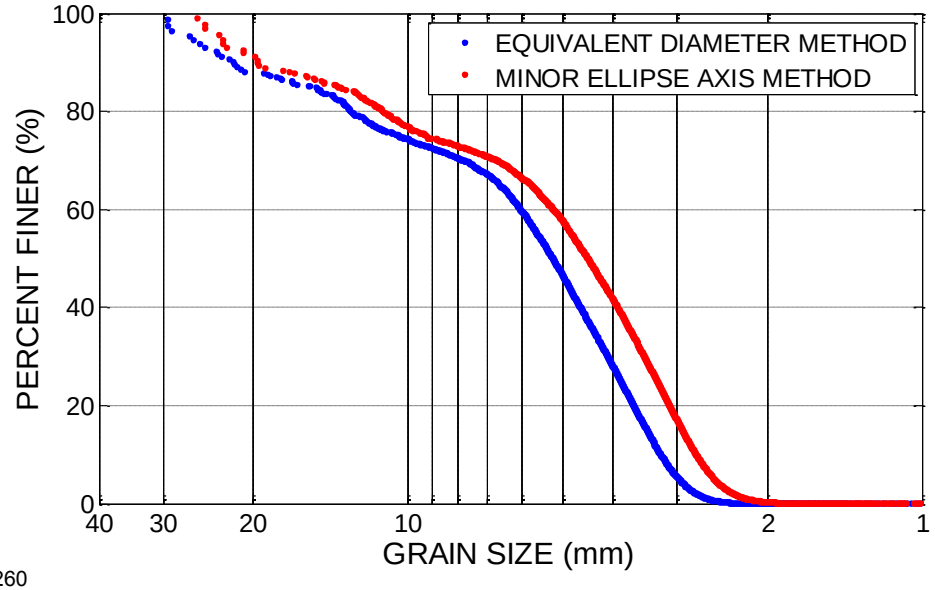
TESTED BY: HS

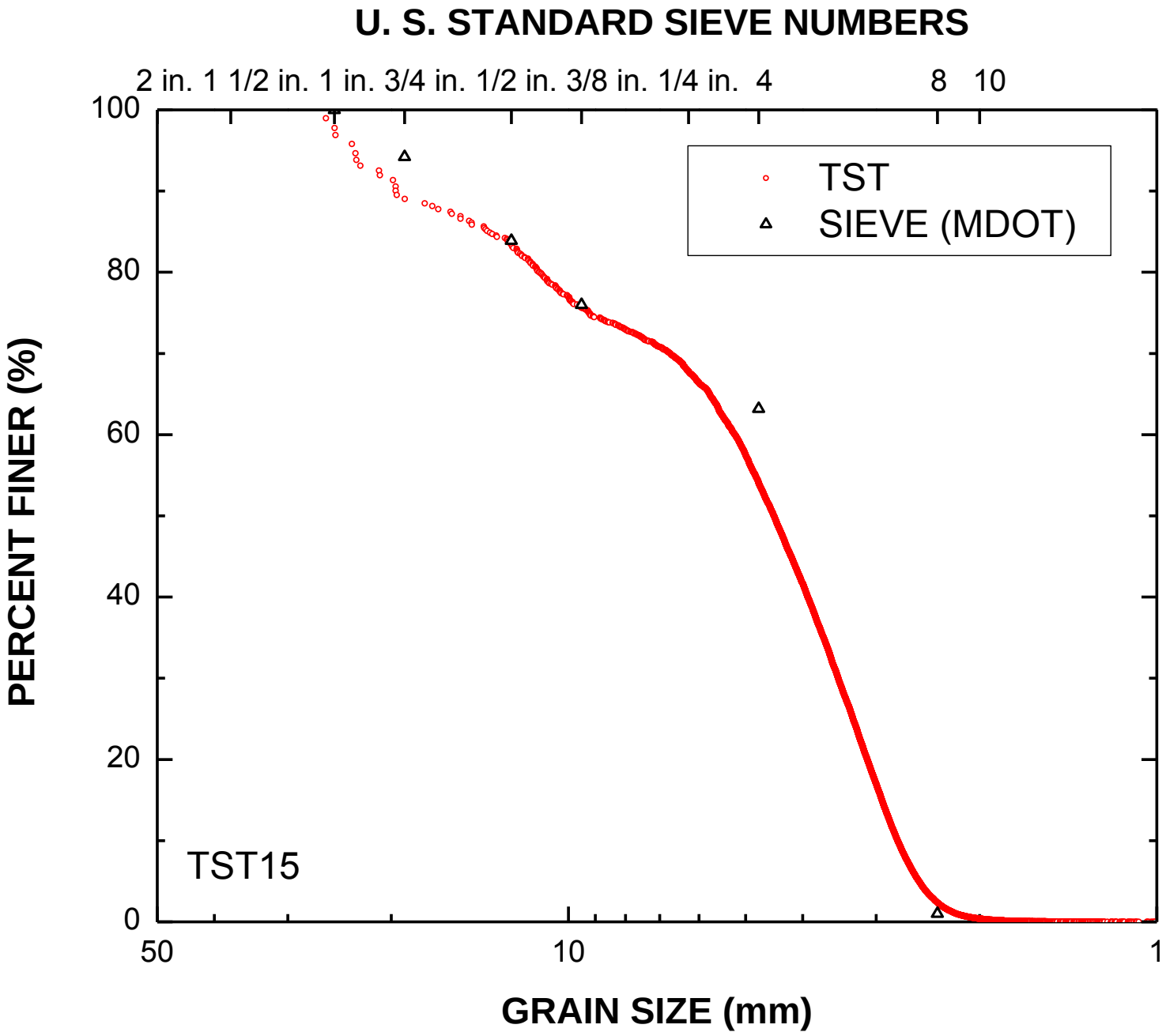
MAGNIFICATION (pix/mm): 5.6

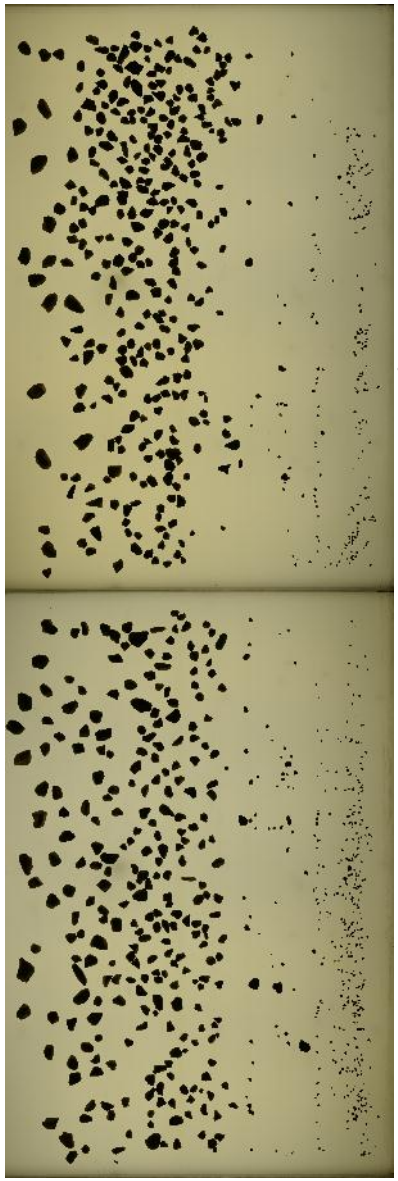
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST15



MATERIAL: TST 16 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

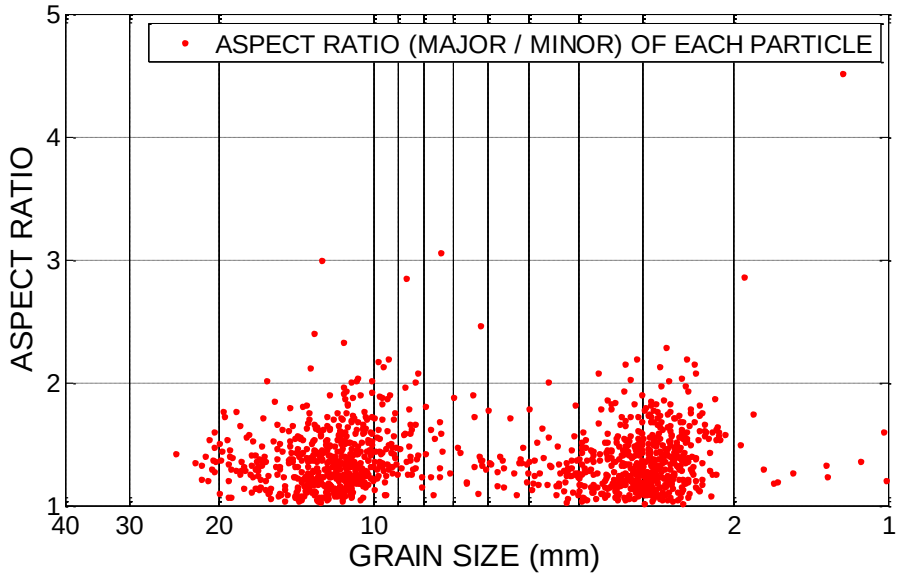
DATE TESTED: 09/20/11

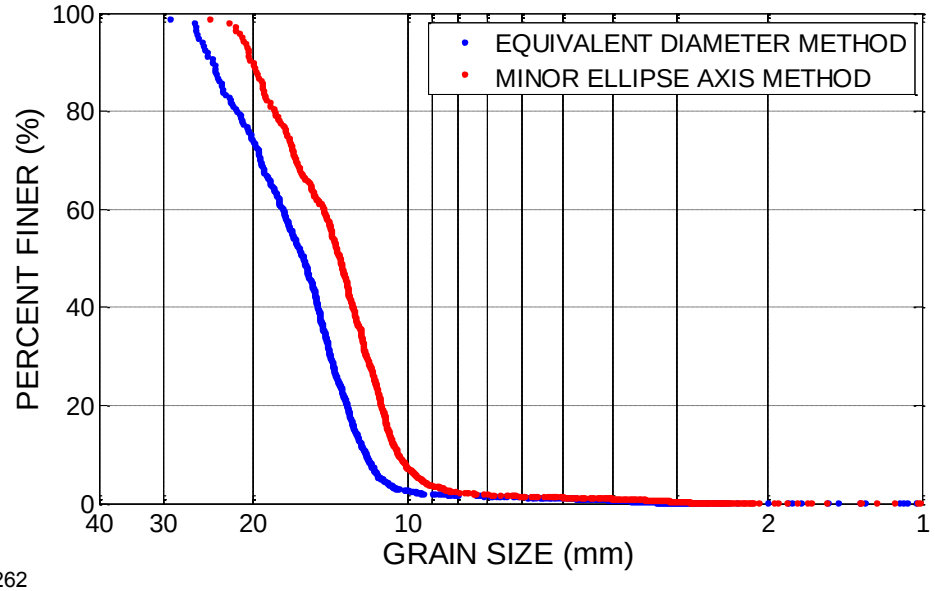
TESTED BY: HS

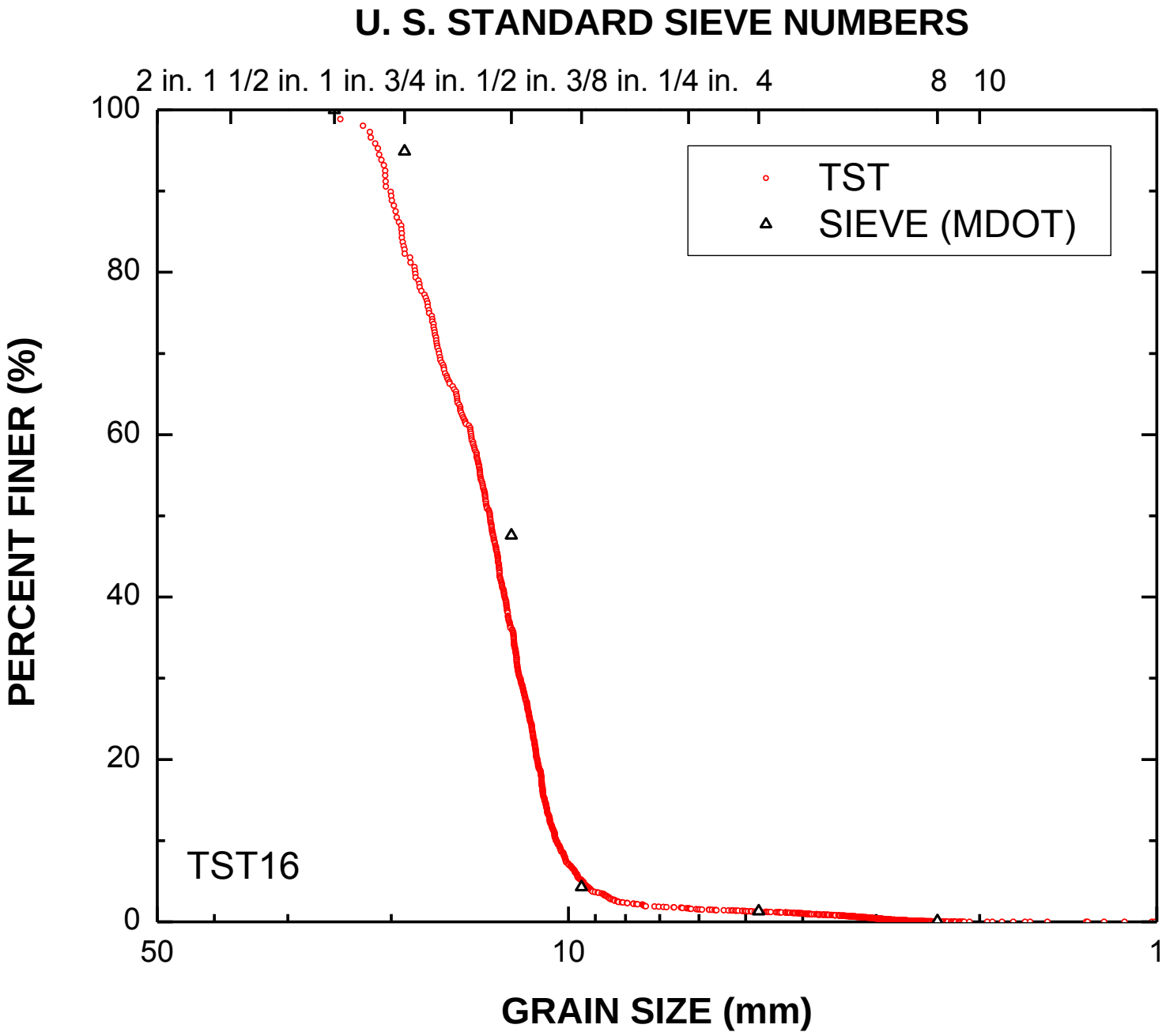
MAGNIFICATION (pix/mm): 5.6

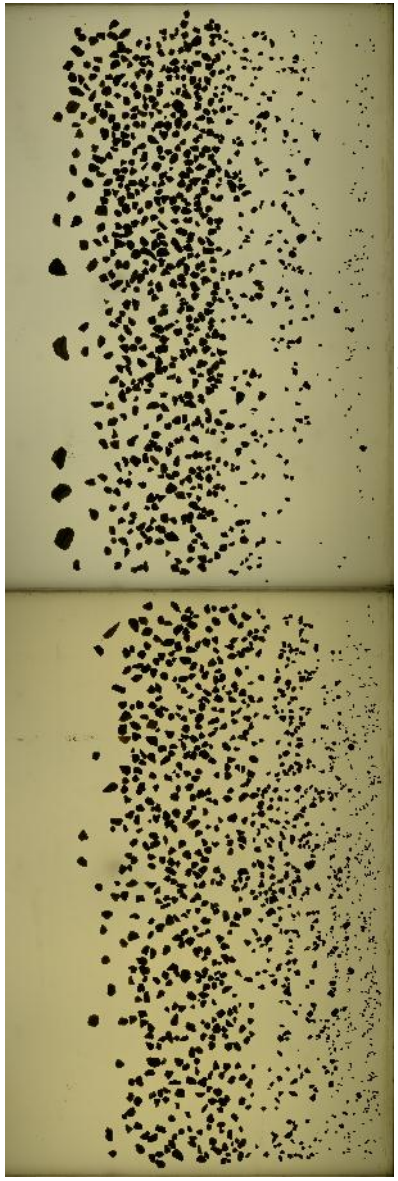
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST16



MATERIAL: TST 17 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

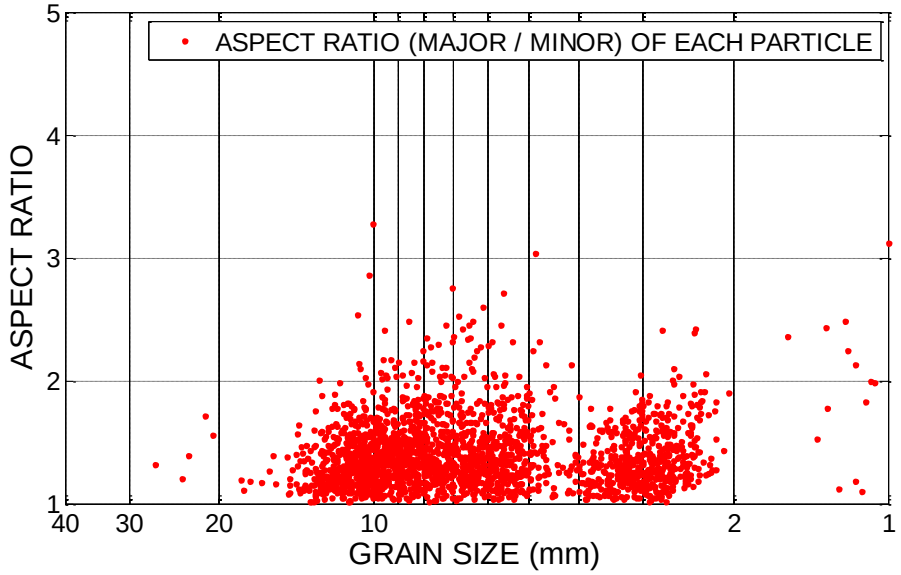
DATE TESTED: 09/20/11

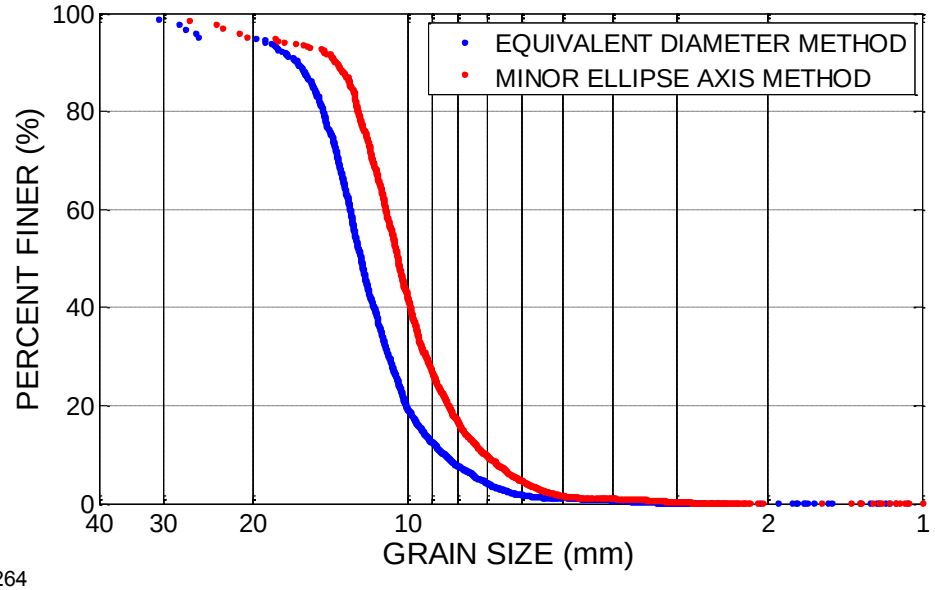
TESTED BY: HS

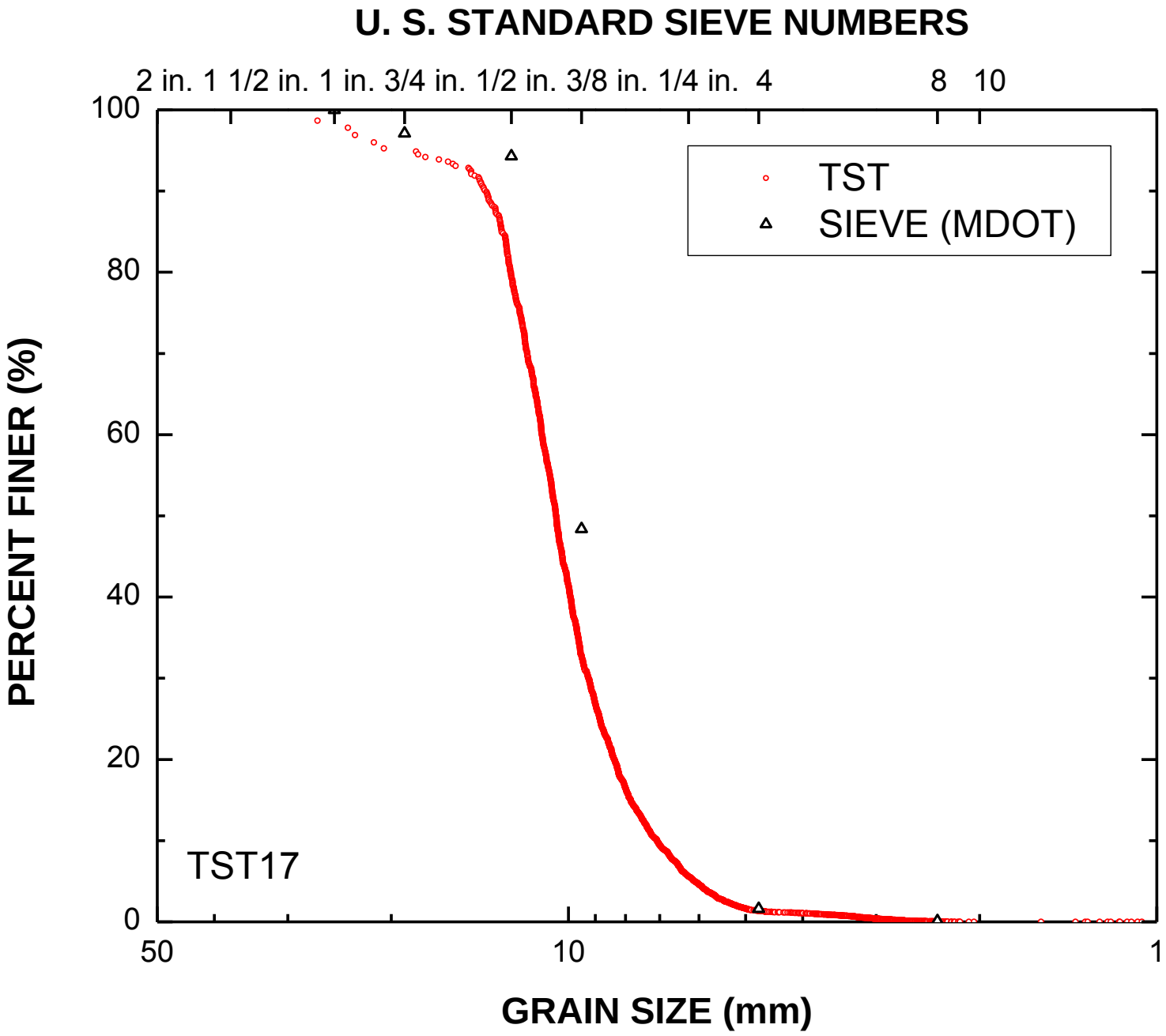
MAGNIFICATION (pix/mm): 5.6

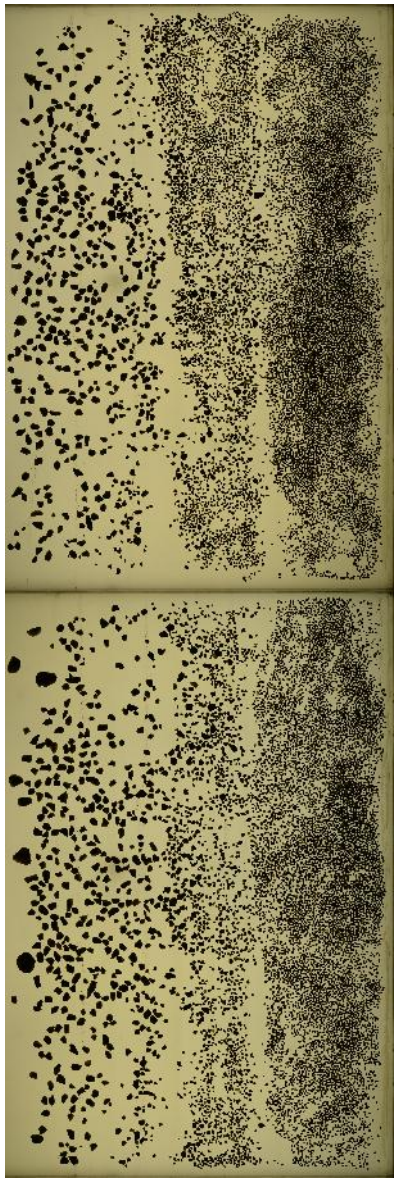
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST17



MATERIAL: TST 18 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

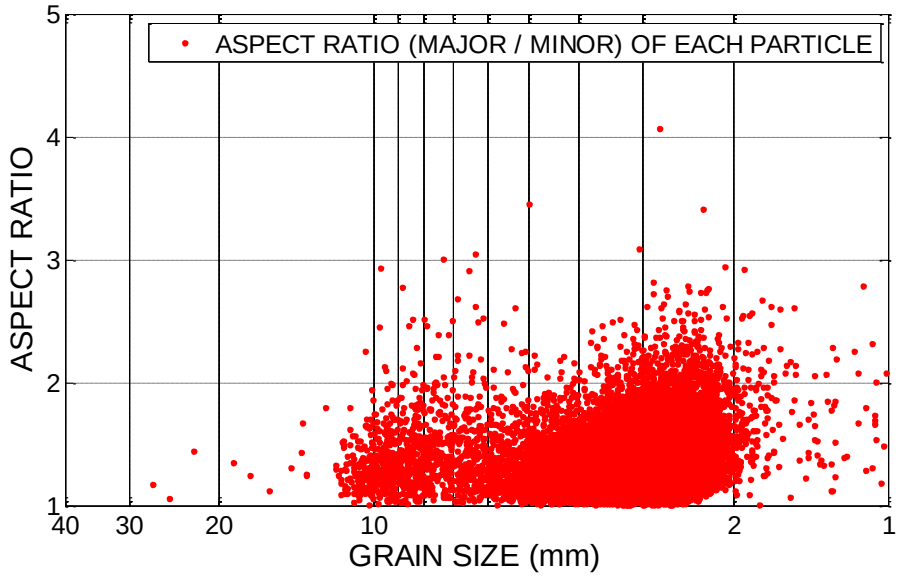
DATE TESTED: 09/20/11

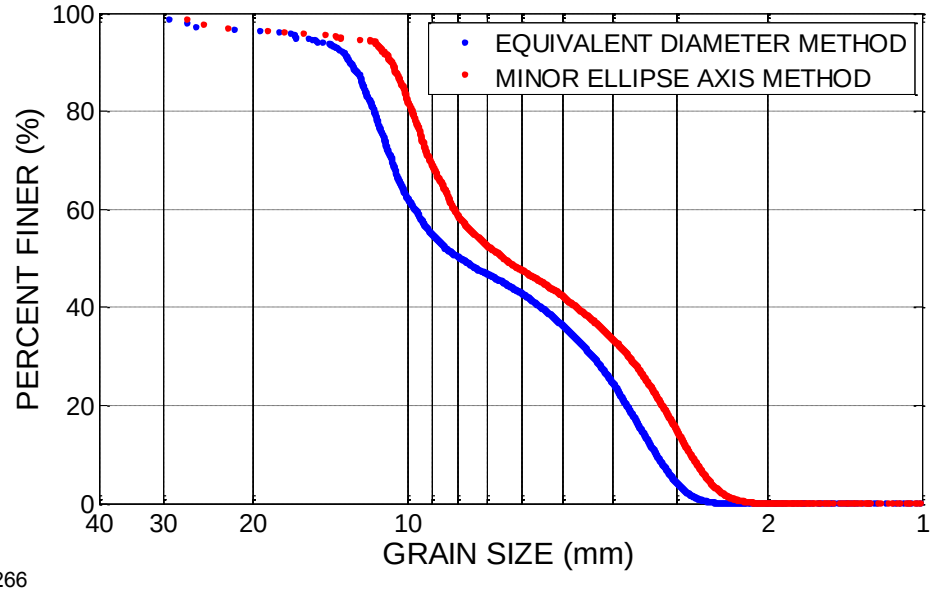
TESTED BY: HS

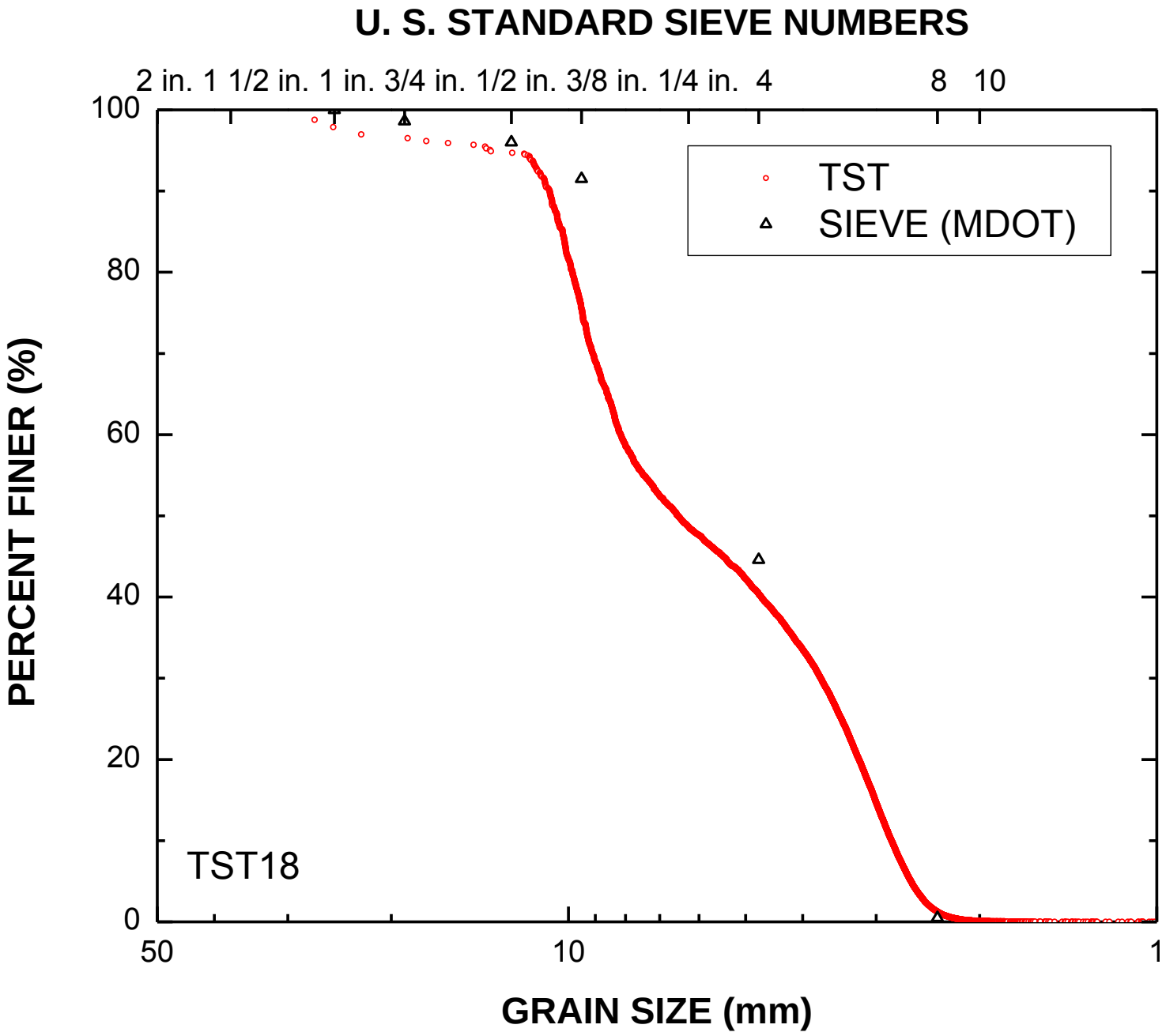
MAGNIFICATION (pix/mm): 5.6

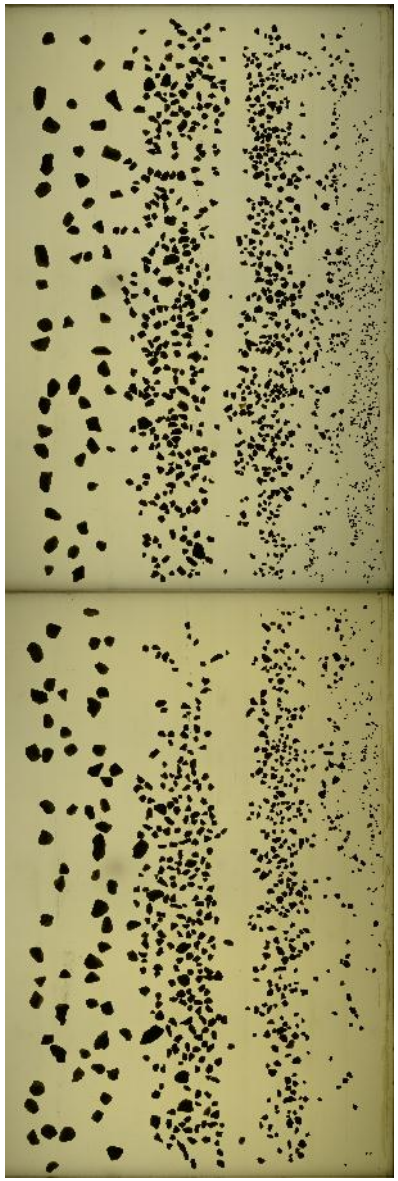
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST18



MATERIAL: TST 19 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

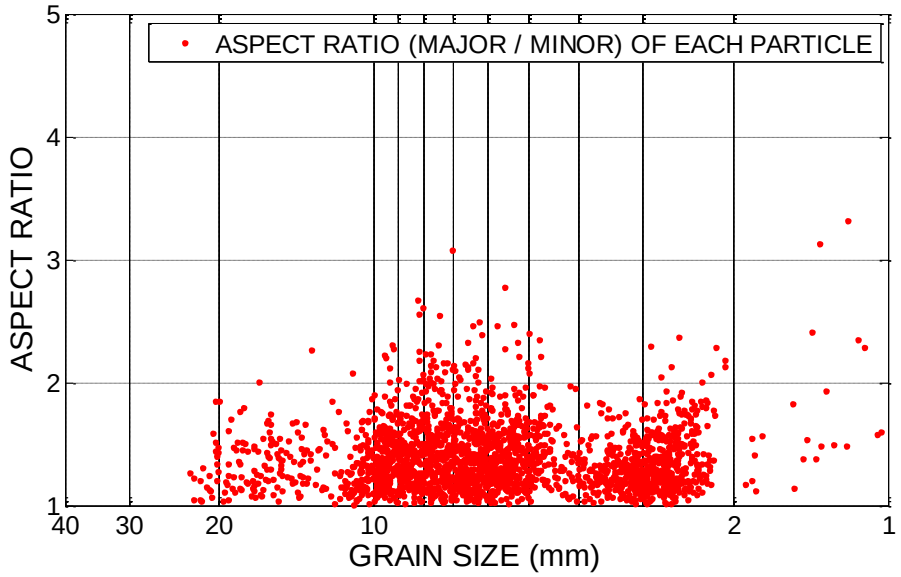
DATE TESTED: 09/20/11

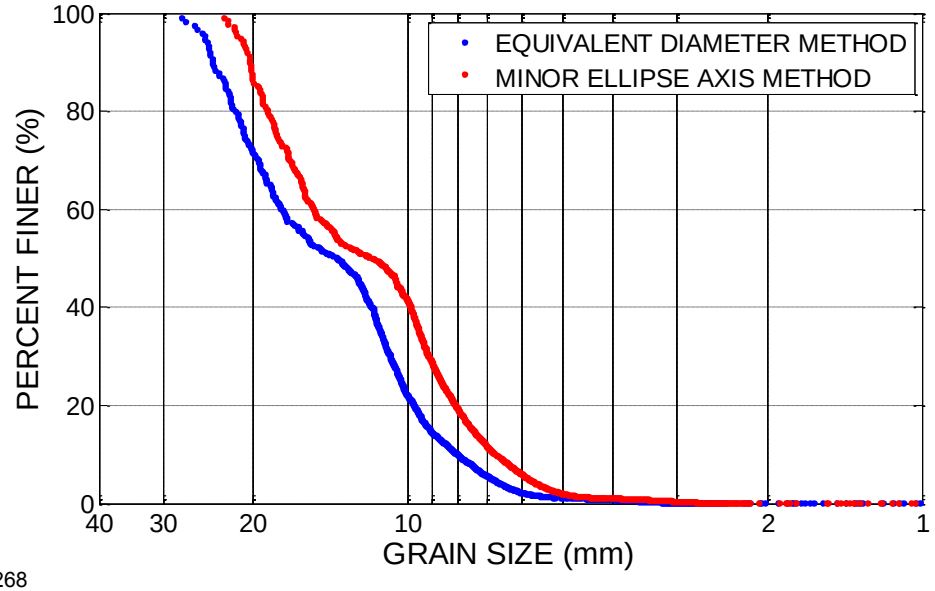
TESTED BY: HS

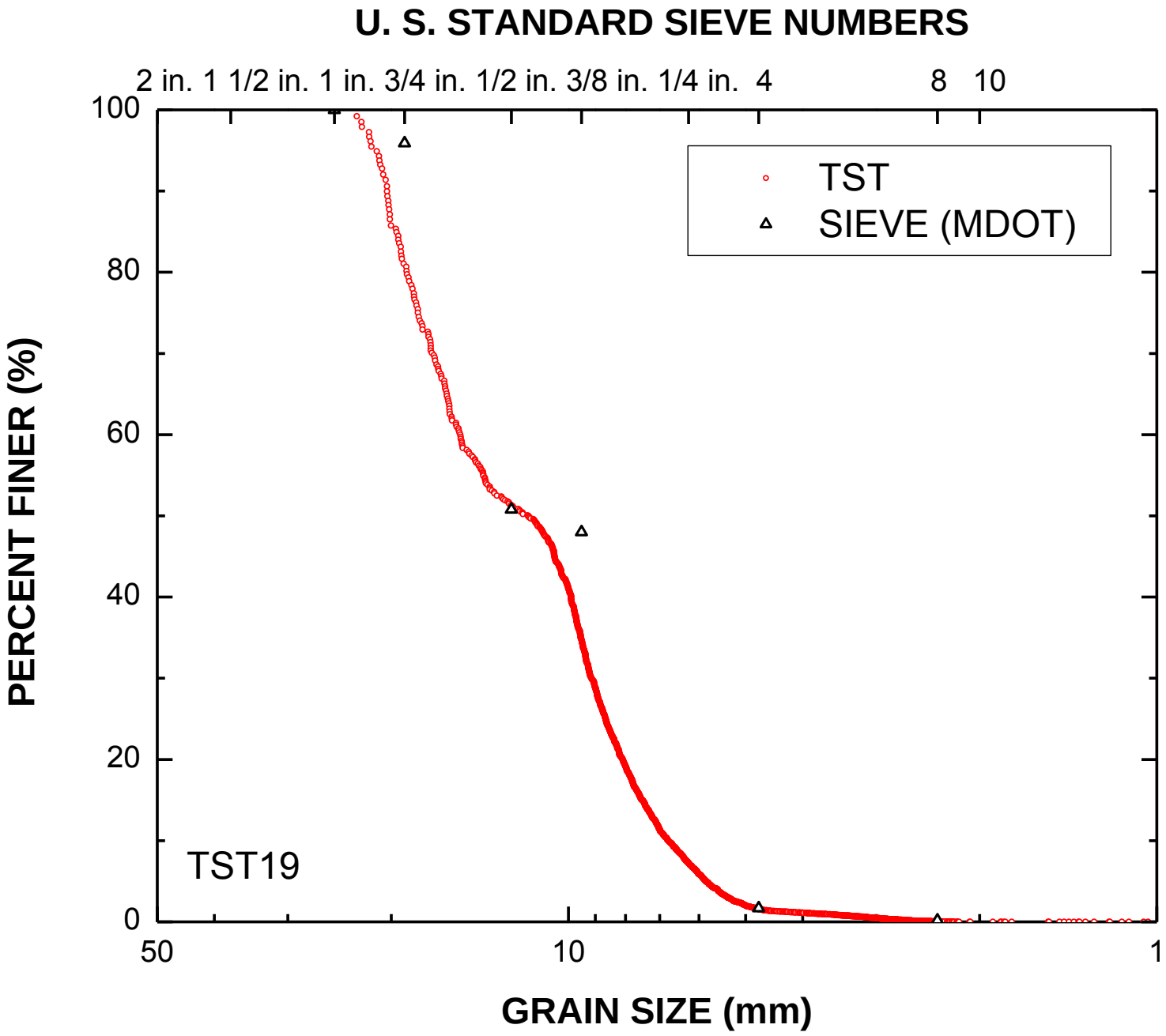
MAGNIFICATION (pix/mm): 5.6

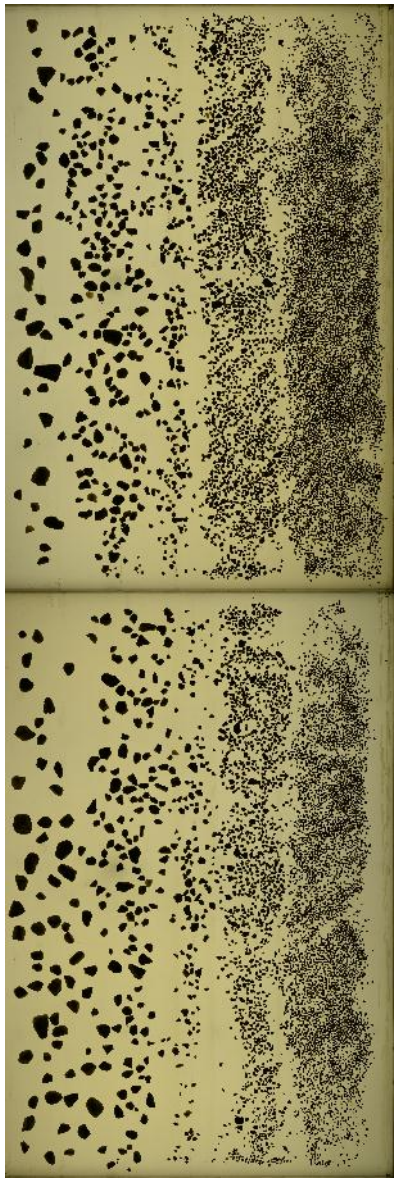
IMAGE SIZE (pix): 3264 x 4928

IMAGE SIZE (mm): 582.9 x 880.0






U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST19



MATERIAL: TST 20 U of M

PIT NUMBER:

PIT NAME:

DATE SAMPLED:

SAMPLED BY:

DATE TESTED: 09/20/11

TESTED BY: HS

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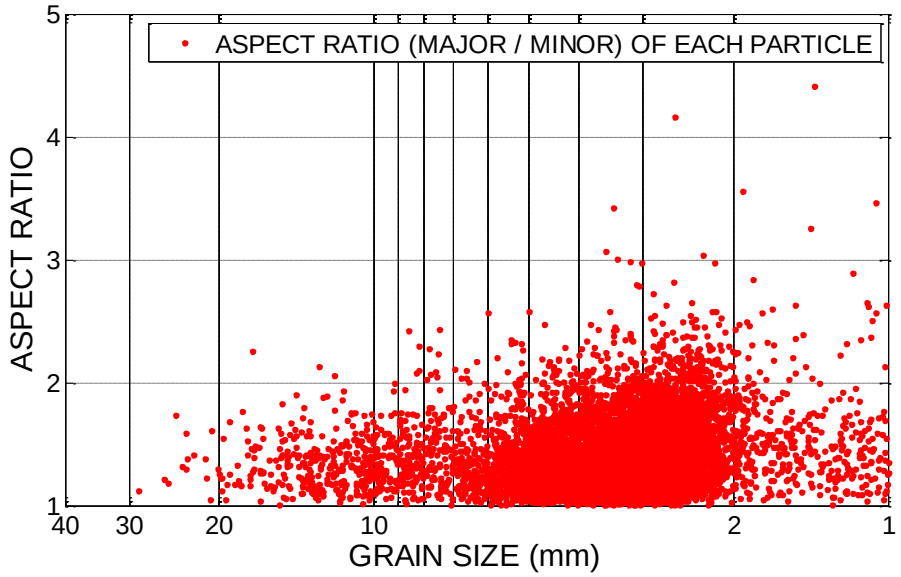

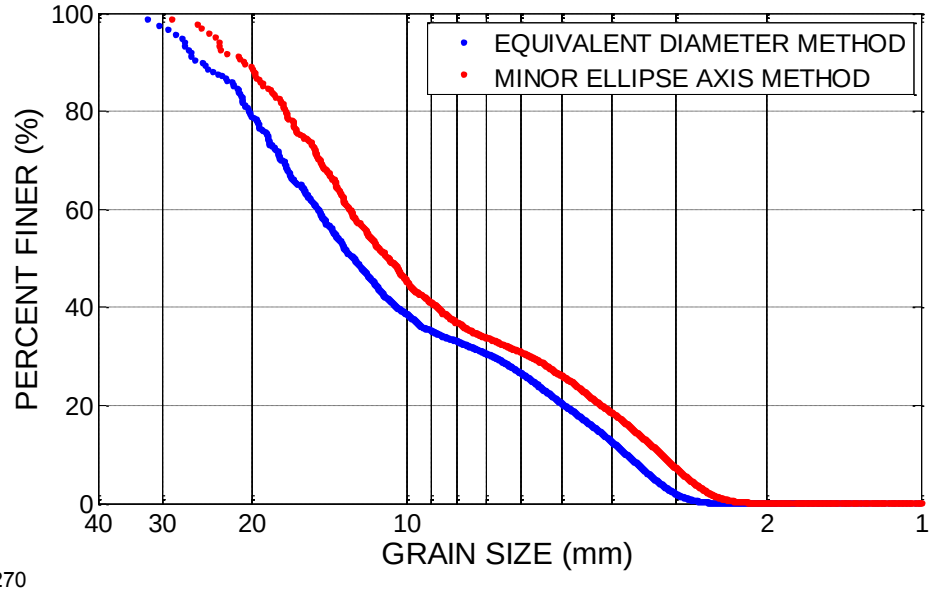

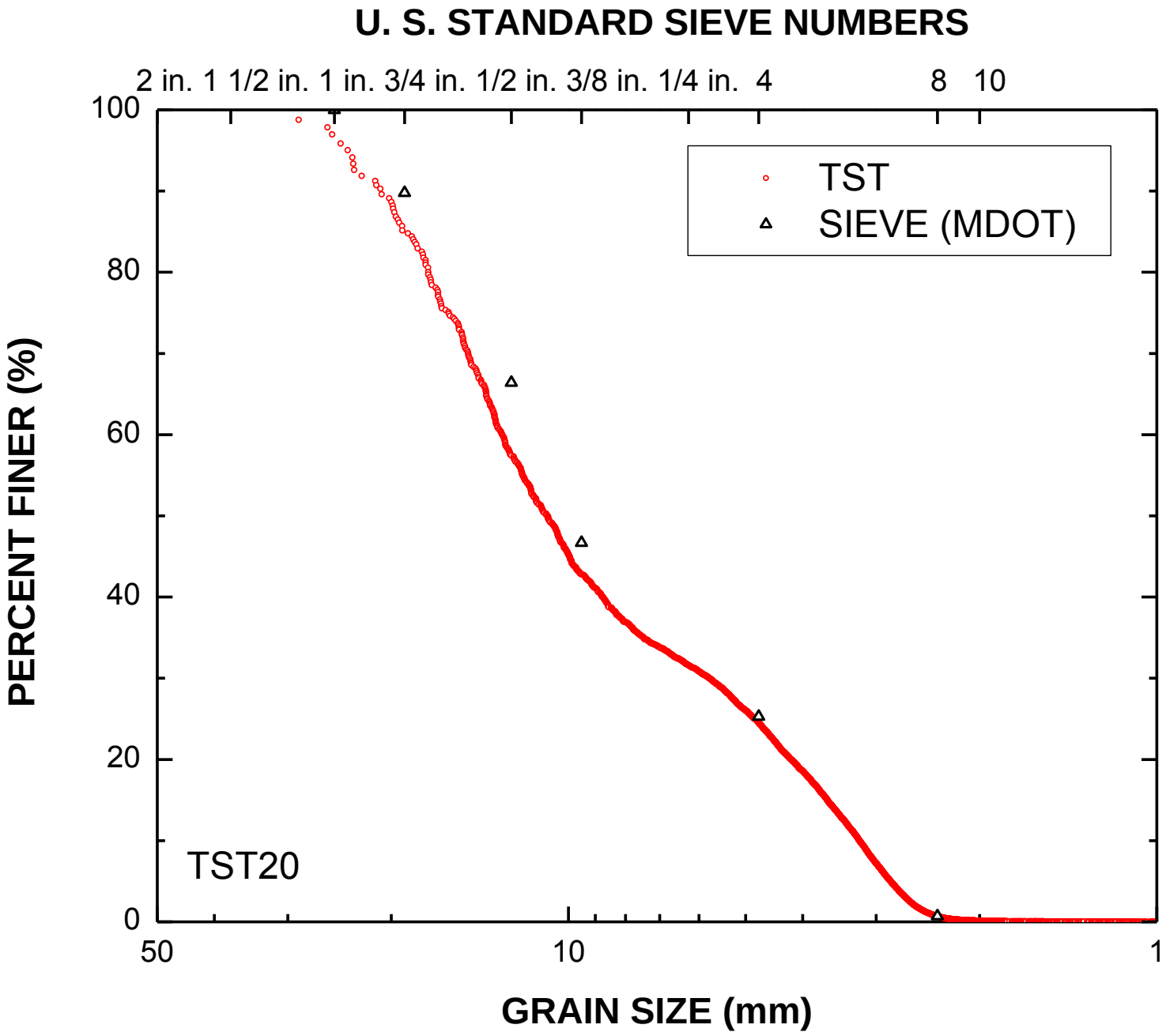
U. S. STANDARD SIEVE NUMBERS
2 in. 1 1/2 in. 1 in. 3/4 in. 1/2 in. 3/8 in. 1/4 in. 4 8 10
100
80
60
40
20
0
PERCENT FINER (%)
50
10
1
GRAIN SIZE (mm)
TST
SIEVE (MDOT)
TST20

APPENDIX H

A REVIEW OF COMMERCIAL SYSTEMS FOR DETERMINATION OF SOIL PARTICLE SIZE DISTRIBUTIONS

A Review of Commercial Systems for Determination of Soil Particle Size Distributions

Report prepared for the Michigan Department of Transportation
Under Contract # 2010-0296
Project Number 109198
ORBP No. ORE0908
Feasibility of Digital Imaging to Characterize Earth Materials

January 27, 2011

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INTRODUCTION

Geotechnical and pavement engineering methods for determining the particle-size distribution of soil samples are well established. The coarsest fraction (> 75 mm) is sized by hand; sieve analysis is used for gravels (75 mm to 2 mm) and sands (2 mm to 0.075 mm) and sedimentation analysis is employed for silts (0.075 mm to 0.002 mm by AASHTO) and clays (< 0.002 mm by AASHTO). In recent decades several new particle-sizing techniques have been developed that utilize advanced technologies. Some have been designed and incorporated into automated systems for commercial usage. This report reviews the geotechnical engineering objectives of particle-size distribution determination and describes the physics and mechanical principles of the available techniques. It also compares the utility and range of application in terms of particle sizes, the equipment costs, testing time and reliability of the advanced methods.

GEOTECHNICAL OBJECTIVES OF PARTICLE-SIZE DISTRIBUTION DETERMINATION

The particle-size distribution (PSD) of a soil specimen may be carried out for purposes of soil classification, for stratigraphic profiling or for compliance to construction specifications such as required for road sub base materials and concrete mixes. The results of testing for the latter purpose can lead to the rejection of construction materials and subsequent contractual disputes; therefore, the compliance testing requires a more accurate PSD (Abireddy et al., 2009). New methods for PSD determination need to be simple and repeatable and testing needs to produce results compatible with results of existing standard methods. Additionally, PSD determination methods must be able to size the entire range of soil particles in a specimen.

PRINCIPLES OF AVAILABLE PSD DETERMINATION TECHNIQUES

'Particle size' can be defined in various ways. Rock and soil particles tend to form irregular complex shapes. Therefore, it is difficult to define size using a single parameter unless the particle is a perfect sphere (Abbireddy et al., 2009). Since different industries (e.g. pharmaceuticals, biotechnology, chemicals, soils) utilize particles of different shapes, different ways of defining and measuring particle size have developed. Figure 1, taken from Abbireddy et al., (2009), illustrates some common definitions of particle size.

The most common current approaches appropriate for PSD determination of a soil specimen include:

1. Sieving
2. Sedimentation
3. Electrical Sensing Zone (ESZ)
4. Laser Diffraction
5. Single Particle Optical Sensing (SPOS)
6. Image Analysis

Each above technique analyzes particles based on different principles of measurement and thus define particle size differently. Generally, the techniques will produce the same measure of size only for perfectly spherical particles (e.g. calibration particles). Each method is also appropriate only for a specific soil particle size range, as listed in Table 1. The principles of each technique are discussed in the following sections.

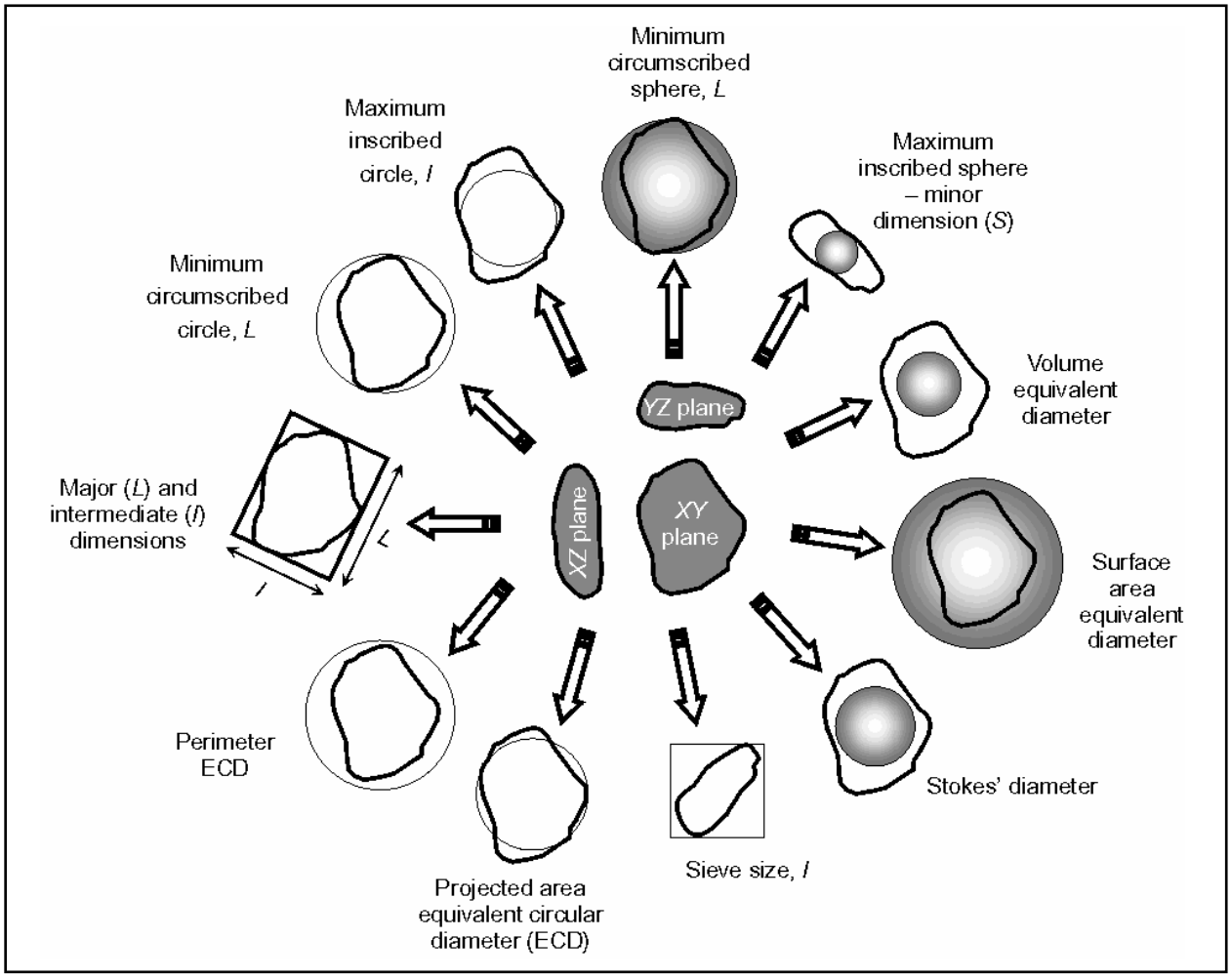

Figure 1. Various Definitions of Particle Size (from Abbireddy et al., 2009)

Table 1: Size Ranges for Various Particle-Size Techniques (modified from Abbireddy et al., 2009)

Measurement Technique	Particle Size Definition	Applicable Size Range (mm)
Sieving	Side of a square sieve aperture	0.063 to 75.0
Sedimentation	Stokes' diameter	0.002 to 0.063
Electrical Sensing Zone (ESZ)	Equivalent spherical diameter of displaced volume	0.0004 to 1.2
Laser Diffraction	Equivalent spherical diameter from Mie scattering	0.0001 to 1.0
Single Particle Optical Sizing (SPOS)	Equivalent circular diameter of projected area	0.0005 to 2.0
Image Analysis	Various definitions can be used	0.0005 to 100.0

1.0 Sieving

Sieve analysis, also known as the gradation test, is the most common method for determining PSD for geotechnical engineering applications, including pavements. Sieving requires prior removal of fines by washing the soil specimen over a #200 (0.074 mm opening) sieve. The remaining coarse soil fraction is dried then sieved though a stack of sieves with a predetermined range of openings. ASTM C136 or AASHTO T27 specify the specimen size and duration of shaking. The PSD is based on the soil weights retained on each sieve. For gravels, a large tray shaker is used, shown in Figure 2. For sands, round 8" or 12" sieves are used in combination with a mechanical shaker, shown in Figure 3. Particle size is defined by the lengths of the sides of the square apertures of the sieves through which the particles pass.

Figure 2. Aggregate Tray Shaker
(from Colonial Scientific Inc., 2011)

Figure 3. Sieve Stack with Shaker
(from Hoskin Scientific, 2010)

2.0 Sedimentation

Sedimentation methods use Stokes' diameter as a definition of particle size. The Stokes' diameter of a particle can be defined as the diameter of an equivalent sphere settling with the same velocity in the same liquid (Abbireddy et al., 2009). The hydrometer, ASTM D422 (Figure 4), pipette, BS 1377 (Figure 5), and X-ray absorption (Figure 6) methods all monitor the density of the fluid during sedimentation. Air floatation (Figure 7) separates particles according to their flow velocity and the siltometer (Figure 8) measures particle size directly by collecting sediment deposited at the bottom of a tube.

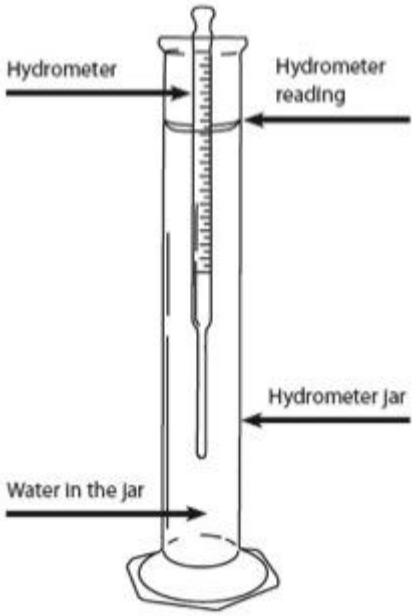

Figure 4. Hydrometer Test Equipment (University of Minnesota, 2011)

Figure 5. Pipette Apparatus (Zeal International)

Figure 6. SediGraph 5120 (Micromeritics Instrument Corporation, 2011)

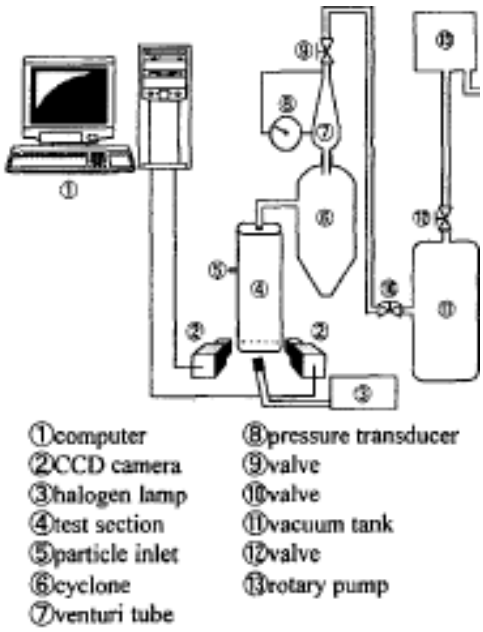

Figure 7. Air Floatation
(Sugita, T. et al., 2001)

Figure 8. Optical Lever Siltometer
(Sangmeshwar Intl., 2010)

Sedimentation methods require that organic matter and soluble salts be removed prior to particle dispersion and size determination (Abbireddy et al., 2009). Organics are removed by pre treatment with hydrogen peroxide (Laswell et al. (undated)) while washing the sample with tap water dissolves salts. Dispersion is achieved chemically using sodium hexametaphosphate or sodium silicate (Lu et al., 1991). Mechanical agitation is used to enhance and accelerate the dispersion.

According to ASTM D422, Standard Test Method for Particle-Size Analysis of Soils, two types of mechanical devices are available for dispersion: the first is a high speed stirrer and the second is air-dispersion. Testing has shown that the air-dispersion technique results in higher dispersion of plastic soils smaller than 0.02 mm in size whereas air-dispersion tests performed on sandy soils of any size produced poor dispersion. As a result of these tests, the recommendation is to use air-dispersion. Dispersion techniques differ in magnitude according to soil type. This leads to noticeable differences in the PSD, especially for particles finer that 0.02 mm.

The SediGraph 5120 by Micromeritics (Figure 9) utilizes x-ray absorption. The SediGraph 5120's "soft" X-rays, measure the concentration of particles with time as they sediment through liquid (Micromeritics, 2001). Just as with the hydrometer test, sedimentation through the homogenous suspension separates the sample by size, i.e. the largest particles fall through the suspension first followed by smaller particles. By measuring the rate at which particles of a known density fall due to gravity through a liquid of known density and viscosity allows for the application of Stokes' law to compute the equivalent spherical sizes of the particles.

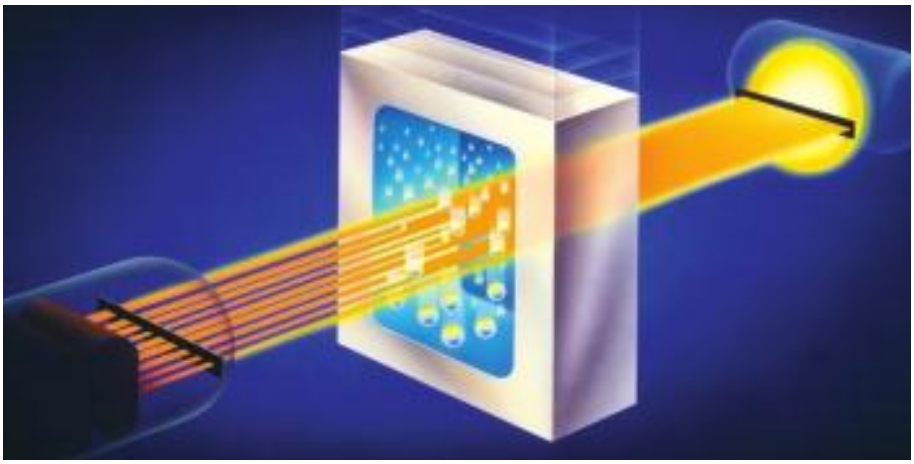

Figure 9. SediGraph X-ray (Micromeritics, 2001)

Using Stokes' law for particle size determination requires the following assumptions: (1) particles are large enough to avoid the effects of Brownian motion, which is random particle motion caused by impact with molecules of the surrounding fluid; (2) particles are rigid, smooth and nearly spherical; (3) particles are falling at a constant rate; and (4) the viscosity of the fluid controls the particles' fall rates (Skinner, 2000). However, very fine soil particles, i.e. clays, do not meet several of these assumptions. Clay particles are not spherical, but platy. Platy particles will have a lower settling velocity than spherical particles of the same volume and will not settle vertically. Instead, drift from side to side (Abbireddy et al., 2009). This results in an underestimate of the true size of clay particles (Abbireddy et al., 2009). Research has been conducted to create upper and lower limits for the applicability of Stokes' law for particle size determination. For quartz spheres settling in solution, the critical upper diameter is about 0.06 mm (Skinner, 2000) while Abbireddy et al., 2009 indicate that the lower limit occurs at about 0.002 mm. Per AASHTO, clays are defined as soil particles smaller than 0.002 mm in diameter.

The pipette method monitors sediment concentration changes by analyzing extracted samples from a solution undergoing sedimentation at predetermined times and known depths (Sympatec). As soon as the particles are dispersed and agitated (zero time) two 10 mL samples are drawn. These first samples are taken to verify the projected soil concentration of 100%, which is also determined by the known weight of the sample and volume of liquid in the suspension (Sympatec). The remaining samples are drawn as mentioned above. To determine the amount of soil in each extracted sample the solution is dried in a desiccator and weighed (Sympatec). The disadvantages of this technique are its labor-intensive procedure and high level of required skill. An experienced technician can achieve reproducibility of ±2% with this technique (Sympatec).

The air filtration method uses two CCD cameras to take pictures of particle concentrations for varying upward air flow velocities within a chamber (Sugita et al., 2001). It was experimentally determined that terminal velocities of particles are related to particle size and that Stokes' definition of size could be employed to determine a PSD (Sugita et al., 2001). Sugita et al. tested flour particles in the range of 0.09 to 0.125 mm and 0.1 to 0.12mm.

The siltometer measures particle size using two techniques: directly through collection of sedimented particles and indirectly by measurements of change in pressure. Puri's siltometer operates

by monitoring the rate of accumulation of material deposited at the bottom of a 200 or 400 cm tube while Vaidhianathan's siltometer measures changes in pressure due to the settling of particles (hec.gov.pk). Both methods rely on a low concentration solution (2% to 5%) and assumptions about the particles to determine a size distribution (Sangmeshwar International, 2010). It is assumed that particles have the same density, are evenly distributed throughout the solution and have fall velocities independent of other particles (Sangmeshwar International, 2010). In Vaidhianathan's siltometer, an optical lever is used to magnify the changes in pressure that are observed on a mercury manometer (hec.gov.pk). Puri's siltometer collects different fractions of settled particles at predetermined intervals of time and then measures the fraction by weight (hec.gov.pk).

3.0 Electrical Sensing Zone (ESZ)

The Electrical Sensing Zone (ESZ) method, ASTM F2149, as seen in Figure 10, is based on the Coulter principle (Ferraris et al., 2002). In this method, a very low concentration (around 5% by volume) of particles is dispersed in a conducting solution (ASTM F2149). The solution is made to flow through an orifice in an insulating wall, the sensing zone, on either side of which electrodes are placed (Ferraris et al., 2002). As particles pass through the orifice they displace their own volume of electrolyte solution, which causes a change in the measured electrical impedance across the opening (Ferraris et al., 2002). The volume of the particle passing through the orifice is proportional to the amplitude of the measured electrical impedance (Ferraris et al., 2002).

It is possible that two or more particles may simultaneously pass through the sensing zone; this would cause the instrument to interpret the combined pulse height of multiple small particles as a single large particle (ASTM F2149). Coincidence of two or more particles results in an overall lower cell count and higher cell volume measurement (ASTM F2149). Instrument software accounts for and corrects the frequency of coincident particles (ASTM F2149). Particle asymmetry (e.g. flaky particles) is another potential problem. Since the volume being measured is the volume displaced by the particle, particle size may be misrepresented (i.e. oversized or undersized), due to the orientation of the particle as it passes through the orifice (Ferraris et al., 2002). Porous particles (e.g. fly ash) are unsuitable for ESZ measurements, because their effective densities are unknown (Ferraris et al., 2002).

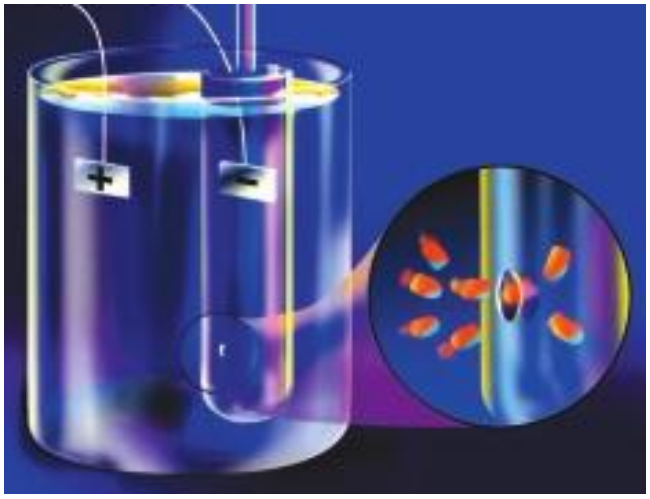

Figure 10. Electrical Sensing Zone (Micromeritics, 2001)

ESZ techniques use small volume samples that have a low concentration of particles. To be able to analyze the full advertised particle size range, different size orifices must be employed, depending on the particle size range being evalauted. For example, to achieve a particle size analysis range between 0.0004 and 1.2 mm the Beckman Coulter Multisizer 3 uses 12 different opening sizes.

4.0 Laser Diffraction (LD)

The LD method, shown in Figure 11, is based on Mie theory or Fraunhofer approximation. Fraunhofer approximation is appropriate for particles with a large wavelength; however, not all soil particles fit this requirement. As a result, Mie theory is used to overcome the Fraunhofer approximation's inability to accurately report fines (Kelly et al., undated). Mie theory describes the scattering of light at a specific angle and intensity relative to an incident laser beam as it illuminates a particle (Micromeritics, 2001). The size of the illuminated particle, wavelength of incident light, and the relative refractive index of the suspension fluid and particle are functions of the relationship between the angle and intensity of the reflected light (Micromeritics, 2001). Multiple particles illuminated at the same time provide a light pattern representative of the summation of all the contributions of intensity by each particle at each angle (Micromeritics, 2001).

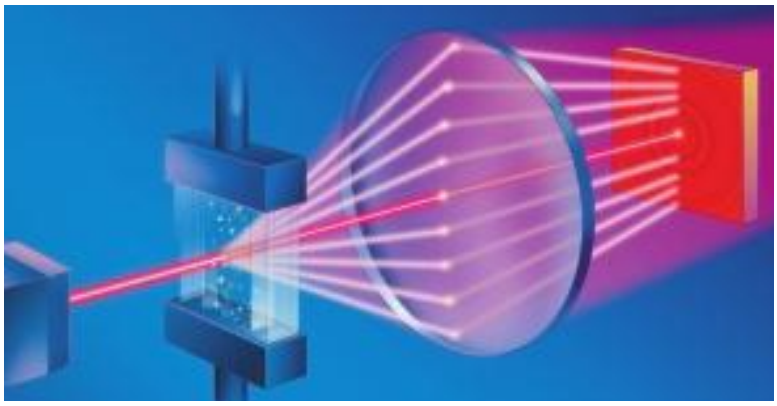

Figure 11. Laser Light Scattering (Micromeritics, 2001)

Several studies, such as by Buurman et al. (2001), Eshel et al. (2004) and Loizeau et al. (1994), compare PSD results of LD with pipette analysis. LD tests conducted on standard spheres with known optical properties provided excellent accuracy and resolution with respect to the true size of the particles; however, since the optical properties of soil are estimated, adjustments are made to the results in order to minimize residual error (Campbell, 2003). In a study performed using a Malvern Mastersizer 2000 (Malvern Instruments), it was suggested the correction factors applied to the assumed optical properties of the soil were responsible for a 15% overestimate of the fine fraction of the material (Campbell, 2003). In tests run by Eshel et al. (2004) LD reports an overestimate of the clay particles for samples of milled quartz. Conversely, as reported by Loizeau et al. (1994), LD tests conducted on soils produce an underestimate of the clay particle fraction with an efficiency of detection of 36% to 70% proportional to the clay content resulting from pipette analysis. Additionally, Eshel et al. (2004) state that LD reports an underestimate of the clay fraction in 40 out of 42 samples when compared to pipette analysis. Equipment used in these studies included the Malvern Mastersizer 2000 and 3600E, Fritsch

A22, Beckman Coulter Multizizer 3 and Beckman Coulter LS series. Other LD systems include the LA-300 and LA-950 by Horiba Instruments and the Saturn DigiSizer 2 by Micromeritics.

Discrepancies in PSD results between the LD and pipette analysis have been attributed to the assumed optical properties of soil, the applied correction factors and the non-spherical shape of particles (Buurman et al, 2001). Additionally, the orientation of the particles as they pass the laser is not always representative of the particles true size. Kelly et al. (undated) state that extremely non-spherical particles orient themselves in the direction of flow, which causes the laser to project the object's surface area instead of its volume, resulting in an overall overestimate of plate-like particles. Studies conducted by Konert et al. (1997) found that measurable ranges of particles is dependent on the focal length of the lens. Konert et al. (1997) go on to say that comparison with the pipette method is further complicated by a detection limit of 0.0005 mm. Detection limits inherent in the lens may be responsible for uncounted particles. This implies that particles successfully detected account for an unknown percentage of the specimen. The applicable size range for LD is from 0.0001 to 1 mm.

5.0 **Single Particle Optical Sizing (SPOS)** (by laser)

The SPOS method, shown in Figure 12, detects particles one by one as they fall through a detection zone and through a laser beam (www.pssnicomp.com). Like ESZ, the particle suspension must be sufficiently dilute so as to prevent coincidence of several particles crossing the detection zone simultaneously. The detector receives measures of scattered or blocked light as the laser is blocked by the falling particles (www.pssnicomp.com). The magnitude of the scattered light received by the detector is related to the diameter of the particle (www.pssnicomp.com). When compared with sieving, it was found that the SPOS method tends to predict particle size between 20 to 30% larger (White, 2003). SPOS is applicable for a size range from 0.0005 to 2.0 mm; however, this range can only be achieved through the use of three interchangeable flow cells. The Agilent AccuSizer 780 uses the SPOS technique.

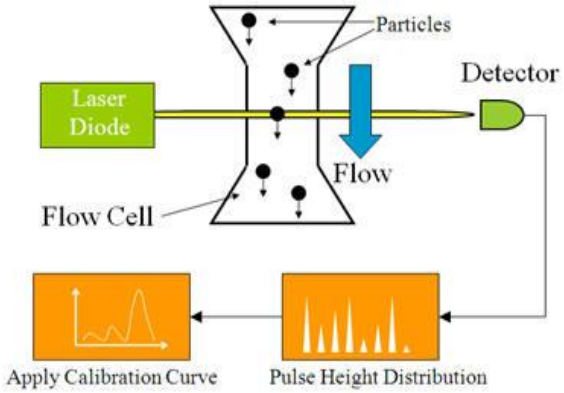

Figure 12. Single Particle Optical Sizing by laser (www.pssnicomp.com)

6.0 Image Analysis

The CAMSIZER, manufactured by Horiba Instruments, employs two digital cameras (CCD) to record falling particles (dynamic image analysis). Figure 13, taken from Horiba Instruments, shows the camera setup. A basic camera records larger particles while a zoom camera captures finer particles. Using two cameras allows the CAMSIZER to process a wide particle size range, from 0.03 to 30.0 mm, without the need to perform adjustments to the apparatus (as is necessary for measurements with the ESZ and SPOS methods). Captured images contain information about particle size, shape, density, transparency and number. Once images have been captured digitally they are processed and analyzed. Particles are assigned to more than 1,000 size classes depending on the density and size range of the sample. Results from the analysis can be displayed according to features that are appropriate to the particular sample (e.g. results can be displayed on a gradation curve like results from sieve analysis). Measurement time typically takes between 2 to 3 minutes per sample depending on sample volume; however, CAMSIZER measurements have no limit to the maximum sample volume. The maximum sample volume is only limited by the computer data storage capacity.

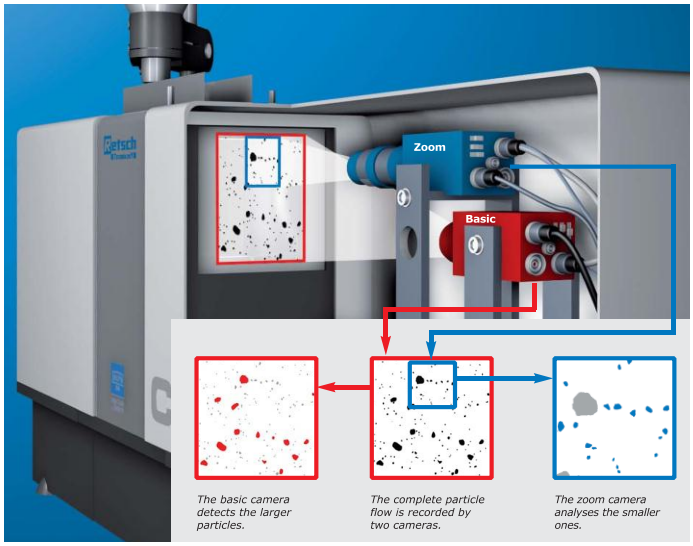

Figure 13. CAMSIZER camera setup (Horiba Instruments, 2011)

The CAMSIZER XT, manufactured by Horiba Instruments, employs an approach to dynamic image analysis similar to the CAMSIZER, but with a focus on particle sizes ranging from 0.001 to 3.0 mm. To accomplish this range of particle size determination, the CAMSIZER XT makes use of three different dispersion principles. Each dispersion principle is designed to achieve maximum dispersion for a specific type of sample. Also, each dispersion principle is appropriate only for a given size range. Table 2, modified from Horiba Instruments, shows particle size range with the appropriate dispersion principle.

Table 2: CAMSIZER XT dispersion principles with size ranges (modified from Horiba Instruments, 2011)

Dispersion Principle	Applicable Size Range (mm)
Free-flowing particles	0.01 to 3.0
Dry powder feeder	0.001 to 1.5
Wet dispersion	0.001 to 0.6

Like the CAMSIZER, the CAMSIZER XT approaches PSD determination with two cameras, one basic and one zoom. Two separate light sources, LEDs, are optimized to supply each camera with the appropriate pulse length and field of view. The LEDs emit light pulses on the falling particles, the shadows of which are captured with the cameras. Figure 14 demonstrates the principle behind the dispersed particle measurement in the CAMSIZER XT.

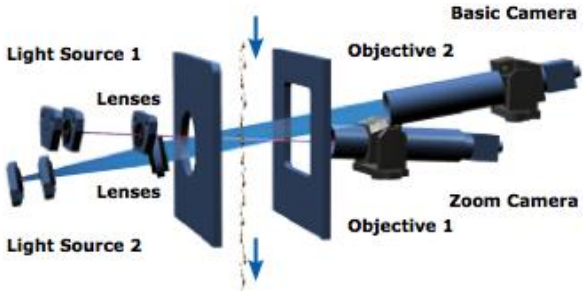

Figure 14. CAMSIZER XT measurement principle (Horiba Instruments, 2011)

The PSA-300, manufactured by Horiba Instruments (Figure 15), automates the static image analysis method traditionally performed by manual microscopy. The PSA-300 employs a single 2.1 megapixel camera that is capable of analyzing particles from 0.0005 to 2.0 mm; however, this size range can only be accomplished through different magnification levels: 50X, 20X, 10X, 5X, 2.5X and 1.25X. A single objective (magnification level) may be performed at a time. As a result, only samples of similar size may be characterized during the same test. Samples having a broad distribution in size would need to be adequately disbursed which, over several orders of magnitude, is nearly impossible.

Figure 15. PSA 300 for static image analysis (Horiba Instruments (Horiba Instruments, 2011)

SUMMARY OF PARTICLE SIZING ABILITIES, COSTS AND TESTING TIMES

The methods for PSD determination described in this report are compared in Appendix A on the basis of their ability to size particles over different ranges. For most of the advanced devices, different settings, "orifice" dimensions, sensors or camera magnifications are needed for different particle size ranges. The ranges shown in Appendix A have been obtained from the system manufacturers or estimated by the authors on the basis of product specifications or published papers. Data collected using the different sensors, magnifications etc. ranges generally cannot be combined to produce a complete grain size distribution, except possibly for the Camsizer. Furthermore, the ability for any one sensor to collect data over its reported range does not necessarily mean that it can size particles over the entire range in a single specimen. The problem of small particles agglomerating or being hidden from view by larger particles is encountered in several of the methods.

Appendix B compares the base costs for each of the commercially available systems. The reported costs do not include maintenance, disposable supplies, recurring calibration costs and other operating expenses. Appendix C compares the times required to perform a single test. They are reported here as claimed by the product manufacturer. As such, in some cases they represent only the actual data collection time while in others they may include the analysis time. In no case do the times include specimen preparation. For example, the reported times for sieving do not include pre-washing to remove fines and drying. The reported times also do not account for laboratory practices such as performance of multiple tests simultaneously. Thus, while a hydrometer test may take a day to perform, many tests may be performed concurrently.

CONCLUSIONS

1. Systems for conventional methods for soil particle size distribution (PSD) analysis by *sieving* (sands and gravels) and *sedimentation* (silts and clays) are much less costly than equipment that utilizes advanced technologies such as *x-ray absorption*, *laser diffraction* (LD), *electrical sensing zone* (ESZ) and *single particle optical sizing* (SPOS).
2. The advanced technologies are geared primarily to particles in the fine sand range and smaller. They were generally designed for non-soil applications such as for pharmaceuticals, commercial powders, chemicals and food ingredients where the range of particles typically does not span more than one order of magnitude in size.
3. While commercial LD products such as the Saturn Digisizer reportedly extend the sizing range up to 2.5 mm, the method is not very precise and test results must be interpreted using complex inversion algorithms.
4. In the SPOS method particles are sized one at a time as they pass through the laser beam in a precisely diluted fluid. The The AccuSizer® 780 by Particle Sizing Systems, ($65,000) may size particles as large as 2 mm with a "Large Volume Sizer" option. The manufacturer claims that the test takes only 3 minutes, however only "a spoon full" of material can be tested at a time. The system requires three sensors for three particle size ranges. It is not clear what range of sizes can be accurately evaluated in a single test.
5. Imaging methods are a viable alternative to traditional sieving and sedimentation methods. They include *static* (flat bed) and *dynamic* (falling particle) approaches to PSD determination. The Camsizer® by Retsch Technology ($65,000) is the best known commercial product in the dynamic category. It utilizes two cameras at different magnifications to capture particles over several orders of magnitude in size. However, product representatives identified two critical issues. First, very

small particles tend to agglomerate. Secondly, small particles are often occluded behind larger ones, even in free-fall. They suggested pre-sieving to reduce the range of particles in any one specimen sent through the apparatus.

6. In the static image analysis category, the leading commercial product is the PSA 300® by Horiba ($85,000). This is essentially a digital microscope with 6 magnifications (1.25, 2.5X, 5X, 10X, 20X and 50X) thereby allowing for the sizing of individual particles over three orders of magnitude; the largest particle being 1 mm. Advanced software may perform shape analysis on individual particles. However the system is not well suited for wider range PSD determination since data from images at different magnifications cannot be merged. Thus, the practical PSD range is at best one to two orders in magnitude. The problem of small particles hiding behind larger ones is not addressed.

The remaining three conclusions are not from the review of commercial products. They are based on research performed at the University of Michigan on development of the "Sedimaging" System described elsewhere and initial observations regarding a flat-bed imaging method being considered for particles larger than 2 mm.

7. Sedimaging utilizes sedimentation only to segregate the particles by size. The sedimented column is photographed and image processing yields the grain size versus height in the column which is easily converted to a conventional grain size curve. Currently, the practical upper limit for Sedimaging is 2.0 mm while the lower limit depends only on the camera (lens) magnification. Particles in the 2.0 mm to 0.07 mm range can be imaged at a single magnification. With a new Nikon 24 Megapixel camera (currently $8,000), only one photograph of the sedimented column at a fixed magnification is required. This eliminates the need for a costly camera positioning system and image processing software (Adobe Photoshop®) to stitch successive overlapping images into one complete column image.
8. Imaging of particles larger than 2 mm would best be accomplished on a flat bed such that the particles are spread out on a 2-D plane surface. To preclude the small particles from rolling under much larger particles, some degree of particle segregation into size "bins" is needed. Ideally, following segregation, the flat bed could be gently vibrated so that particles in each "bin" detach from one another. However, this separation may not be necessary since image processing may be able to digitally segment the particles from one another.
9. As inexpensive as current sieving and sedimentation methods are, the cost of image-based methods such as Sedimaging and flat-bed photography are likely to continue downward as the price of high resolution cameras falls. The cost of hardware for segregating particles in the sedimaging device and the flat bed segregator have not been established but they are sure to be less expensive than commercial products such as the Camsizer and Accusizer (appox. $65,000+ each).

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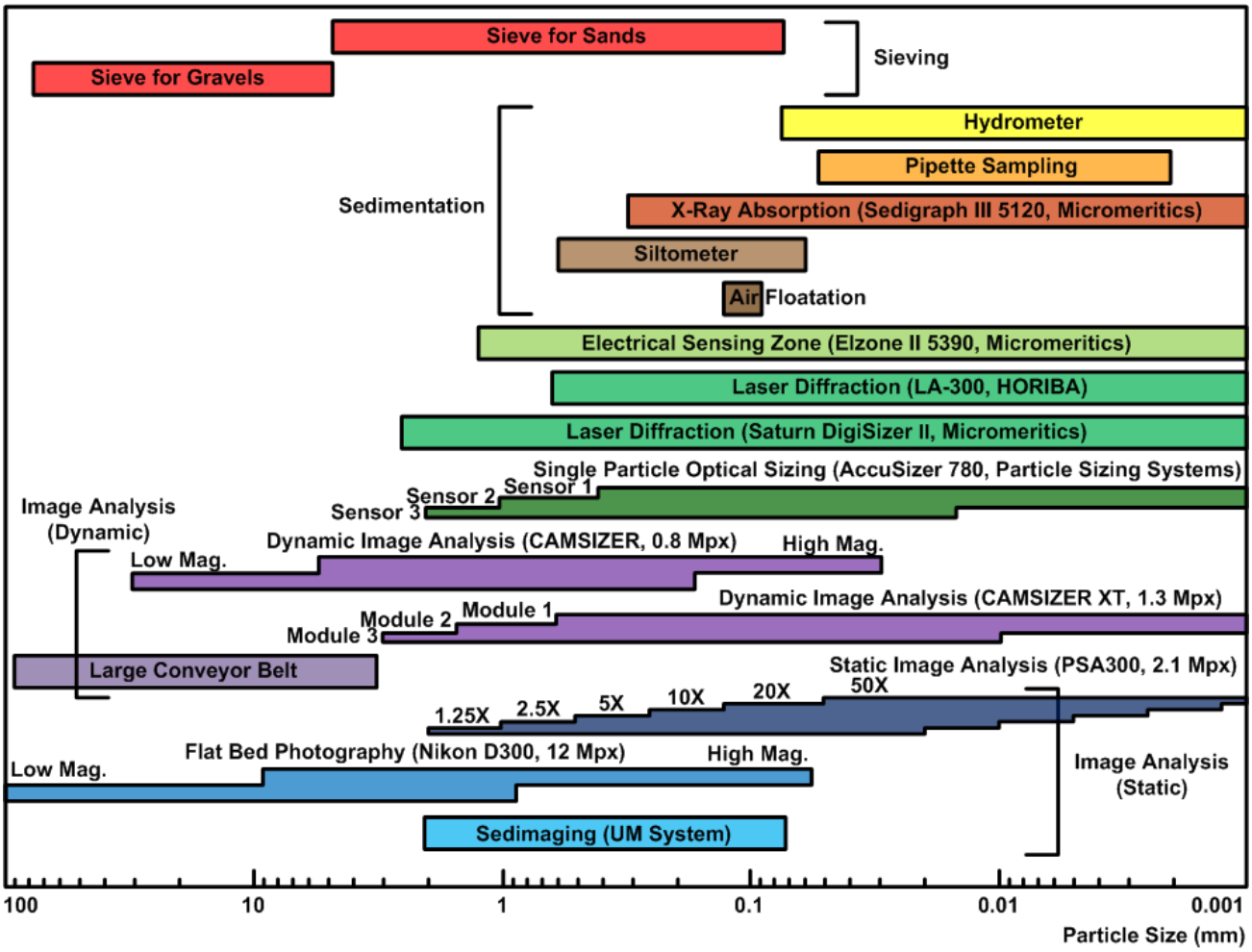
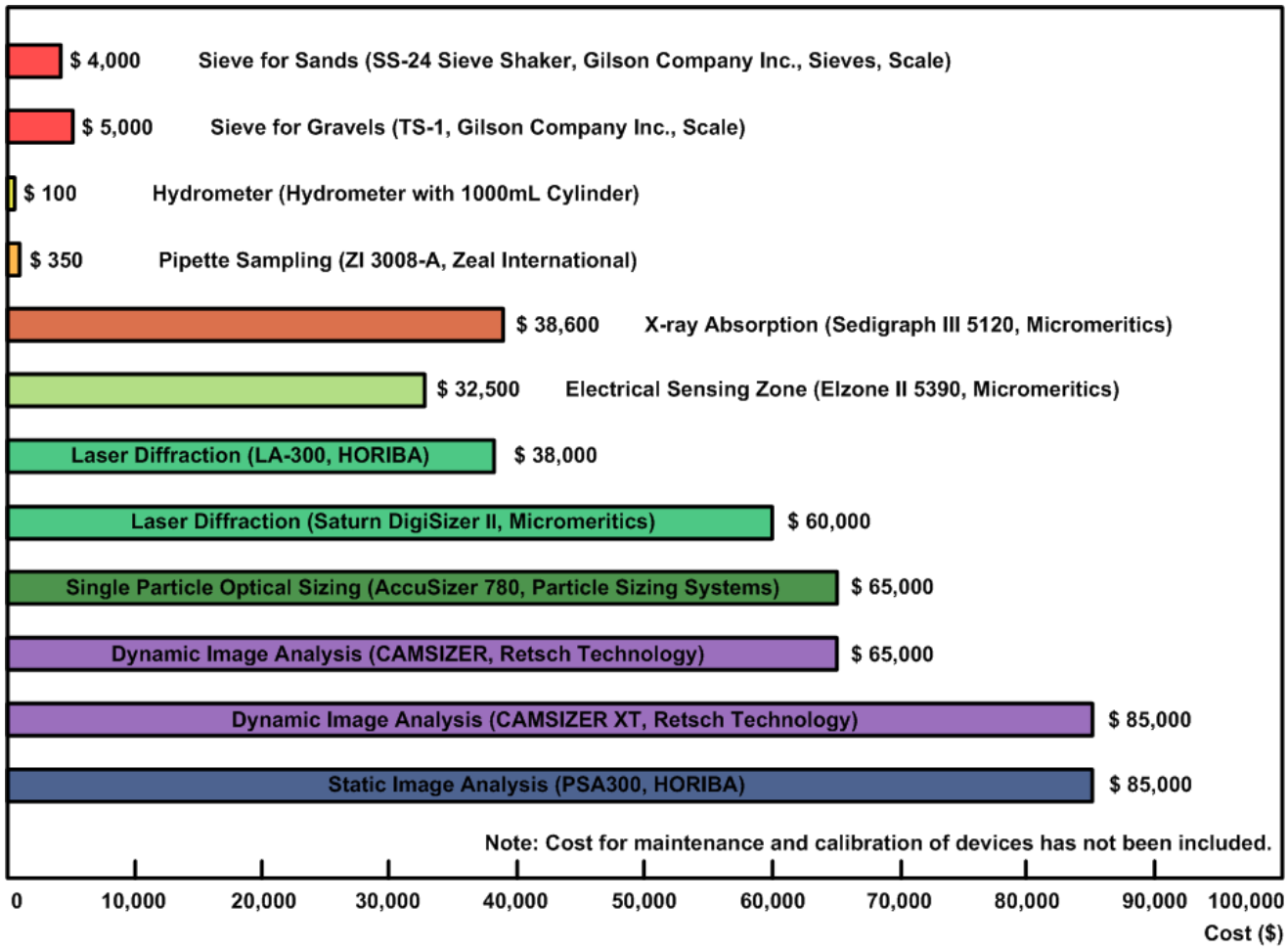
Appendix A

Comparison of Particle Sizing Ranges for Various Systems Described in this Report



Appendix B

Comparison of Base Costs for Various Systems Described in this Report



Appendix C

Comparison of Testing Times for Various Systems Described in this Report