A Simple Test Method for Rapid Measurement of Fines Content in Soils
Ahmad Mousa,1 Mohamed Mahgoub,2 and Piotr Wiszowaty3

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Reference

Abstract
Visual soil classification methods used for estimating fines content are often relied upon in geotechnical investigations. The estimations of these methods are highly judgmental, generally erratic, and typically necessitate a confirmation. Laboratory mass-based wash tests are regularly performed on selected soil samples in order to verify or complement in situ visual classifications. Therefore, there is a dire need to improve the accuracy of fines content estimates of the visual methods. A preliminary study was conducted to assess the principle of estimating fines content by measuring relative volumes of the coarse-grained to fine-grained soil fractions. The results indicated soundness and adequacy of the principle. Utilizing this volume-based concept and the standard sample washing methods, a pilot study was conducted to develop and evaluate a more precise testing method, the mold test. Triplicate test runs were carried out on 144 soil samples. With run times of 5 to 15 min, the test is sufficiently rapid. The estimated fines contents of the samples were compared with that determined by the ASTM D1140 test. The absolute differences between the two estimates fell within ±5 % range, which is an appreciably higher accuracy than those of commonly used visual soil classification methods. Analysis performed on the results of the pilot study attested statistical competences of the proposed test method. This study has proven that the mold test is convenient for measuring fines content in soils at almost no cost—except minor consumables. The test method eliminates the subjectivity associated with current visual classification tests as well as the time and cost of the standard laboratory wash tests. While it is not intended to be a substitute for the latter, the mold test is an economically viable option that maintains balance between laboratory accuracy and practicality of the field methods.

Keywords
visual soil classification, mass-based fines content, volume-based fines content
Introduction

Soil’s behavior is impacted by a wide range of characteristics including shape of the soil particles, mineralogy, soil-water interaction, and density of particle packing. The presence of fines content in soils plays a major role in controlling mechanical, hydraulic, and dynamic characteristics of geologic materials. The Unified Soil Classification System (USCS) defines fines content as the percentage of the tested sample (by mass) that passes the 0.075 mm sieve—typically referred to as passing the No. 200 sieve or fines content. A wide spectrum of applications in geotechnical engineering can be appreciably affected by the presence of fine material in soils, e.g., seepage analyses for earth structures and evaluation of well permeability (USACE 1986), material suitability for borrow sites (USACE 1994), and liquefaction potential of foundations (Seed et al. 2003). Therefore, field identification of soil types and their basic characteristics (e.g., ASTM D2488) is of great importance in geotechnical engineering. As part of this field characterization, estimating fines content with reasonable accuracy during subsurface investigation is quite instrumental. Several rapid rules of thumb and approximate visual classification guidelines are commonly used for estimating fines content in soils, such as the “domino” wash test and the jar test (ATT-29 1995; ASTM D 2488; Caltrans, 2010). These approximate “rules-of-thumb” are generally centered on washing out fine materials or based on the sedimentation principle. Their success is highly dependent on judgment and experience of the field operator and; therefore, the field estimations of fines content in soils remain inclusive. This would typically require performing a standard laboratory wash test for confirmation.

Laboratory grain-size and wash tests are not always sufficiently budgeted in all projects. Driven by their limited finances, it is customary for some projects to even rely chiefly on visual soil classification methods to estimate fines content. Even for large projects, when the need for estimating fines content is dominant, in situ approximate estimation of fines content can be instrumental. Therefore, it is paramount that in situ visual classification of soil be conducted with acceptable accuracy so that duplicate samples for laboratory testing are held to a minimum.

DETERMINATION OF FINES CONTENT IN FIELD AND LABORATORY: AN OVERVIEW

Common field methods used to estimate fines content in soils, such as the cube (“domino”) and jar tests, are by default simple tests. A group of these methods is centered on washing out the fines particles of an initially known soil sample volume and comparing the remaining volume of the washed sample to the original volume. Another group of visual soil classification methods utilizes the sedimentation principle for identifying relative volume fractions of soil constituents. Several laboratory tests, mostly mass-based such as ASTM D1140, are used to estimate fines content in order to complement or verify field classifications. The following is a summary of field and laboratory tests used for estimating fines content in soils.

Field Tests

The cube test is a crude test that is used to estimate fines content in a pre-determined soil volume. The test is based on washing fine particles out of the soil sample. Fines content is estimated by comparing the final volume of the sample to its initial volume. Despite simplicity and convenience, results of the domino test are generally very erratic and its success is unquestionably operator-dependent. The test can be summarized as follows (ASTM D2488):

1. A pre-determined volume (e.g., 1-in. (25.4-mm) cube) of soil is formed using a cubical or prism mold.
2. The soil cube is cut in half, one half is set to the side and the other half is placed in a small washing dish.
3. The half in the dish is washed thoroughly with clean water to break any lumps of fines.
4. The wash water is decanted and washing is repeated until water is judged clear.
5. Using a knife or spatula, the washed portion of the cube is formed into a prism-like shape and its volume is visually compared to that of the set aside half. The relative volume proportion is used as a measure of the fines content.

Utilizing the sedimentation principle, the jar (bottle or tube) test is used to estimate the relative volume of the major soil constituents (sand, silt, and clay) with respect each other. One minute is typically sufficient to allow sand particles to settle. Silt generally settles in about 1/2–2 h. Clay could take a long time to settle and may not completely settle. Depending on clay content and type, this test could take from 24 h to several days. While the visual identification of interface between the soil constituents is often difficult, their relative thicknesses (volume) give a general indication of their proportions in the soil sample. The test can be summarized as follows:

1. A medium-size jar is filled with about 50 mm-thick layer of soil.
2. Water is added to about two-thirds of the jar (a teaspoon of liquid dish detergent or table salt could be added to facilitate breaking of clay lumps).
3. The jar is thoroughly shaken to mix the soil sample with the added water until no soil remains on the walls or bottom of the jar.
4. Soil particles are allowed to settle and the interface between the distinct layers is identified.
5. The thicknesses of the soil layers are measured and recorded.

Laboratory Tests

Standard mass-based tests for determination of fines content in soils, such as ASTM D1140, are performed by wet sieving. An
oven dry specimen of a known mass is washed on the No. 200 sieve until wash water is clear. The retained material is retrieved and oven dried again. The difference between the initial and final dry masses is fines content. The prime source of error could be driven by the presence of clay lumps due to inadequate washing. This can be overcome by soaking the soil sample in a dispersing agent prior to washing (ASTM D1140—Method “B”). The grain size analysis test (ASTM D422) is comprised of mechanical sieving and complemented by the hydrometer test and conducted for full size characterization. The fines content is one of readily available test measurements.

The pipette method utilizes Stoke’s Law by the extraction of subsamples of the soil suspension at a given depth after a pre-determined settling time for each size fraction of interest (BS 1377-2 1990; Day 1965). As time passes, larger particles pass by the sampling depth, and smaller size fractions can be sampled. After extracting the sample, it is dry weighed, and the percentage of the total soil in suspension present in each sample is determined. The pipette method is generally accurate, but it is time consuming.

Based on the ASTM D1140 standard test, Brown and O’Harra (1969) proposed an enhanced wash test by which the material passing the No. 200 sieve is washed off of a pre-weighed oven dry soil sample. The sample is transferred to a transparent cylindrical container (washer) supplemented by windows covered with the No. 200 sieve. The method facilitates more efficient and quicker washing through the No. 200 sieve via introducing compressed air into the washer. The amount of material finer than the No. 200 sieve is the difference between the initial and final dry masses of the sample.

There is a wide range of more advanced techniques that could be used for grain-size distribution, such as laser diffraction particle size analysis, X-ray absorption (Vitton et al. 1996), and elutriation (Mills 1969). The reader is referred to relevant references for details.

**MOTIVATION**

Visual identification combined with laboratory testing is necessary for complete soil classification. A reliable field test for estimating fines content in soils could assist field logging, particularly for projects where fines content is critical for analysis, design, and planning. Full sieve analysis including the hydrometer test is performed on select soil samples in order to verify or complement field logging (USDR 1998). Depending on project, application, and testing budget, the wash test (passing #200) is typically performed more often than the full sieve test. The wash test, despite its relatively low cost, could be a prime laboratory component for some projects. Geographically variable, the current cost of a single wash test could range from $30 to $80. The test involves two cycles of oven drying the sample, which typically requires about 48 h. Therefore, a higher quality of visual soil classification could help in optimizing laboratory test assignments, which would reduce the number of the required laboratory wash tests for confirming - direct savings in time and testing budget.

The common “rules-of-thumb” used for visual classification are fundamentally sound but they rely heavily on the logger’s experience and their results remain qualitative or indicative at best. Some government and large-scale infrastructure projects seek more accurate estimation of fines content during logging and possibly reporting them at some selected precision. For example, during the field investigation program of the levee system in the central valley, the California Department of Water Resources requested estimation of fines content to the nearest 5 %, so as to improve the quality of visual classification (DWR 2008). This could be somewhat challenging, particularly in the presence of non-plastic silt that could be mistakenly classified as very fine sand.

**OBJECTIVE**

The study aimed at developing a reliable test that eliminates the shortcomings of the current visual classification tests used for estimating fines content. In order to achieve this goal, the proposed mold test should have the following characteristics: simple and quick test procedure; suitable for coarse- and fine-grained soils, reasonably accurate and repeatable, and inexpensive. The success of the proposed test will be judged in its ability to meet these requirements in a balanced fashion.

Estimation of the fines content using the mold test must be comparable to those determined in the laboratory using standard wash methods (e.g., ASTM D1140). The proposed test, however, is not meant to be a replacement to the current laboratory mass-based tests. Like most laboratory tests in geotechnical engineering, some level of variability in their results should be expected. Thus, it could be argued that the proposed mold test should be considered robust and reliable only if its results warrant an “acceptable” level of variability.

This research is comprised of three prime components: a preliminary study, a pilot study, and a statistical evaluation. The preliminary study was conducted to establish confidence in the proposed test concept. The pilot study focused on improving the accuracy and applicability of the proposed test. The statistical evaluation was performed on the results of the pilot study to evaluate the statistical soundness of the test.

**Preliminary Study: Assessment of Volume-Based Measurements**

**APPARATUS AND TEST**

Inspired by the “domino” test, a cut-out plate test was developed for estimating fines content in a soil sample by measuring the final volume of the specimen after washing out the fines. As shown in Fig. 1(a), the rectangular cut-out dimensions are 1 by...
1/2 by 1/4 in. (25.4 by 12.7 by 6.35 mm). A soil specimen (about 8 to 10 g) is thoroughly mixed by hand at its natural moisture content. All clay lumps should be broken and any coarse aggregate, rock fragments, and inferior material should be removed. The cut-out is then carefully filled with soil (initial volume of the specimen). The specimen is carefully extruded out of the mold and placed in a cup or bowl filled with water. Then the specimen is thoroughly stirred with water. Depending on the predominant soil type, the suspension (cloudy-water) is carefully decanted in 5 to 10 s following mixing, which leaves the coarse-grained soil (sand) at the bottom of the cup. The washing process is repeated (typically 2–3 times) until the mixing water is judged clean (free of fines). The sand settled at the bottom of the cup is reshaped into the cut-out as shown in Fig. 1(a).

Like the domino test, the cut-out plate test is based on the assumption that the % of volume of washed out fines from the specimen is equivalent to the mass-based fines method (e.g. ASTM D1140). The length of the specimen after the test is measured using a 40-division ruler along the largest side of the cut-out. This precision allows reporting the fines content to the nearest 2.5 %. As indicated in Fig. 1(a), the difference between the length of the cut-out rectangle \(L_o\) and the length of the reshaped specimen after washing \(L_f\) is used to estimate volume-based fines content in the soil sample. Fines content can be mathematically expressed as follows:

\[
Fines \text{ Content (\%)} = \frac{L_o - L_f}{L_o} \times 100
\]

RESULTS AND ASSESSMENT

The cut-out plate test was performed on 39 control samples having known fines content. The samples were obtained from the central valley in Northern California. The measured fines content were qualitatively satisfactory but were somewhat erratic (Fig. 1(b)). For coarse-grained soils, the fines content were generally overestimated, which indicates losing sand particles during washing. This trend seems to be somewhat reversed for fine-grained soils. The test generally suffers from inherent shortcomings and approximations. Judgment exercised during specimen washing and final volume (length) measurement is believed to be the major source of error. It is also believed that the small size specimen (8 to 10 g) is another source of variability. The arbitrary 5–10 s wait period during which sand particles are assumed to settle in the washing container is obviously judgmental. In addition, our observations indicated that the assumption that the prepared specimen is a perfect right-angled prism completely hand-formed into the cut-out appears to be idealistic. In fact, the absence of internal “air pockets” or irregular inter-particle voids within the specimen can never be guaranteed. Moreover, both initial and final volumes of the specimen undergo an unknown and non-homogenous “compaction/compression” during hand-forming. Despite the shortcomings, the results indicate that the volume-based principle is generally suitable for a wide range of soils, but a higher accuracy would necessitate unifying and standardizing the test procedure.

Pilot Study

Utilizing the volume-based principle, the proposed mold test was designed to account for the potential sources of error in the cut-out plate test. The mold test was developed primarily to eliminate the subjectivity and randomness involved in washing, forming, and measuring the initial and final volumes of the specimen. It is paramount to realize that the mold apparatus presented herewith is a prototype that would undergo some minor modifications and further manufacturing alternations before it can be used for commercial purposes. As such, the pilot study introduces the idea and sets ground for a paradigm shift towards enhancing in situ soil classification.
**APPARATUS**

The test apparatus consists of two prime components, the preparation tube and the mold, and auxiliary components and peripherals for mixing, forming and measuring heights (Fig. 2). The preparation tube is a 1-in. (25.4-mm) diameter pipe with a side cut-out for sample introduction and a push rod for specimen extrusion. The mold is a 1-in. (25.4-mm) diameter cylindrical tube with a No. 200 woven wire sieve attached to its bottom. The upper end of the mold is connected to a 3-in. (76.2-mm) diameter washing chamber (collar) via a conical v-shaped PVC adapter. The preparation tube and the mold are made of transparent acrylic in order to allow for monitoring specimen preparation and washing.

**DESIGN RATIONALE**

In order to achieve the objectives of this research, balance between practicality and accuracy should be ensured for effective design (Geem et al. 2012). An optimization scheme was implemented for identifying the optimum specimen initial size as well as apparatus design and dimensions. This scheme has considered several parameters including ease of specimen preparation and extrusion, washing time, number of needed washing cycles, precision of height measurements, accuracy of fines content determination, and ergonomics of apparatus. The proposed apparatus (mold), however, should be considered a prototype not a final product. It should also be noted that the proposed test procedure was also simultaneously modified to utilize the changes made to the apparatus. Manufacturing details including materials, fittings, connections, and assembly were accordingly modified.

Soil samples with initial masses ranging from 15 to 60 g were selected to cover a wide range of fines content. The samples were initially tested using 1/2-, 3/4, 1, and 2 in. (12.7, 19.05, 25.4, and 50.8 mm) diameter molds. The fines content of the selected sub-samples were pre-determined in accordance with ASTM D1140 for comparison with those determined by the different prototypes built. In order to narrow the prototypes to a manageable number and minimize optimization effort, the success of the “optimum” setup and test procedure was largely judged by closely monitoring washing time and accuracy of fines content measurements (closeness of a test result to that of ASTM D1140).

For any given mold diameter, larger soil samples (particularly with high fines content) yielded long washing time that could be impractical. On the other hand, observed accuracy of height measurements for soil samples near the 15 g indicated unrepresentativeness and notable variability. For any given specimen size (mass), small diameter molds (<1 in. (25.4 mm)) yielded larger specimen heights. Therefore, contribution of any imperfections in specimen preparation (e.g., air pockets) to errors in specimen height measurements is smaller than those of the large size molds. However, washing problems and rapid screen clogging were encountered, particularly for soils with high fines content. For the same specimen mass, the height of a 2 in. (50.8 mm) diameter specimen is less than one-half that of the 1 in. (25.4 mm) diameter specimen. For the former, it was...
rather difficult to guarantee flatness of the top surface of the specimen during preparation as will be discussed in the procedure. In addition, the corresponding small specimen height could cause significant variability in height measurements. For short specimens, minor imperfections in height measurement such as soil particles trapped between assembled components of the mold could have an adverse impact on the accuracy of the estimated fines content. In order to overcome this, specimen size was increased, but the wash time (soil dependent) increased to approximately 30 min for fat clays. Therefore, the 2 in. (50.8 mm) diameter preparation tube and mold were deemed unsuitable.

While the prototypes were not examined for all selected soil samples, the performed optimization process concluded that a 1 in. (25.4 mm) diameter mold and about 25 g initial specimen mass is the most suitable combination that maintains good balance between acceptable accuracy and reasonable wash time. It was observed that preparation of specimen by placing soil through the end of the 1 in. (25.4 mm) diameter tube causes soil particles to stick to the inner walls of the tube at the entry end. Therefore, an oval side cutout at about mid height of the preparation tube was proposed. In order to facilitate adequate specimen washing, the 1 in. (25.4-mm) mold (tube) is attached to a 3 in. (76.2 mm) washing chamber (collar) via a conical v-shaped PVC adaptor as shown in Fig. 2.

**SCOPE AND LIMITATIONS**

The focus of this study was centered on reliably estimating fines content in various soils having a wide range of fines contents. The proposed method should be reasonably accurate and sufficiently rapid. The test must lend itself to the field as well as the laboratory. 144 soil samples were obtained from the Greater New Orleans area for this purpose. Each sample was tested three times at its natural moisture content by a single operator using the proposed mold and ASTM D1140 methods. Figure 3 shows the tested soil samples classified in accordance with the USCS. Approximately 60% of the tested samples were coarse-grained soils. The consistency of the fine-grained samples is depicted in Fig. 4.

The mold test should be only used for soils passing through the No. 4 sieve (sand, silt, and clay). It is suitable for soils at their natural moisture content in the field under normal conditions. As shown in Fig. 4, the moisture of the most fine-grained soils falls between their respective plastic and liquid limits. However, about one quarter of the specimen had moisture contents below their plastic limits. A few specimens had moisture contents above their liquid limits. The mold test is not applicable to organic soils containing decaying or fibrous substances (e.g. marsh-like). Such soils typically have free water appreciably in excess of their liquid limit. Any present coarse aggregate, rock fragments, shell, asphalt fragments, foreign, and man-made objects, organic material (particularly fibrous-like) rootlets, twigs, or wood fragments must be excluded from a soil sample prior to testing. If traces of these substances are observed during washing of the specimen, this sample must be discarded. Like mass-based wash tests, the mold test cannot be used to determine clay and silt proportions in a soil specimen.

**TEST PROCEDURE**

The proposed test procedure involves three steps: sampling, specimen preparation, and determination of the initial height of the specimen, and specimen washing and determination of the final height of the specimen. Photos of the test steps are depicted in Fig. 5. Prior to testing, all components of the apparatus must be clean, intact, and operable.

**Sampling**

A representative 25 g to 35 g sub-sample is obtained from a field (parent) sample at its natural moisture content. Any clay lumps or friable material present should be broken down and pulverized by hand or by using a kneading tool. All the foregoing
objectionable materials and substances must be excluded from the sub-sample prior to testing.

In order to investigate the effect of soil variability on the results of the mold and ASTM D1140 tests, the parent samples were divided into 3 or more 25 to 35 g sub-samples after thorough hand mixing. The relatively small sub-samples used for the ASTM D1140 test were selected in so as to have comparable size to those of the mold test. Due to the repeated test determinations, the available parent sample would have been insufficient if larger amount of soils were tested.

Specimen Preparation and Determination of Initial Height
Prior to sample introduction, a reference height should be measured or zeroed for the push rod-preparation tube assembly. The sub-sample is incrementally introduced into the preparation tube through its side cut-out. An initial specimen height of approximately 20 to 25 mm is targeted (Fig. 5(a)). The soil is placed in approximately three equal-height layers (lifts). In order to minimize introduction of large air pockets within the specimen, each layer is lightly but sufficiently compressed by the forming rod 3 to 5 times (Fig. 5(b)). The absence of visible gaps along the perimeter of the inner wall is deemed to be an adequate criterion for reliable height measurements. Prior to placement of the next layer, the push rod is used to gently flatten the top of each layer by rotating it 2–3 times in a twisting fashion. Finally, the full length of the prepared specimen should be carefully checked for any visible air pockets before measuring the initial height of the specimen ($H_i$) using the gage (Fig. 5(c)).

The bottom lid of the preparation tube is removed to allow specimen extrusion into the mixing cup for washing. In order to retrieve the specimen, the push rod is inserted through the preparation tube as shown in Fig. 5(d). Specimen preparation should be repeated if any visible voids are observed in the
extruded specimen. Care should be exercised during extruding the initial specimen into the mixing cup in order to not lose any soil particles. Soil particles adhering or remaining on the inner walls of the preparation tube and bottom lid should be carefully transferred to the mixing cup.

**Specimen Washing and Determination of Final Height**

Tap water is added to the extruded specimen in the mixing cup to approximately half of its capacity. Hand breaking and squeezing of any observed lumps should be carefully performed in order to homogenize the soil-water mix (Fig. 5(e)). Soil particles remaining or sticking on hand must be carefully washed back into the mixing cup using a squirt-bottle. The hand-held mixer could be used to further break any remaining lumps and friable material in the mixture. The mold is gently attached to the mixing cup as shown in Fig. 5(f). This must be done slowly to avoid spilling or splashing the soil-water mixture. Repetitive flipping and vigorous shaking of the mold-cup assembly for 1 to 2 min is generally sufficient for most soils (Fig. 5(g)). Rotational shaking should be performed as needed to ensure thorough washing. While the cup is held down in one hand, the mold is slowly detached from the assembly (Fig. 5(h)). Some water is added to the mixture in the cup and the mixture is stirred by hand, stirring tool, or the hand-held mixer as necessary (Fig. 5(i)). The soil–water mixture in the cup is carefully poured into the mold (Fig. 5(j)). For more efficient washing, the mold should be shaken up and down and gently tapped while pouring the soil–water mixture. The wash water is allowed to drain through the No. 200 screen placed at the bottom of the mold. For rapid removal of fines material and minimization of potential screen clogging by very fine sand or coarse silt, the soil–water mixture in the cup should be decanted immediately after detaching the assembly. Specimen washing should be carried out (the steps in Fig. 5(g) through Fig. 5(i)) until the wash water is clear, i.e., the retained sand is fines-free, as shown in Fig. 5(k). During the wash process, the screen should be carefully checked for clogging and replaced if necessary. Three cycles of washing are generally sufficient. The remaining soil in the cup is carefully washed with a squirt bottle (Fig. 5(l)) and the wash water is poured into the mold. Upon completion of washing, the cup, the inner wall of the mold, and the collar should be free from any soil residue.

The plunger is inserted into the mold and carefully brought in contact with the top of the retained soil (Fig. 5(m)). In order to flatten the top surface of the specimen the plunger is gently twisted 2–3 times, while tapping the walls of the mold adjacent to the specimen to eliminate potential air pockets. Care should be exercised not to compact the retained soil or damage the screen by excessive downward pushing. The final height \(H_f\) of the specimen (retained soil) is measured using the gage as shown in Fig. 5(n). Fines content in a specimen can be calculated as follows:

\[
\text{Fines Content} (\%) = \frac{H_i - H_f}{H_i} \times 100
\]

**CALIBRATION**

In order to ensure precise height measurements, calibration of the preparation tube and mold must be performed. A 1 in. (25.4 mm) diameter and 1 in. (25.4 mm) high steel cylinder is used for this purpose. The calibration cylinder is inserted into the preparation tube and mold and the respective heights are measured. The fact that the bottom of the preparation tube is a solid plastic disc while the bottom of the mold is flexible woven wire mesh is the main source of error in measuring specimen heights. A correction factor is defined as the difference between the height of the calibration cylinder determined by the preparation tube and that determined using the mold. Corrections up 0.05 in. (1.3 mm—approximately 5 % of the initial height of the specimen) apply to the measured heights. Larger correction values are indicative of a damaged wire mesh that requires replacement. The correction factor must be routinely determined and applied. Other minor sources of errors that are, unfortunately, unquantifiable include the presence of imperfections in fittings, soil particles within the threaded components, and deep scratches on the inner walls of the mold.

**Results and Discussion**

As previously indicated, this proposed volume-based test is fundamentally different from the standard laboratory mass-based tests used for determination of fines content in soils. In addition, measuring heights of the relatively small soil specimens makes the mold test more prone to variability and uncertainty. This coupled with natural soil variability and the precision associated with volume measurements, does not warrant yielding exactly the same fines % by mass, and; therefore, comparing a single mold test measurement with that of the ASTM D1140 may be inherently inconclusive. In the absence of an independently accepted reference value or universally approved theoretical or experimental value for the proposed test, an agreed upon reference value obtained using an accepted method (ASTM E177). Averaging of test determinations is often used to reduce the effect of local variations of the property within the material (ASTM E691). As such, and for the purpose of this study, it is postulated that comparing the arithmetic averages of several mold test determinations (runs) to those of the ASTM D1140 could be a statistically acceptable approach. Averaging fines content of triplicate runs could eliminate bias, improve accuracy, and minimize the effect of natural soil variability on the
results. The arithmetic average of the fines content determined by ASTM D1140 will be used as suggested acceptable reference value. The deviation from this reference value (algebraic difference) can be used as an indication of the success of the mold test.

The fines content was measured using ASTM D1140—Method "A" (no soaking) for each sub-sample and averaged. As shown on Fig. 6, the arithmetic averages of the fine contents determined using the mold test are plotted against those of the ASTM D1140. Absolute differences of less than 5 % (5 % band) and less than 2 % (2 % band; not shown) between fines content determined using the mold test and those of the reference ASTM D1140 values were observed for approximately 95 % and 72 % of the tested samples, respectively. These results are believed to be satisfactory from a practical standpoint.

Initial (before washing) moisture content of the specimen is determined using three moisture sub-samples. Using the measured initial height ($H_i$) and initial mass ($m_i$) of specimen, and the internal diameter of the preparation tube ($D$), the initial bulk density of a specimen can be determined as follows:

\[
\text{Initial Bulk Density} = \frac{m_i}{H_i \times \frac{\pi D^2}{4}}
\]

Average measured initial bulk density and moisture content are depicted in Fig. 7. The majority of the specimens had an initial moisture content ranging from 10 to 30 % and an average initial bulk density within 1.8–2.1 g/cm³ (Fig. 7(a)). Obviously, due to natural randomness and differences in soil types, there is no control over the initial moisture content and bulk density of a specimen. This, however, is believed to be a good representation of field conditions. The effect of the initial density and moisture content on the difference in fines content is depicted in Fig. 7(b). As shown, it is evident that the deviation (absolute difference) in the estimated fines content by mold is generally insensitive to these two parameters. This is indicative of the universality of the proposed test, i.e., the mold test can be conducted on a wide range of soils.

The effect of the Atterberg limits and consistency of the fine-grained specimens on the difference between the fines content of the mold and ASTM D1140 methods are depicted in Fig. 8. The observed randomness also suggests no correlation
between soil’s consistency and the accuracy of the measured fines content—another observation that supports the test applicability to a wide range of fine-grained soils.

Statistical Evaluation

A statistical analysis was performed on the results of the pilot study. The statistical analysis closely examined the variability in the mold test results as compared to those of the standard mass-based method (ASTM D1140). The test variability was also compared to typical natural randomness (variability) of fines content in soils.

SOURCES OF ERROR

There are numerous sources of variability and uncertainty in any laboratory test. These include operator, apparatus, environment, sample, and time (Lacasse and Nadim 1996; ASTM E177). The following are deemed to be the prime sources of errors in the mold test.

Natural Variability and Sample Representativeness

Like all tests in geotechnical engineering, it is believed that the observed natural variability in the selected samples and, thus, their representativeness is a major source of error in this study. Regardless of effort, sample representativeness and uniformity are typically not guaranteed in geotechnical testing (Arman and McManis 1976) and, therefore, variability of test results should always be expected (ASTM E177). Natural variability and sample representativeness could overwhelm the precision of the measurements. To minimize the impact of this, the ASTM D1140 requires minimum oven-dry masses of 20 and 100 g for maximum particle sizes of 2 and 4.75 mm, respectively. AASHTO T-11, however, requires a minimum oven-dry mass of 300 g for a nominal maximum size of 4.75 mm. Commercial laboratories generally follow internally accepted standards of practice as long as minimum requirements of the standard test methods are met. Depending on soil type, commercial laboratories generally perform the ASTM D1140 test on 50 to 150 g of soil. The small size samples (about 25 g) selected for this study upon optimized mold design, are very likely to yield measurable variability compared to those of the standard mass-based wash test. However, should the measurable variability fall within some “acceptable” limits, the test is deemed suitable for most practical purposes.

Test Principle

The principles of the mass-based and volume-based methods for determining fines content in soils are fundamentally different. Mass-based methods (e.g. ASTM D1140) eliminate the effect of particle shape, fabric, inter-particle bonds, particle packing, and arrangement. Utilizing oven-dry soil masses in the determination of fines content leaves small room, if any, for judgment to impact the test result. Therefore, the results of the mass-based methods are generally consistent, unbiased, and largely unaffected by the operator’s skill. Conversely, the foregoing factors have a more pronounced impact on fines content estimated by the volume-based method. In fact, two specimens with “identical” fines content by mass may have slightly different volumes (heights) due to differences in particle packing and gradation. While objectionable substances, such as fibrous-like organic material, were carefully removed during testing, the presence of unnoticeable traces of these substances cannot be guaranteed. Their contribution to volume measurements could be a major source of error.

Apparatus and Test Procedure

It was noted that soil particles could be trapped between the threaded components of the preparation tube and the mold. In addition, despite being supported by the plastic disc, minor sagging of the #200 screen cannot be entirely avoided. Soils having coarse silt-size particles or very fine sand seem to partially obstruct specimen washing through the small diameter screen of the mold. Therefore, repeat washing of these specimens was necessary. All these observations could collectively affect the accuracy of the initial and final height measurements and give rise to some of the noticed variability and randomness.

Operator

While most of the test determinations were performed by a single operator, multiple operators were involved in testing at some stages of the pilot study. The operators did not perform
equal number of tests on all samples, but the results (average of fines content) for a few repeated samples were almost identical.

**DATA REDUCTION**

The foregoing sources of error collectively contributed to the observed fines content measurements in this study. Attempts were made to minimize the impact of these factors during testing and eliminate questionable measurements for proper data reduction. Outliers were excluded from the statistical population in accordance with the ASTM E178 standard. An arbitrarily chosen one-sided same sample 5% significance level was used to reduce the data population. In this context, given the nature and purpose of the proposed test, statistical significance does not imply importance. Therefore, absolute difference between the fines content determined by the mold test and that of a mass-based test may imply more significance than any arbitrarily adopted statistical criterion (e.g., 5% significance level). Intuitively, the absolute difference should be compared to soil type and fines content. For example, an observed 10% absolute difference between the two methods for a fat clay specimen is practically tolerable, but the same difference for a relatively clean sand specimen is completely unacceptable.

**OBSERVED VARIABILITY**

The coefficient of variation in fines content for the samples tested using the mold method was calculated and plotted against those tested using ASTM D1140 (Fig. 9). Some scatter is noted. However, approximately 72% and 54% of the results of the mold test have a coefficient of variation of less than 10% and 5%, respectively. For all practical purposes, the shown variability in the measured fines content is within reportable limits of natural variability in fines content. According to Lee et al. (1983), the observed coefficient of variation of sand or clay contents in soil samples collected from the same depth typically falls between 20 to 25% (Beacher and Christian 2003). It should be noted that natural soil variability combined with other sources of error (systematic, random, and operator’s) contribute to the overall coefficient of variation in fines content. However, the impact of these sources of variability on test results is inherently uncoupled.

**Summary and Conclusions**

The proposed mold test is a volume-based test method developed for rapid measurement of fines content in soils at their natural moisture content. Unlike the visual classification methods commonly used to estimate fines content, specimen preparation and washing are performed in a standard manner. The
principle of the volume-based methods for determining fines content in soils has proven to be adequate. A pilot study involving washing 144 soil samples was conducted. The study yielded fine contents within $\pm 5\%$ from those determined using mass-based methods (ASTM D1140). The mold method, however, should not be construed as a substitute for standard laboratory wash tests.

With 5 to 15 min testing time—depending on soil type—and elimination of oven-drying, the mold test lends itself well to field testing. Thus, fewer number of standard laboratory tests are necessary for verification or complementing field classification. The test is unequivocally more cost-effective, more convenient, and quicker than the standard laboratory mass-based wash tests. While the results of the mold test did not meet the stringent precision and bias limits required by standard mass-based wash tests, the observed variation in the measured fines content using the mold test were generally comparable to those of the mass-based wash methods performed on equal sample masses. In addition, the results of the mold test fell within the typically reported natural variability ranges for fines content in soils. The statistical analysis showed that averaging triplicate mold test runs generally yields satisfactory results. The proposed test is believed to set a paradigm shift towards enhancing the current visual soil classification.

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