Repeatability of Minimum and Maximum Density Testing on Clean and Fouled Ballast

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Abstract. Ballast material is a critical part of the safety of railways, padding tracks to prevent dynamic vibrations from causing trains to derail. The effectiveness of this material is closely tied to the percentage of fouling that is intermixed with the material. Generally, ballast is placed as compact as practical, but overtime, fouling of the ballast changes the composition of the placed material. Relative density could provide insight into the relative compactness and strength of the material. Unfortunately, the results of minimum or maximum density tests are not well documented in the existing literature. Although, ASTM D4254 and D4253 do provide guidelines for minimum and maximum density testing of large particle diameters, there is minimal discussion in the literature regarding the anticipated error when testing with ballast and fouling. Tests to attempt to characterize this behavior, minimum and maximum density tests were run using Connecticut Granite ballast with granite stone dust used as a fouling material. The samples contained fouling at intervals of 0, 15, 30, 45, and 60% by mass and were placed in a 12-inch interior diameter cylinder mold in accordance with the ASTM standards. For each fouling condition, two operators each conducted 10 minimum density and 5 maximum density tests for a total of 100 minimum density tests and 50 maximum density tests. The effect of fouling, density, and operator, on the repeatability of the tests on ballast is discussed.

Keywords: Ballast, Minimum Density Testing, Maximum Density Testing, ASTM standards.

1 Introduction

ASTM standard D4254 and D4253 outline proper methods for performing maximum and minimum density tests on soils, however, research on the applicability of said standards to large particle soils such as railroad ballast are limited. Ballast material, the padding used on tracks to prevent dynamic vibrations from passing trains, is majorly composed of coarse gravel. Because the ASTM standards, particularly the minimum density, require approximations from the human eye the error arising from this process may increase when dealing with the coarser soil. To test this effect samples of AREMA #4 ballast mixtures containing 0, 15, 30, 45, and 60% fouling by mass were tested using each of the standards.

100 minimum density tests and 50 maximum density tests are used to discuss the effects of fouling, density, and operator on the repeatability and accuracy of these tests on the ballast material.

2 Background

Relatively speaking, the volume of research on the ASTM minimum and maximum density standards is very small for ballast-sized particles. Previous studies that do exist have been focused primarily on the methods when sands/silt mixtures are considered. The extent of the repeatability on larger particle materials does not extend far beyond the ASTM publication itself [1]. The ASTM publication specifies that all minimum density tests should be as follows for samples with particles over ¾ -in in diameter [2]:

> "9.2.3.1 Fill the mold to overflowing but no more than 1 in (25 mm) above the top. For solids where the maximum particle size passes the ¾-in. (19.0-mm) sieve, use the steel straightedge (and the fingers when needed) to level the surface of the soil with the top of the mold. For soils with a large maximum particle size, use the fingers in such a way that any slight projections of the larger particles above the top of the mold shall approximately balance the larger voids in the surface below the top of the mold."

The latter allows for a large degree of human error and variation from test to test. Acceptable Range and Standard Deviation were assessed by ASTM when the standards were published in 2016, but only on USCS Classification SP soil types, nothing as coarse as the ballast materials (with particles up to 60 mm) tested in this project. They found that in both Single and Multi-laboratory results the average value tests was the same, but standard deviation was significantly lower for the single operator tests. The average value found when triplicate tests were conducted also varied slightly from the single-test results. The precision and accuracy are still untested for coarser samples.

The ASTM Standard for Maximum density testing using a vibrating table cites the procedure as such [3]:

> "11.1.4 Attach the mold to the vibrating table.
> 11.1.5 Firmly attach the guide sleeve to the mold and lower the appropriate surcharge weight onto the surcharge base plate.
> 11.1.7 Vibrate the mold assembly and specimen for 8 ± ¼ min at 60 ± 2 Hz or for 12+/- ¼ min at 50 +/- 2 Hz. Remove the surcharge weight and guide sleeve from the mold. Check that the surcharge base place is firmly and uniformly in contact with the surface of the soil."

The surcharge weight is determined to give a surcharge stress of 2.00 ± 0.20 lb/in^2 on the sample. The mass of the sample should be no less than $M_r = 0.0024 * V_m$ where V_m is the volume of the mold.

Examinations of the Maximum Density standards are slightly more common. A group of researchers in Italy published a paper in 1992 comparing the results of the ASTM standard and the pluvation technique to calculate the maximum dry density of soils ranging up to $D_{max} = 9.5\ mm\ (3/8")$ [4]. Their project shows some variation in the maximum standard but does conclude that the pluvation technique is more desirable. Furthermore, the pluvation technique is likely impractical for large particles, such as ballast. Similarly, a project done by researchers at Johns Hopkins University used both the maximum and the minimum techniques to determine the effects of non-plastic fines on the void ratios of sands. This examination was done on a much smaller scale (~800g sample size), to minimize the amount of particle breakage during the tests of non-plastic fines on the void ratios of sands [5].

3 Methods

3.1 Minimum Density

The fouling material used in this experiment was defined as anything passing a 3/8" sieve. The fouling, therefore, can be smoothed from the surface of the sample using a straightedge, but the ballast requires a human eye to estimate the projections above and below. This somewhat complicates the ASTM minimum density standard.

Samples of granite ballast from Connecticut were used to construct an AREMA #4 gradation/fouling mixtures for the minimum and maximum density tests. A grain size curve for each mixture is shown in Fig. 1. The minimum tests were run ten times by two different operators at fouling percentages of 0, 15, 30, 45, and 60% by mass. Each mix was prepared by measuring out dry ballast and fouling separately according to a target mass, thoroughly mixed and then placed into the testing mold. Each specimen was prepared in a 12"x12" cylinder mold to constrain movement along the horizontal axis. For each test the ballast/fouling mixture was placed in an 8" tube that was centered in the mold. Once full, the tube was removed, and ballast allowed to pour out into a minimum density configuration. The excess mixture was then removed in conjunction with the ASTM standard outlined above and density values calculated.

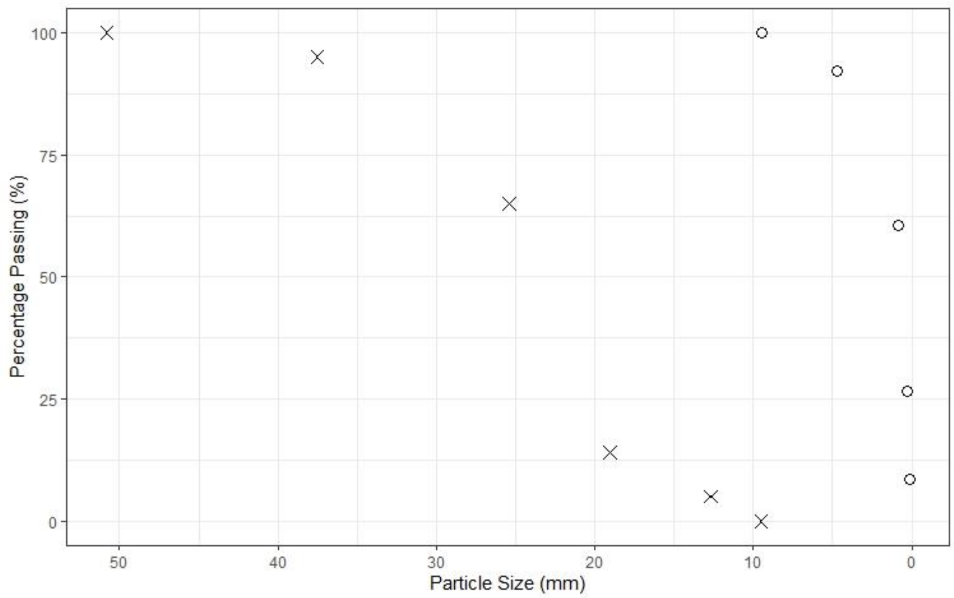

Fig. 1. Grain size curve displaying percentage passing for AREMA #4 ballast mixture (X) and fouling materials (O).

Fig. 2. Maximum density set up with cylinder, surcharge weights, and shaker table.

3.2 Maximum Density

Maximum density tests were run on the same AREMA #4 Connecticut Granite ballast at fouling percentages of 0, 15, 30, 45 and 60% by mass. Five trials by two different operators were run to compare the human influence on data. Samples were placed in the cylinder mold and bolted to a shaker table. A surcharge weight of 200 kg, approximately 10 times the sample mass, was secured to the sample on top of a plate. Figure 2 shows a picture of the set up including the filled cylinder and surcharge load.

Samples were then run in general accordance to the ASTM standard outlined in the background section. From the completed samples depth measurements were taken to analyze the skew of the plate and density was computed for each sample.

4 Results

4.1 Minimum Density Analysis

Data from the minimum density tests, shown in Figure 3, demonstrate an unevenness between the two operators' results across each fouling percentage. While certain values, like those at 0 and 30 percent fouling show nearly indistinguishable values, others are distinct.

The data from the two operators was taken and using a paired two tailed t-test the sample means were compared. At the 5% significance level the 0 and 30% fouling tests showed equivalent means for the two operators, but the other three fouling percentages failed to satisfy this test. This indicates that there is a statistically significant difference in results from the operator on the dry density value for certain mixtures.

Under the Section 'Precision and Bias', of ASTM standard D4254 – 16 it specifies that for any replicate test of three or more trials performed by the same operator using the same equipment and material in the same time period should differ by no more than the single operator d2s limit defined as $sd * 1.96\sqrt{2}$. For replica tests performed by multiple operators the values should differ by no more than the multiple operator d2s limit, defined similarly but using the multiple operator standard deviation. Corresponding values for the minimum tests are shown in Table 1.

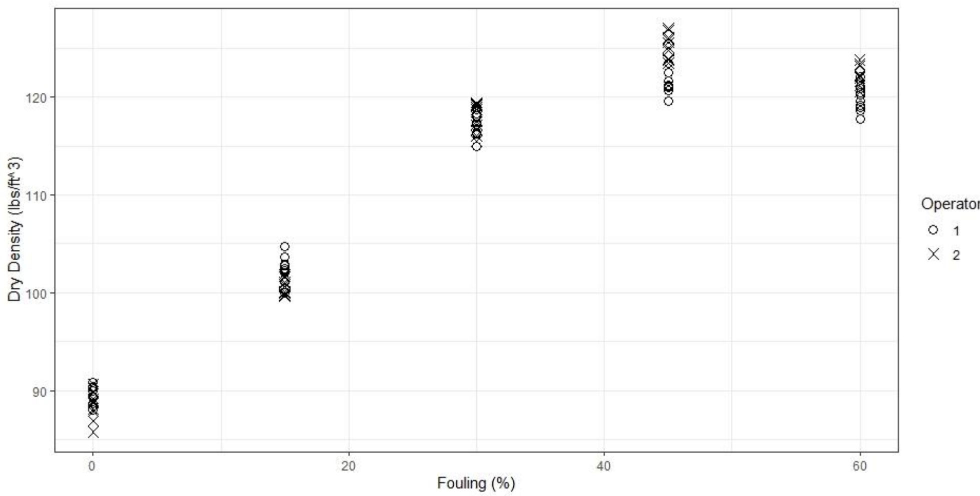

Fig. 3. Data from Minimum density tests. Operator 1 shown in 'X' and Operator 2 in 'O', ten tests conducted by each operator.

Table. 1. Summary of results from minimum density tests

	Average Value (lbf/ft^3)	**Standard Deviation (lbf/ft^3)**	**Acceptable range of two results (lbf/ft^3)**	**Average Value (lbf/ft^3)**	**Standard Deviation (lbf/ft^3)**	**Acceptable range of two results (lbf/ft^3)**
Single Operator Results						
	Operator 1			Operator 2		
0	89.647	0.812	2.249	88.460	1.342	3.720
15	102.632	1.423	3.945	100.659	0.737	2.042
30	117.365	1.192	3.305	117.864	1.386	3.842
45	121.672	1.174	3.253	125.230	1.186	3.288
60	119.8617	1.242	3.444	122.296	0.924	2.561
Multiple Operator Results						
0	89.085	1.248	3.461	-	-	-
15	101.633	1.505	4.170	-	-	-
30	117.614	1.317	3.651	-	-	-
45	123.483	2.148	5.953	-	-	-
60	121.110	1.623	4.499	-	-	-

A similar limit is set for single tests performed by multiple laboratories. While the ASTM uses 12 different laboratory tests to determine the standard deviation of the single laboratory tests, the two operators collected in this project are not enough to make an accurate prediction of the acceptable range for single tests. But, a comparison of the mean over 20 tests and the first dry density test by each operator shows an average error over the five fouling levels of 2.14% with the range from 0.03 to 3.00%. Within each fouling data set there are no trends, such as later tests approaching the sample mean, to suggest that the operator is getting better with each iteration.

4.2 Maximum Density Analysis

Similar to the minimum density tests, the maximum density standard also specifies that for any replicate test of three or more trials performed by the same operator using the same equipment and material in the same time period should differ by no more than the single operator d2s limit defined as $sd * 1.96\sqrt{2}$.

The empirical maximum data, shown in Figure 4, at the 5% significance level shows the same mean for both Operator 1 and Operator 2 data at all fouling levels. Unlike the minimum data, the values at each fouling increment show similar accuracy, and only slight variations in precision.

Data in Table 2 shows the summary of the acceptable ranges for the maximum ballast tests. Single tests, using the first run from each operator, show an average margin of error of 1.9%, ranging from 0.55% to 5.09% maximum fluctuation from the sample mean on the first test. Once again, within each fouling data set there are no trends such as tests 8,9,10 approaching the sample mean to suggest that the operator is getting better with each iteration.

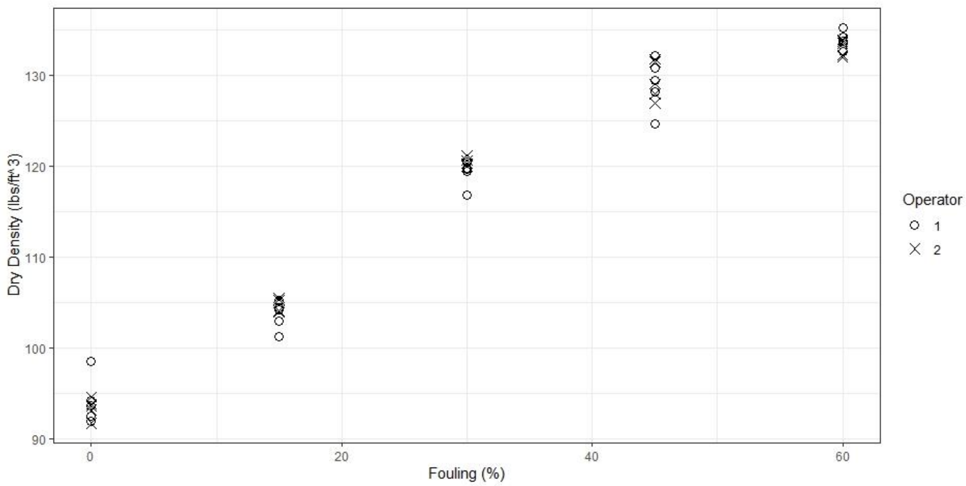

Fig. 4. Data from Maximum density tests. Operator 1 shown 'X' and Operator 2 in 'O', five tests conducted by each operator.

Table. 2. Summary of results from maximum density tests

	Average Value (lbf/ft^3)	**Standard Deviation (lbf/ft^3)**	**Acceptable range of two results (lbf/ft^3)**	**Average Value (lbf/ft^3)**	**Standard Deviation (lbf/ft^3)**	**Acceptable range of two results (lbf/ft^3)**
Single Operator Results						
	Operator 1			Operator 2		
0	93.426	0.942	2.611	94.202	2.333	6.467
15	104.58	0.705	1.957	103.637	1.376	3.813
30	120.42	0.458	1.269	119.27	1.242	3.442
45	129.42	1.912	5.300	129.04	2.578	7.147
60	133.09	0.791	2.193	133.84	0.836	2.317
Multiple Operator Results						
0	93.814	1.821	5.048	-	-	-
15	104.11	1.190	3.299	-	-	-
30	119.84	1.098	3.044	-	-	-
45	129.23	2.278	6.313	-	-	-
60	133.47	0.896	2.482	-	-	-

5 Discussion

In order to conclude on the effectiveness of the ASTM Minimum and Maximum standards with respect to density testing, the influence of fouling, density, and operator on the variability of the data need to be discussed.

For the minimum tests 100 data points were collected, the most to date on such a material, at 0, 15, 30, 45, and 60% fouling by mass. Amongst the data collected by the two operators, only two sets, at 0 and 30, were found to be statistically similar. This shows variation between the two operators, and that tests performed by the different laboratories may not necessarily be concluded to have the same mean. In the summary of triplicate tests from the minimum density ASTM record both single-operator and multi-laboratory results on SP soil types showed the same average value to 4 significant figures.

When examining the range of the minimum density data for a single operator the 'Acceptable Range of Two Results' from the ASTM standard was set at 1.4 lbf/ft^2 for an average density value of 98.17 lbf/ft^2. Across all fouling percentages for single operators, the ballast data shows a range of nearly twice that. See Table 1. However, the acceptable range for the multi-laboratory results from the ballast is well under that listed in the ASTM standard for the same test (6.9 lbf/ft^2). Therefore, we see that there is a change in accuracy and a general increase in precision when the standard is applied to larger grains.

Within the minimum density tests, the amount of fouling and the mean dry density have no visible effect on the accuracy of the data. The maximum density data shows very little trend as well but does show clear peak variability (high standard deviation) with the peak average density value at 45% fouling.

For the maximum density data only 50 data points were collected, so no firm conclusions can be drawn due to the smaller sample size. However, using the same methodology as for the minimum tests it is seen that the acceptable range of two results is larger for ballast material for both single and multi-laboratory tests. In the case of Operator 2 results the range for 0 and 45% fouling is four times that found for SP soils in the ASTM standard. Unlike the ASTM standard, which suggests greater variability in minimum tests when compared to maximum tests, the data for ballast shows a greater variability in maximum than minimum tests.

The data from the maximum density two operators is statistically similar for all fouling points. Therefore, any maximum density tests run by different laboratories are likely to achieve the same mean.

6 Conclusion

Tests to attempt to characterize this behavior, minimum and maximum density tests were run using Connecticut Granite with granite stone dust used as a fouling material and compared to ASTM standards D4254 and D4253 completed for SP soil types. 100 data points from minimum density tests concluded that multi-laboratory results will find an average value within 2% of each other and have a higher precision between operators than the SP types. Single tests by each operator show an average error range from the five fouling levels of 2.14% from the population mean with the range from 0.03 to 3.00%. For maximum density testing sample size was not large enough to conclude, but trends show that ballast data is both less accurate and less precise then on SP soil types. Average values for each fouling level were within 2% of the mean value for each operator, even though the corresponding acceptable range is significantly larger than the one in the ASTM standard. Single tests show an average margin of error of 1.9%, ranging from 5.09% to 0.55% maximum fluctuation from the sample mean on the first test.

Although the results showed a greater variability than those deemed acceptable by the ASTM standard, it is worth considering if the variability from the minimum and maximum density test would be suitable for ballast applications. In the future, it would be worthwhile to consider what level of accuracy would be required for testing on ballast. If the current ASTM methodology is not capable of achieving those results, an improved methodology should be developed for large diameter particles.

In the future more maximum density tests will help solidify the tentative conclusion about the variability of the tests. Additionally, using more operators would provide more insight into the variability of the samples. The ASTM standard uses 12 different operators in their single-test analysis and 8 in their triplicate-test analysis. Completing the range of fouling percentages from 0 to 100 would help illustrate the comparison of the density tests for coarser grains (lower fouling) to finer grains (higher fouling).

Additionally, data on the Elastic Modulus of the AREMA #4 mixtures was taken at the same time as the described data. For further description see “Measuring Railroad Ballast Modulus of Elasticity Using Light Weight Deflectometer” by E. Akey et. Al. (Paper ID #266).

7 References

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