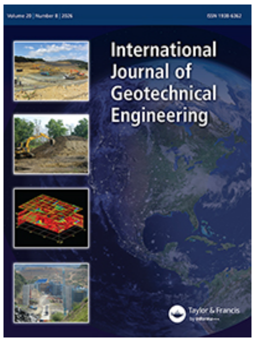


Taylor & Francis
Taylor & Francis Group

International Journal of Geotechnical Engineering

ISSN: 1938-6362 (Print) 1939-7879 (Online) Journal homepage: www.tandfonline.com/journals/yjge20

Experimental evaluation of procedural parameters affecting minimum density determination of low-fines poorly graded sands

B. Sai Laxman & P. Anbazhagan

To cite this article: B. Sai Laxman & P. Anbazhagan (30 Jul 2026): Experimental evaluation of procedural parameters affecting minimum density determination of low-fines poorly graded sands, International Journal of Geotechnical Engineering, DOI: 10.1080/19386362.2026.2711005

To link to this article: https://doi.org/10.1080/19386362.2026.2711005

Published online: 30 Jul 2026.

INTERNATIONAL JOURNAL OF GEOTECHNICAL ENGINEERING
https://doi.org/10.1080/19386362.2026.2711005

Experimental evaluation of procedural parameters affecting minimum density determination of low-fines poorly graded sands

B. Sai Laxman and P. Anbazhagan

Department of Civil Engineering, Indian Institute of Science, Bengaluru, India

ABSTRACT
Soil behaviour is influenced by particle packing, with minimum density defining the loosest reference state of sands. However, its determination is procedure-dependent, resulting in variability among existing methods. This study investigates the effects of deposition technique, funnel spout diameter, and mould dimensions on the minimum density of three low-fines poorly graded sands and proposes an alternative configuration. Thirty-three configurations based on IS 2720 (Part 14), ASTM D4254 Method C, JIS A 1224, Lade's, and the proposed method were examined. Deposition technique had the greatest influence: zero free fall height (ZFFH) produced minimum densities 0.07 to 0.16 g/cc lower than spiral motion under otherwise identical conditions. It also achieved coefficients of variation below 1%, whereas inversion-based methods reached 3.14%. Spout diameter had a minor effect, with mean differences of 0.00 to 0.03 g/cc. The alternative mould improved repeatability under ZFFH and provided a small-scale configuration for the investigated sands.

ARTICLE HISTORY
Received 26 February 2026
Accepted 11 July 2026

KEYWORDS
Minimum density; deposition technique; funnel spout diameter; mould geometry; mould size; alternative test method

1. Introduction

Understanding soil behaviour is fundamental in geotechnical engineering, as all structures transfer loads to the subsurface. Among soil parameters, density strongly influences shear strength, compressibility, and liquefaction resistance. In a theoretical sense, the loosest packing state represents the lowest stable density that a cohesionless soil may attain under specified conditions. In laboratory practice, however, the minimum density is an operational index determined by a prescribed test method, and its measured value can vary with deposition procedure, mould geometry, sample quantity, and handling technique (Mijic et al. 2021; Muszynski 2006). Therefore, determining the minimum soil density is not merely a laboratory exercise but a critical step in predicting soil response and improving its performance in engineering practice.

Numerous procedures exist for determining minimum density, including ASTM D4254-16 (ASTM International 2016), JIS A 1224:2009 (Japanese Geotechnical Society 2009), IS 2720 (Part 14) – 1983 (Reaffirmed 2020), along with methods proposed by Kolbuszewski (1948), D'Appolonia (1969), Brand (1973), Yoshimi and Tohno (1973), Oda (1976), Lade, Liggio, and Yamamuro (1998), Cubrinovski and Ishihara (2002), Muszynski (2006), Mijic et al. (2021). These procedures can be broadly classified into two categories: (i) methods based on depositing a known mass of soil into a mould of known volume, and (ii) methods based on loosening soil within a calibrated container by either inverting or rotating the container. These methods differ in mould size, deposition technique, sample mass, and particle distribution mechanism. Revisions and withdrawals of certain standards further emphasize the need for improved, reproducible, and material-efficient laboratory procedures.

Previous studies have shown that laboratory minimum density is strongly dependent on specimen formation procedure. Kolbuszewski (1948) reported that porosity during loose deposition depends on the deposition medium, pouring rate, and drop height. Comparative studies by Mehdiratta and Triandafilidis (1978) and Walter, Highter, and Vallee (1982) showed that different procedures can produce different measured values and levels of repeatability. Muszynski (2006) and Mijic et al. (2021) also emphasized the need for controlled and reduced-scale procedures when testing clean sands or limited quantities of soil. These studies indicate that the measured minimum density is a procedure-dependent index influenced by deposition mode, apparatus configuration, and sample handling.

Although previous studies have examined particle characteristics, mould or sample size, and small-

CONTACT P. Anbazhagan anbazhagan@iisc.ac.in Department of Civil Engineering, Indian Institute of Science, Bengaluru, India

quantity testing, the combined influence of deposition technique, funnel spout diameter, and mould geometry has received comparatively limited attention within a single controlled experimental framework. The present study, therefore, evaluates these procedural parameters for selected low-fines poorly graded sands and examines an alternative small-scale mould configuration aimed at improving repeatability and reproducibility while maintaining reduced material requirements.

2. Testing materials and methods

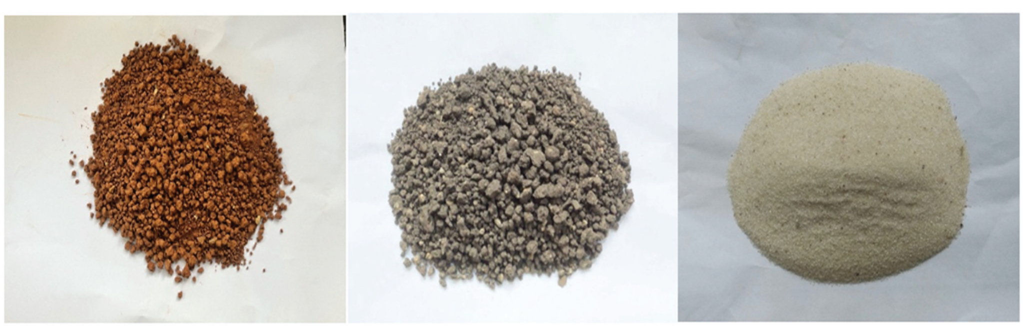
2.1. Soil samples

Three locally sourced cohesionless soil samples, designated as Soil A, Soil B, and Soil C, were investigated. All samples were classified as poorly graded sand (SP) as per the Unified Soil Classification System (USCS), following ASTM D2487-17(2025) (ASTM International 2025). Although similar in classification, the soils differ in gradation characteristics: Soil A is predominantly composed of medium sand, Soil B mainly consists of fine sand particles, and Soil C contains nearly equal proportions of medium and fine sand particles. These variations in gradation provide a suitable basis for assessing the influence of testing procedures on minimum density determination. The visual appearance of these three samples is shown in Figure 1. Relevant index properties and gradation characteristics are presented in Table 1 and Figure 2.

The scope of the present experimental program is limited to poorly graded sands with a low fines content of 2% to 4%. Therefore, the conclusions drawn from this study are applicable primarily to low-fines SP sands tested under the adopted laboratory conditions. The observed trends should not be directly generalized to silty sands, sand-fines mixtures with higher fines content, or gravel-dominated soils, for which particle size distribution, fines content, interparticle interaction, and flow characteristics may alter the measured minimum density and repeatability.

2.2. Test methods considered

The primary objective of this study is to evaluate how the selected procedural parameters, namely deposition technique, funnel spout diameter, and mould geometry, influence the measured minimum density and repeatability of low-fines poorly graded sands. The existing procedures



(a) (b) (c)

Figure 1. Visual appearance of the investigated soil samples: (a) Soil A, (b) Soil B, and (c) Soil C.

Table 1. Soil properties of selected sands.

Parameter	Values Soil A	Soil B	Soil C
Specific Gravity	2.64	2.66	2.64
Gravel (%)	1	1	0
Sand (%)	97	96	96
(i) Coarse Sand (%)	3	0	0
(i) Medium Sand (%)	51	26	50
(i) Fine Sand (%)	46	74	50
Fines (%)	2	3	4
Coefficient of Uniformity (C_u)	6.25	4.17	4.18
Coefficient of Curvature (C_c)	0.87	1.13	0.96
D10 (mm)	0.12	0.12	0.11
D50 (mm)	0.62	0.45	0.41
Soil Classification	SP	SP	SP

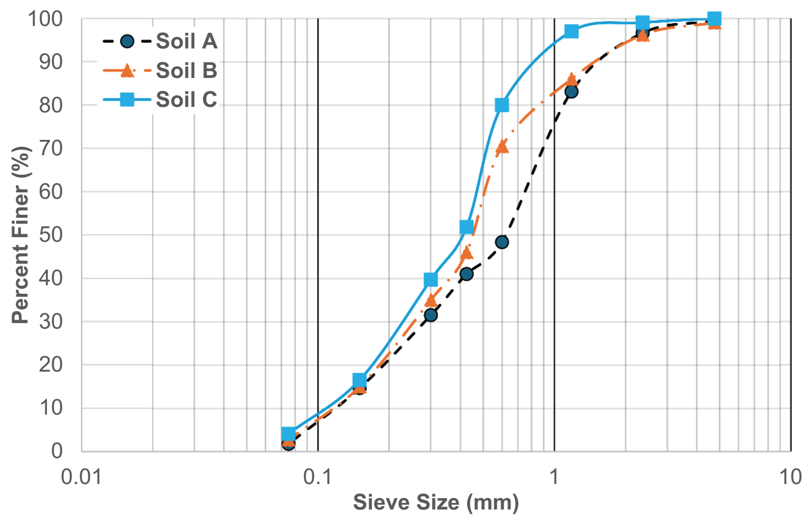


Figure 2. Grain size distribution curve for soil samples in the present study.

considered in this study are used as benchmark methods rather than as procedures for selecting a universally representative minimum density procedure. For this purpose, IS 2720 (Part 14) – 1983 (Reaffirmed in 2020) (which closely aligns with ASTM D4254-16 (Method A)), ASTM D4254-16 Method C, JIS A 1224:2009, and Lade, Liggio, and Yamamuro (1998) were selected for comparison. In addition, a modified small-scale configuration based on the JIS A 1224:2009 deposition principle was evaluated as an alternative arrangement to examine whether improved repeatability can be achieved under controlled deposition conditions.

The selected methods were classified based on the mechanism by which the loose state is generated. The IS 2720 (Part 14)/ASTM D4254 Method A procedure represents a free-fall/spiral deposition approach, in which soil is placed into the mould with a specified fall height and lateral motion. The JIS-based configuration represents zero-free-deposition, where particle impact during placement is minimized. ASTM D4254 Method C and Lade's method represent inversion-based procedures, in which the loose state is generated through internal rearrangement of soil within a container.

2.3. Alternative test configuration

To examine the influence of procedural parameters, an alternative cylindrical mould (70 mm internal diameter, 49 mm height) was fabricated, representing an intermediate size between JIS and larger IS moulds. The selected internal diameter also satisfies the special-mould dimensional requirement in ASTM D4254-16, section 6.2.2, which specifies that the inside diameter of special moulds should be ≥ 70 and <100 mm. Therefore, the fabricated mould was treated as a small-volume alternative configuration for the present comparative study, rather than as a universally optimized mould. The geometry and dimensions of the fabricated mould are shown in Figure 3.

In addition, two funnel spout diameters (8 mm and 12 mm) and two deposition techniques (zero free fall height (ZFFH) and spiral motion (SM)) were adopted for both the modified JIS procedure and the alternative method. Based on preliminary qualitative trials, spout diameters smaller than 8 mm caused obstruction of soil flow, whereas diameters larger than 12 mm produced visibly greater disturbance during placement. Therefore, funnels with spout diameters of 8 mm and 12 mm were only selected for systematic testing.

3. Experimental program

A total of 33 test configurations were evaluated by combining soil type, test method, deposition technique, funnel spout diameter, and mould size. Each test configuration was repeated five times to assess the repeatability and reliability, except IS 2720 (Part 14) – 1983 / ASTM D4254-16 (Method A), which was limited to three times due to the large quantity of soil required for each trial (12 kg per test). The reduced number of repetitions in the IS-based configurations is recognized as a limitation, as SD and CoV estimates based on three trials are less robust than those based on five trials. Accordingly, the repeatability indices for the IS method are interpreted with appropriate caution. Table 2 provides a concise summary of all test configurations in the experimental program. The systematic experimental design enabled independent assessment of the

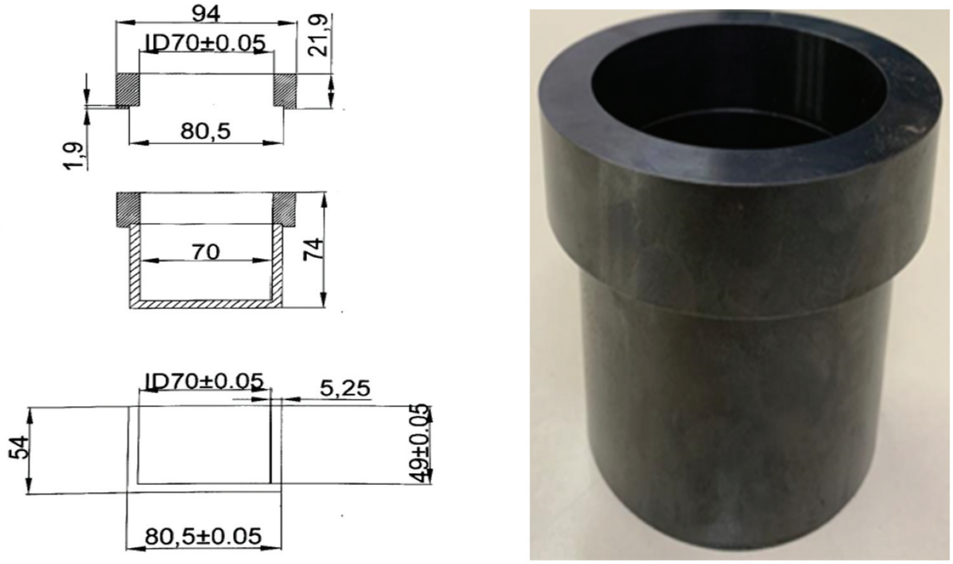


Figure 3. (a) Dimensions and (b) geometry of the fabricated mould that was used in the study.

deposition technique, funnel spout diameter, and mould dimensions on the minimum density of soil samples. To minimize the influence of factors other than the selected procedural parameters, the soil type, oven-dried state of the specimen, method of surface levelling and calculation method were kept consistent within each test series. The tests were also performed using a consistent handling procedure as far as practicable. However, operator-dependent factors such as discharge rate, manual control of spiral motion, and inversion rate were not independently measured, and may contribute to experimental variability. After each trial, the mould, funnel, and accessories were cleaned and visually checked to avoid bias from residual particles. The same oven-dried condition, weighing procedure, and surface-levelling method were maintained throughout the test program. Although the test sequence was not formally randomized, consistent cleaning and handling procedures were used to minimize systematic bias. This limitation was considered while interpreting small differences between configurations.

4. Test procedure

All experiments were conducted either in accordance with the respective standard procedures or as controlled modified variants introduced to examine the effects of deposition technique, funnel spout diameter, and mould dimensions. The standard procedures, namely IS 2720 (Part 14) – 1983, ASTM D4254-16 Method C, JIS A 1224:2009, and Lade's method, were followed as benchmark tests. The modified JIS and alternative configurations were not treated as equivalent to the original standards, but were used only for comparative evaluation of selected procedural parameters under controlled laboratory conditions.

4.1. Standard test procedures

Minimum density tests were conducted in accordance with IS 2720 (Part 14) – 1983 (Reaffirmed 2020), ASTM D4254-16 (Method C), JIS A 1224:2009, and Lade, Liggio, and Yamamuro method (1998). In the IS method, 12 kg of soil was deposited into a 3000 cm^3 mould using a funnel with 12 mm spout diameter under 25 mm free-fall height and spiral motion. Although the IS method is a standard procedure for determining minimum density, the specified free-fall height and spiral motion may introduce particle impact and rearrangement during filling. Therefore, in the present study, the IS method is treated as a benchmark standard procedure rather than as an unquestioned representation of the loosest attainable packing state.

ASTM D4254-16 (Method C) and Lade's method involved inversion of 1000 g and 822 g of soil respectively, in a 2000 mL graduated cylinder to achieve loosening. Since inversion-based loosening may be influenced by the manner of inversion and particle redistribution within the cylinder, these methods were evaluated in terms of both measured density and repeatability. The JIS method used controlled deposition of a 500 g sample under zero free-fall height in a calibrated mould.

All tests were performed following the essential requirements of the respective standards, with only minor controlled modifications for comparative assessment. Figure 4(a-c) illustrates representative specimens

Table 2. Summary of tests performed in the study.

Test ID	Soil Sample	Method	Filling Technique (ZFFH/SM)	Spout Diameter (mm)	No. of Trials	Remarks
A1	Soil A	IS 2720 (Part 14) – 1983 / ASTM D4254-16 (Method A)	SM	12	3	Adopted procedure as per the standard
A2		ASTM D4254-16 (Method C)	–	–	5	Adopted procedure as per the standard
A3		Lade's	–	–	5	Adopted procedure as per the standard
A4		JIS A 1224:2009	ZFFH	8	5	Studies the effect of spout diameter
A5		JIS A 1224:2009	ZFFH	12	5	Adopted procedure as per the standard
A6		JIS A 1224:2009	SM	8	5	Studies effect of deposition technique and funnel spout diameter
A7		JIS A 1224:2009	SM	12	5	Studies effect of deposition technique and funnel spout diameter
A8		Alternative	ZFFH	8	5	Studies the effect of mould size, deposition technique and funnel spout diameter
A9		Alternative	ZFFH	12	5	Studies the effect of mould size, deposition technique and funnel spout diameter
A10		Alternative	SM	8	5	Studies the effect of mould size, deposition technique and funnel spout diameter
A11		Alternative	SM	12	5	Studies the effect of mould size, deposition technique and funnel spout diameter
B1	Soil B	IS 2720 (Part 14) – 1983 / ASTM D4254-16 (Method A)	SM	12	3	Adopted procedure as per the standard
B2		ASTM D4254-16 (Method C)	–	–	5	Adopted procedure as per the standard
B3		Lade's	–	–	5	Adopted procedure as per the standard
B4		JIS A 1224:2009	ZFFH	8	5	Studies the effect of spout diameter
B5		JIS A 1224:2009	ZFFH	12	5	Adopted procedure as per the standard
B6		JIS A 1224:2009	SM	8	5	Studies effect of deposition technique and funnel spout diameter
B7		JIS A 1224:2009	SM	12	5	Studies effect of deposition technique and funnel spout diameter
B8		Alternative	ZFFH	8	5	Studies the effect of mould size, deposition technique and funnel spout diameter
B9		Alternative	ZFFH	12	5	Studies the effect of mould size, deposition technique and funnel spout diameter
B10		Alternative	SM	8	5	Studies the effect of mould size, deposition technique and funnel spout diameter
B11		Alternative	SM	12	5	Studies the effect of mould size, deposition technique and funnel spout diameter
C1	Soil C	IS 2720 (Part 14) – 1983 / ASTM D4254-16 (Method A)	SM	12	3	Adopted procedure as per the standard
C2		ASTM D4254-16 (Method C)	–	–	5	Adopted procedure as per the standard
C3		Lade's	–	–	5	Adopted procedure as per the standard
C4		JIS A 1224:2009	ZFFH	8	5	Studies the effect of spout diameter
C5		JIS A 1224:2009	ZFFH	12	5	Adopted procedure as per the standard
C6		JIS A 1224:2009	SM	8	5	Studies effect of deposition technique and funnel spout diameter
C7		JIS A 1224:2009	SM	12	5	Studies effect of deposition technique and funnel spout diameter
C8		Alternative	ZFFH	8	5	Studies the effect of mould size, deposition technique and funnel spout diameter
C9		Alternative	ZFFH	12	5	Studies the effect of mould size, deposition technique and funnel spout diameter
C10		Alternative	SM	8	5	Studies the effect of mould size, deposition technique and funnel spout diameter
C11		Alternative	SM	12	5	Studies the effect of mould size, deposition technique and funnel spout diameter

Note: ZFFH stands for Zero Free Fall Height and SM stands for Spiral Motion.

prepared using the IS, Lade's, and JIS methods, respectively.

4.2. Modified JIS and alternative method procedures

The JIS A 1224:2009 and the alternative method were evaluated under controlled variations of deposition techniques (ZFFH and SM) and funnel spout diameter (8 mm and 12 mm). The original JIS mould was used for the modified JIS tests, while a fabricated mould (70 mm internal diameter and 49 mm height) was used for the alternative method. In each case, oven-dried soil was placed into the mould using the selected funnel and technique. For ZFFH, the funnel tip remained in contact with the rising soil surface to minimize particle free-fall during filling. The funnel was withdrawn gradually as

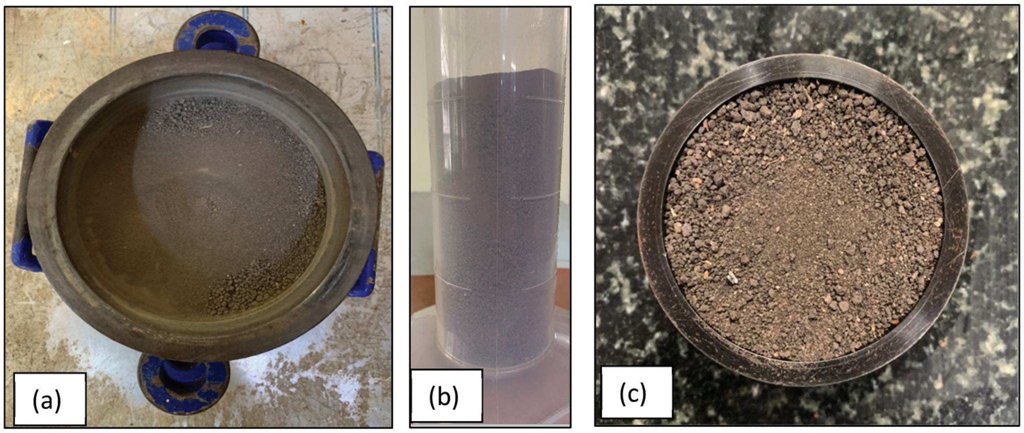


Figure 4. Soil specimens prepared using different minimum density determination methods: (a) IS 2720 (part 14) – 1983, (b) Lade's method, and (c) JIS a 1224:2009 mould configuration.

the soil level increased, and the filling process was completed within 30–45 seconds for each trial. For SM, the funnel was moved manually in a spiral path over the mould opening while maintaining a free-fall height of approximately 10 mm. The spiral motion was performed continuously from the outer region towards the centre and repeated until the mould was filled. After filling, the surface was levelled, the mass was recorded, and the minimum density was calculated from the known mould volume.

5. Results and discussion

The minimum density results for all the test configurations are summarized in Table 3. Mean, standard deviation (SD), and coefficient of variation (CoV) were computed to assess the repeatability. Figure 5 shows the variation in mean minimum density values across various testing methods for the three samples. Further, statistical analysis was carried out to provide supporting evidence for examining whether the observed differences among test configurations were statistically distinguishable. For each soil, a one-way ANOVA was performed by considering the 11 test configurations as separate groups. The number of repetitions was three for the IS configuration and five for the remaining configurations. Therefore, the statistical results were interpreted together with mean values, SD, and CoV, rather than as the sole basis for ranking the methods. The ANOVA showed significant differences among configurations for Soil A, Soil B, and Soil C, with $p < 0.001$ in each case. Since the deposition technique was the main procedural variable, Welch's t-test was used to compare ZFFH and SM configurations, as equal variance could not be assumed. The ZFFH-SM comparison was significant for all three soils, with $p < 0.001$. The corresponding mean differences between SM and ZFFH were 0.128 g/cc, 0.122 g/cc, and 0.072 g/cc for Soil A, Soil B, and Soil C, respectively.

Substantial variation in minimum density values was observed among the different tests. Inversion-based methods (ASTM D4254-16 (Method C) and Lade's methods) produced the lowest numerical densities; however, these methods exhibited the highest scatter with CoV reaching up to 3.14% (Test ID – B3). In contrast, the ZFFH-based configurations produced slightly higher density values in some cases but significantly improved repeatability (CoV below 1%). Therefore, the evaluation of a minimum density procedure should consider both the lowest attainable density and its repeatability across repeated trials, rather than relying solely on the lowest numerical density.

5.1. Comparison of test methods

The comparison of test methods shows that the measured minimum density varied noticeably with the adopted procedure. Across the three soils, inversion-based methods, namely ASTM D4254-16 Method C and Lade's method, generally produced lower mean minimum density values, whereas the IS method and SM-based configurations produced comparatively higher values. The interpretation is based on mean values, repeated-trial ranges, SD, and CoV reported in Table 3, rather than on individual minimum or maximum observations.

For Soil A, the lowest mean minimum density values were obtained using Lade's method (Test ID – A3) and ASTM D4254-16 (Method C) (Test ID – A2), with mean values of 1.19 g/cc and 1.21 g/cc, respectively, whereas the alternative method under SM deposition technique

Table 3. Summary of experimental results.

Test ID	Soil Sample	Method	Filling Technique (ZFFH/SM)	Spout Diameter (mm)	No. of Trials	Minimum Dry Density (g/cc)					Average	Standard Deviation	Coefficient of Variance
A1	Soil A	IS 2720 (Part 14) – 1983	SM	12	3	1.36	1.37	1.37	–	–	1.37	0.006	0.42
A2		ASTM D4254-16 (Method C)	–	–	5	1.21	1.20	1.21	1.25	1.19	1.21	0.023	1.88
A3		Lade's	–	–	5	1.20	1.18	1.21	1.20	1.18	1.19	0.013	1.12
A4		JIS A 1224:2009	ZFFH	8	5	1.24	1.25	1.26	1.24	1.24	1.25	0.009	0.72
A5		JIS A 1224:2009	ZFFH	12	5	1.27	1.27	1.25	1.26	1.27	1.26	0.009	0.71
A6		JIS A 1224:2009	SM	8	5	1.36	1.39	1.39	1.35	1.35	1.37	0.020	1.50
A7		JIS A 1224:2009	SM	12	5	1.36	1.34	1.37	1.36	1.35	1.36	0.011	0.84
A8		Alternative	ZFFH	8	5	1.24	1.22	1.22	1.24	1.24	1.23	0.011	0.89
A9		Alternative	ZFFH	12	5	1.25	1.26	1.25	1.25	1.25	1.25	0.004	0.36
A10		Alternative	SM	8	5	1.37	1.37	1.37	1.41	1.41	1.39	0.022	1.58
A11		Alternative	SM	12	5	1.40	1.39	1.40	1.39	1.40	1.40	0.005	0.39
B1	Soil B	IS 2720 (Part 14) – 1983	SM	12	3	1.25	1.27	1.31	–	–	1.28	0.031	2.39
B2		ASTM D4254-16 (Method C)	–	–	5	1.08	1.08	1.08	1.05	1.07	1.07	0.013	1.22
B3		Lade's	–	–	5	1.12	1.07	1.08	1.10	1.03	1.08	0.034	3.14
B4		JIS A 1224:2009	ZFFH	8	5	1.09	1.10	1.09	1.11	1.07	1.09	0.015	1.36
B5		JIS A 1224:2009	ZFFH	12	5	1.10	1.10	1.12	1.08	1.09	1.10	0.015	1.35
B6		JIS A 1224:2009	SM	8	5	1.21	1.22	1.23	1.21	1.20	1.21	0.011	0.94
B7		JIS A 1224:2009	SM	12	5	1.20	1.20	1.19	1.18	1.15	1.18	0.021	1.75
B8		Alternative	ZFFH	8	5	1.08	1.09	1.10	1.08	1.07	1.08	0.011	1.05
B9		Alternative	ZFFH	12	5	1.07	1.09	1.09	1.08	1.08	1.08	0.008	0.77
B10		Alternative	SM	8	5	1.22	1.22	1.23	1.24	1.24	1.23	0.010	0.81
B11		Alternative	SM	12	5	1.20	1.21	1.22	1.22	1.22	1.21	0.009	0.74
C1	Soil C	IS 2720 (Part 14) – 1983	SM	12	3	1.39	1.44	1.46	–	–	1.43	0.036	2.52
C2		ASTM D4254-16 (Method C)	–	–	5	1.28	1.30	1.28	1.26	1.26	1.28	0.017	1.31
C3		Lade's	–	–	5	1.22	1.28	1.27	1.30	1.27	1.27	0.029	2.33
C4		JIS A 1224:2009	ZFFH	8	5	1.32	1.30	1.32	1.31	1.31	1.31	0.008	0.64
C5		JIS A 1224:2009	ZFFH	12	5	1.31	1.31	1.31	1.31	1.31	1.31	0.000	0.00
C6		JIS A 1224:2009	SM	8	5	1.38	1.38	1.39	1.38	1.38	1.38	0.004	0.32
C7		JIS A 1224:2009	SM	12	5	1.38	1.40	1.38	1.38	1.38	1.38	0.009	0.65
C8		Alternative	ZFFH	8	5	1.33	1.34	1.33	1.34	1.33	1.33	0.005	0.41
C9		Alternative	ZFFH	12	5	1.32	1.30	1.30	1.31	1.30	1.30	0.009	0.68
C10		Alternative	SM	8	5	1.40	1.40	1.40	1.40	1.40	1.40	0.000	0.00
C11		Alternative	SM	12	5	1.41	1.38	1.37	1.38	1.37	1.38	0.016	1.19

Note: Minimum dry density and mean values are reported to two decimal places. SD and CoV values reported as 0.000 and 0.00 indicate no variation at the reported precision and should not be interpreted as the absence of experimental uncertainty.

(Test ID – A10 and A11), produced higher mean values, ranging from 1.39 to 1.40 g/cc. For Soil B, the lowest mean values were obtained using ASTM D4254-16 (Method C) (Test ID – B2), Lade's method (Test ID – B3), and the alternative ZFFH (Test ID – B8 and B9) configurations with values ranging from 1.07 g/cc and 1.08 g/cc, while IS method (Test ID – B1) produced higher mean value of about 1.28 g/cc. For Soil C, Lade's method (Test ID – C3) and ASTM (Method C) (Test ID – C2) method gave mean values of 1.27 to 1.28 g/cc, whereas the IS method (Test ID – C1) gave the highest mean minimum density of 1.43 g/cc.

Although inversion-based methods produced lower numerical density values, they also showed greater scatter across repeated trials. For example, Soil B tested using Lade's method showed a CoV of 3.14%, whereas the alternative ZFFH configurations showed lower CoV values of 0.77–1.05%. Since no quantitative stratification or segregation measurements were performed, visual observations are not used as the basis for interpretation. Furthermore, the IS-based variability indices are interpreted cautiously as only three repetitions were performed.

5.2. Influence of deposition technique

The influence of deposition technique is evident from Table 3 and Figure 6, which compares ZFFH and SM techniques for the JIS and the alternative methods. For this comparison, the effect of deposition technique was evaluated pairwise while keeping soil type, mould configuration, and funnel spout diameter constant. For all three soils, ZFFH consistently produced lower minimum density values than SM, irrespective of funnel

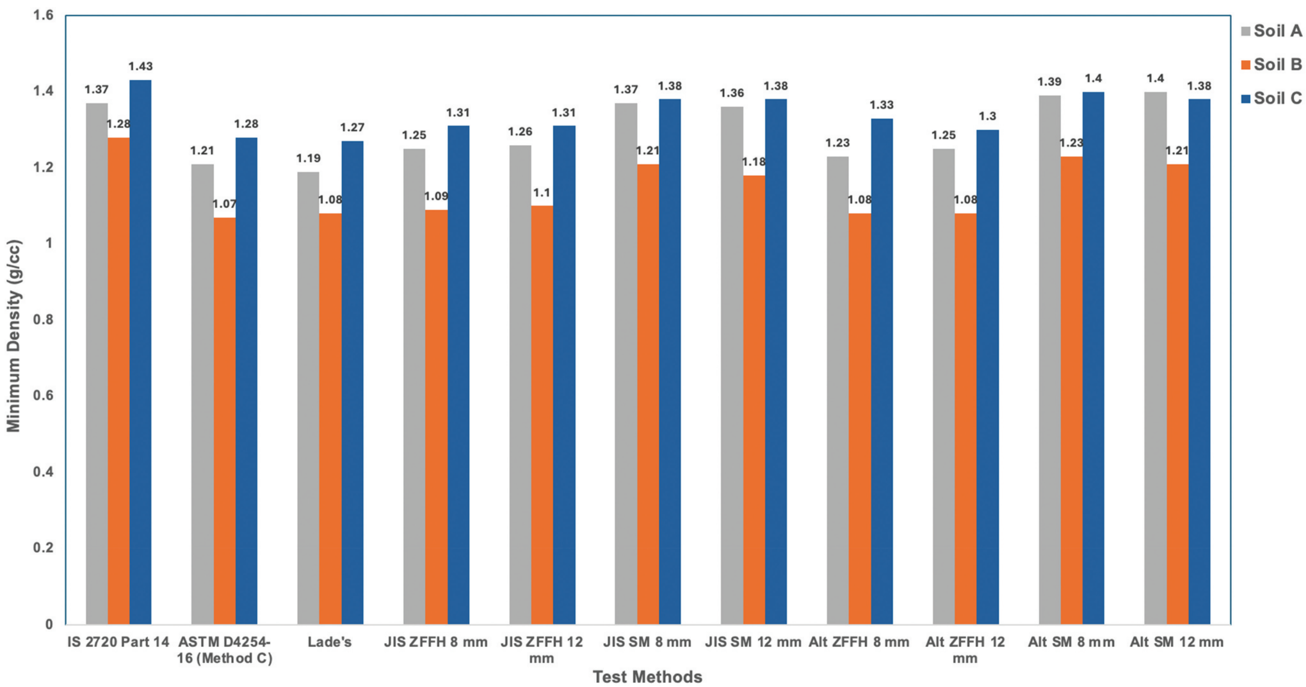


Figure 5. Variation in average minimum density values with test methods for soils under study.

spout diameter or mould size. For example, for Soil A, the alternative method with ZFFH and an 8 mm spout diameter (Test ID – A8) yielded a mean minimum density value of 1.23 g/cc, whereas the corresponding SM configuration (Test ID – A10) yielded 1.39 g/cc. Similar trends were observed for Soil B (1.08 g/cc under ZFFH versus 1.23 g/cc under SM) and Soil C (1.33 g/cc under ZFFH versus 1.40 g/cc under SM). Based on the pairwise comparisons, the difference between ZFFH and SM ranged approximately from 0.07 to 0.16 g/cc. This consistent behaviour demonstrates that the deposition technique is the dominant procedural parameter influencing the measured minimum density within the investigated configurations. This behaviour can be attributed to the lower placement disturbance in ZFFH than in SM. In ZFFH, soil particles were deposited with minimal free fall, whereas SM involved a free-fall height of about 10 mm along spiral funnel movement. This additional disturbance can promote particle rearrangement into denser configurations, thereby increasing the measured minimum density. It should also be noted that the term deposition technique in the present study includes both the mechanical characteristics of placement and the degree of operator control. Parameters such as discharge rate, spiral path speed, and manual movement consistency were not independently measured. Therefore, part of the observed difference in CoV between ZFFH and SM may also reflect the greater ease of maintaining consistent placement under ZFFH conditions compared with manually controlled SM deposition. Soil B consistently exhibited lower density values than Soils A and C under identical test procedures. This trend may be associated with its measured gradation characteristics, particularly its higher fine-sand fraction and lower D_{50} value. However, this interpretation is limited to the observed association between gradation parameters and measured minimum density.

5.3. Influence of funnel spout diameter

The effect of funnel spout diameter (8 mm and 12 mm) on minimum density is shown in Table 3 and Figure 7 for all three soil samples. For this comparison, the spout-diameter effect was evaluated pairwise by keeping the soil type, mould configuration, and deposition technique constant. The results indicate that spout diameter had a smaller influence on the minimum density compared with the deposition technique. Based on the mean values reported in Table 3, the difference between the 8 mm and 12 mm spout diameters ranged from 0.00 to 0.03 g/cc across the tested configurations. For example, under the JIS method with SM deposition for Soil B, the mean minimum density decreased from 1.21 g/cc for the 8 mm spout (Test ID – B6) to 1.18 g/cc for the 12 mm spout (Test ID – B7), corresponding to a difference of 0.03 g/cc. Similarly, under the alternative ZFFH configuration, Soil A showed a difference of 0.02 g/cc between the 8 mm and 12 mm spouts, whereas Soil B showed no measurable difference in the mean value.

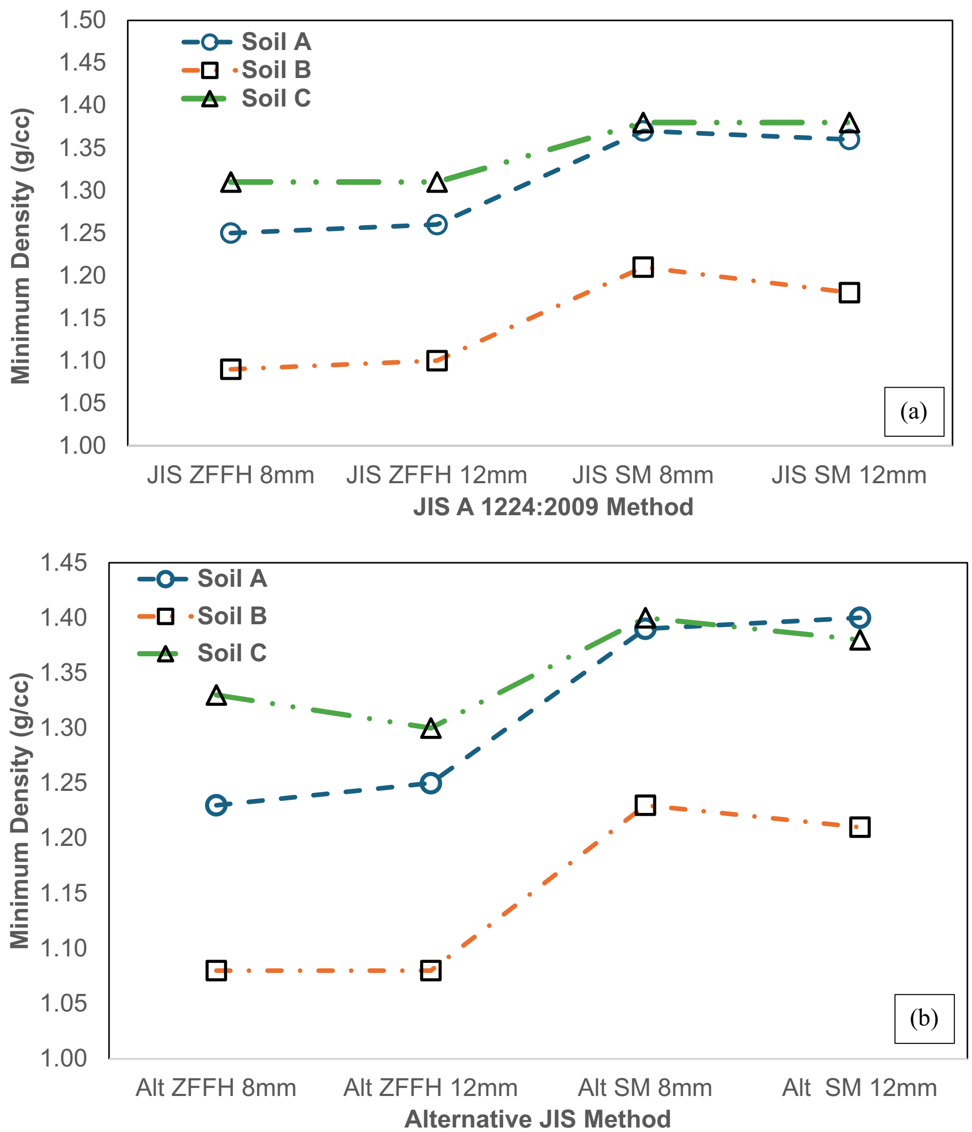
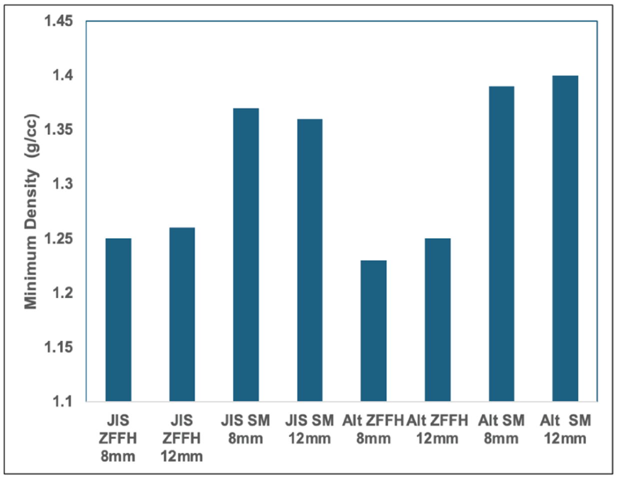
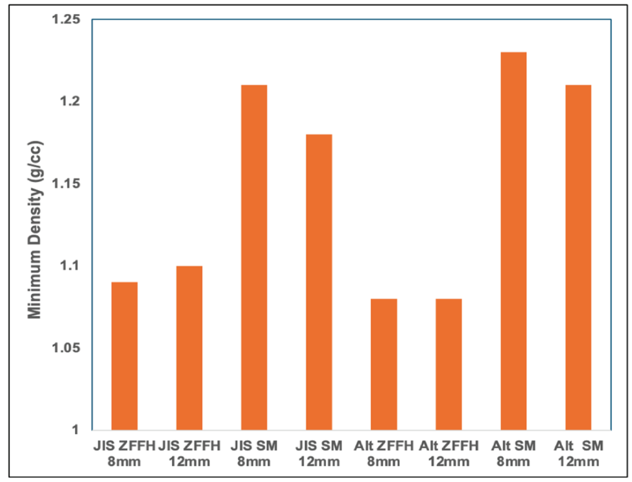


Figure 6. Variation of average minimum density values with deposition techniques for (a) JIS a 1224:2009 method and (b) proposed alternative method.

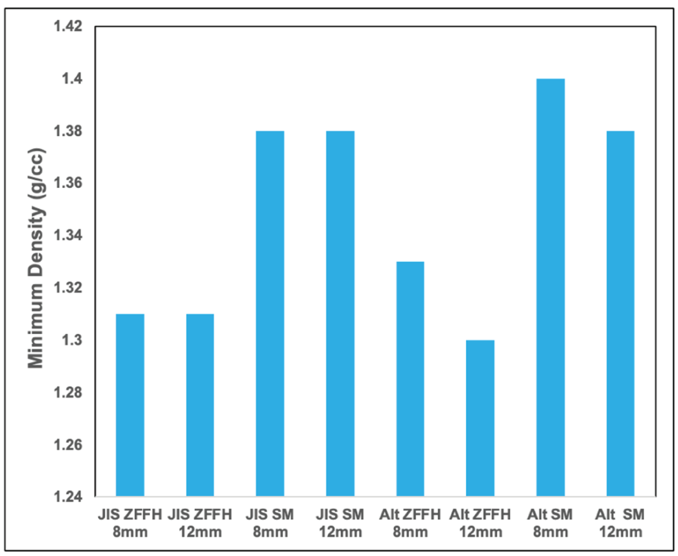
Although this spout diameter effect was smaller than the ZFFH-SM difference, it should not be considered negligible in all cases because small changes in minimum density can influence calculated relative density. For example, for Soil A under the alternative ZFFH configuration, the mean minimum density changed from 1.23 g/cc for the 8 mm spout to 1.25 g/cc for the 12 mm spout. Considering a maximum density of 1.84 g/cc and a representative dry density of 1.45 g/cc, this change in minimum density alters the calculated relative density from approximately 46% to 43%, corresponding to a difference of about 3% points. This indicates that the spout diameter effect, although secondary compared with the deposition technique, may still influence relative density interpretation. Therefore, funnel spout diameter is interpreted as a secondary procedural parameter rather than as an insignificant factor. A general trend was observed in which the 8 mm spout produced slightly lower density values under ZFFH conditions, whereas the 12 mm spout produced marginally lower values under some SM configurations. However, this trend was not uniform across all soils and methods, indicating interaction between spout diameter, deposition technique, and gradation. In the present study, the maximum particle size of the tested soils was considerably smaller than both spout diameters (8 mm and 12 mm), allowing uninterrupted flow without visible arching or blocking. Therefore, the observed spout-diameter effect is limited to the tested low-fines sands and the adopted spout range of 8–12 mm. The role of



(a) Soil A



(b) Soil B



(c) Soil C

Figure 7. Variation in average minimum density values with respect to 8 mm and 12 mm spout diameter for (a) Soil A, (b) Soil B, and (c) Soil C.

the spout-to-particle size ratio for coarser or broadly graded soils was not evaluated and requires separate investigation.

5.4. Influence of mould configuration

The effect of mould dimensions on the minimum density was evaluated by comparing the JIS A 1224:2009 mould with the fabricated mould used in the alternative method under ZFFH conditions. For all three soils, the alternative mould consistently produced a narrower range of minimum density values over repeated trials compared with the JIS mould. For Soil A, the minimum density values obtained using JIS mould with an 8 mm spout diameter ranged from 1.24 to 1.26 g/cc, and 1.25 to 1.27 g/cc for the 12 mm spout, whereas the alternative mould produced a range of 1.22 to 1.24 g/cc for 8 mm spout and 1.25 to 1.26 g/cc for 12 mm spout. A similar trend was observed for Soil B, where the JIS mould produced the minimum density values ranging from 1.07 to 1.11 g/cc for the 8 mm spout diameter and 1.08 to 1.12 g/cc for the 12 mm spout diameter. In contrast, the alternative method exhibited a smaller spread of values, ranging from 1.07 to 1.10 g/cc and 1.07 to 1.09 g/cc for 8 mm and 12 mm spout diameters, respectively. For Soil C, both methods yielded relatively stable results; however, the alternative method again shows a narrower distribution of measured values. The JIS mould produces values between 1.30 and 1.32 g/cc, considering both the spout diameters, whereas the alternative mould yielded values between 1.33 and 1.34 g/cc for 8 mm spout diameter and 1.30 and 1.32 g/cc for the 12 mm spout diameter, indicating a uniform packing behaviour across the repeated trials.

Overall, the alternative mould configuration showed a more closely clustered distribution of minimum density values for the tested sands under ZFFH conditions. However, this trend is interpreted as the response of the adopted mould configuration rather than as a direct isolated effect of mould size, because factors such as diameter, height, height-to-diameter ratio, wall surface condition, and manufacturing tolerance were not independently varied.

5.5. Repeatability and engineering significance

The repeatability and reliability of the minimum density measurements were evaluated using the average, standard deviation (SD), and coefficient of variation (CoV) reported in Table 3. ASTM D4254-16 (Method C) and Lade's method exhibit comparatively higher variability, with CoV values ranging from 1.12% to 3.14%. However, the observed variability may reflect both method-specific effects, such as inversion-induced particle redistribution, and uncertainty associated with the number of repeated trials. Since the IS method was repeated only three times, its SD and CoV values are interpreted with greater caution than those of the configurations repeated five times.

The highest CoV was observed for Soil B using Lade's method (Test ID-B3) with a value of 3.14%. The IS method also showed relatively high CoV values for Soils B and C, but these values are treated only as indicative, as they are based on three repetitions. In contrast, several JIS A 1224:2009 and alternative ZFFH-based configurations demonstrated lower scatter, indicating better repeatability under the adopted test conditions. However, some SM configurations also showed low CoV values. Therefore, repeatability is interpreted based on configuration-specific SD and CoV values rather than as a global ranking of deposition techniques.

Overall, among the configurations repeated five times, many ZFFH-based JIS and alternative configurations showed lower scatter and more consistent minimum density values. The IS-based CoV values are not directly ranked against these results, as they were obtained from only three repetitions and therefore have greater statistical uncertainty. It is also noted that, for the three soils considered in this study, the IS method did not yield the lowest mean minimum density value. The deposition technique was the dominant factor, influencing the measured minimum density, with the ZFFH consistently yielding lower values than the SM when compared at fixed soil type, mould configuration, and funnel spout diameter. The funnel spout diameter had a secondary effect, with 8 mm slightly more effective for ZFFH and 12 mm for SM, while mould dimensions have only a marginal influence and primarily contribute to improved uniformity of soil deposition.

Although the present study does not propose a universal CoV acceptable limit, CoV values close to or below 1% were considered to indicate comparatively better repeatability within the tested configurations. Among the configurations repeated five times, 17 out of 30 showed CoV ≤ 1%. In contrast, all ASTM D 4254–16 Method C and Lade's method configurations showed CoV greater than 1%, indicating higher scatter despite producing lower numerical minimum density values. Therefore, the selection of a minimum density procedure should consider both the measured density value and its repeatability under repeated trials.

Although the variations in minimum density may appear small, they can appreciably affect the calculated relative density. For Soil A, Table 3 shows that the alternative mould with an 8 mm spout gave a mean minimum density of 1.23 g/cc under ZFFH and 1.39 g/cc under SM. Figure 8 illustrates this effect using a maximum density of 1.84 g/cc, which was experimentally determined for Soil A using IS 2720 (Part 14) – 1983. The dry density values of 1.45, 1.55, and 1.65 g/cc were selected within the measured minimum-maximum density range to represent possible in-situ density states for the sensitivity analysis. The results show that the adopted minimum density can substantially change the interpreted compactness state.

6. Conclusions

The experimental study systematically examined the influence of deposition technique, funnel spout diameter, and mould dimensions on the minimum density determination for three cohesionless soil samples classified as poorly graded sand with low fines content. The influence of these properties on soil samples was quantitatively investigated using established standard methods such as IS 2720 (Part 14)-1983, ASTM D4254-16 (Method C), Lade's method, JIS A1224:2009, and an alternative small-scale mould configuration. From the experimental findings, the following major conclusions are drawn:

(1) The experimental investigation comprising 33 test configurations demonstrates that the minimum density determination of the tested low-

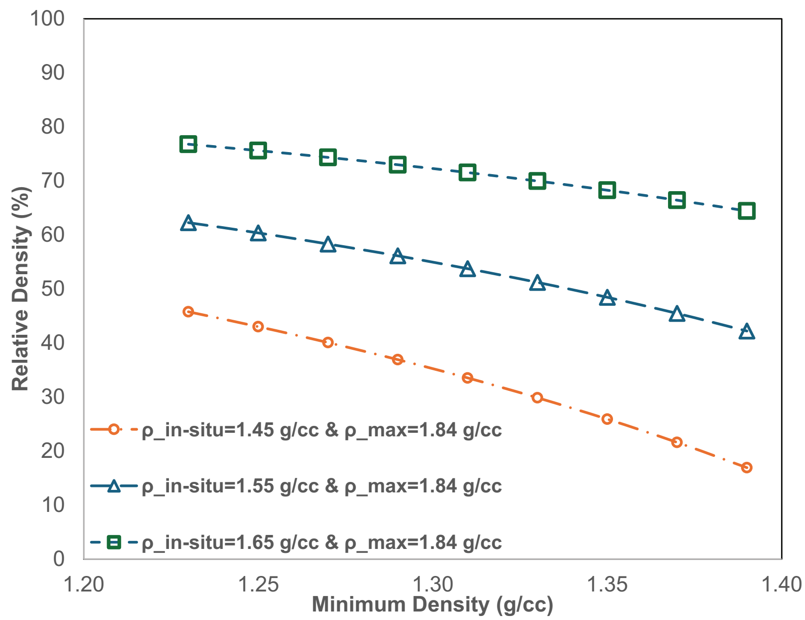


Figure 8. Sensitivity of relative density to minimum density for Soil A.

fines poorly graded sands is strongly dependent on laboratory procedure.

(2) The deposition technique is the dominant parameter influencing both magnitude and repeatability.

(3) Inversion-based procedures (ASTM D4254-16 (Method C) and Lade's method) yielded lower numerical densities (as low as 1.18 g/cc for Soil A and 1.03 g/cc for Soil B) but exhibited greater variability across repeated trials, with CoV values reaching 3.14%.

(4) Under the adopted test conditions, Zero Free Fall Height (ZFFH) deposition produced lower mean minimum density values with comparatively lower scatter for the tested low-fines SP sands.

(5) The funnel spout diameter exerted only a secondary influence on the measured minimum density. The maximum difference between the 8 mm and 12 mm spout diameters was approximately 0.05 g/cc (Soil B using the JIS method), whereas for most configurations the difference remained below 0.04 g/cc.

(6) The effect of mould dimensions on the minimum density was found to be secondary to that of deposition technique for the tested sands. Under the adopted test conditions, the alternative mould produced more closely clustered values than the JIS A 1224:2009 mould. However, this observation is limited to the present mould configuration and may reflect the combined influence of mould dimensions, height-to-diameter ratio, wall surface condition, and handling procedure.

(7) The combined implementation of ZFFH deposition technique and the adopted alternative mould provided a controlled test arrangement for the three low fines poorly graded sands examined in this study. Further validation using additional soils, mould geometries, operators, and laboratories is required before generalizing this arrangement.

(8) The results emphasize that the minimum density should not be defined solely by the lowest attainable numerical value but should also consider repeatability under repeated preparation.

(9) The alternative configuration with ZFFH deposition produced internally consistent minimum density values for the tested low-fines poorly graded sands under the adopted laboratory conditions. However, external reproducibility across silty sands, sand-fines mixtures with higher fines content, gravelly soils, or different mould configurations and different operator conditions require further investigation.

Future studies should extend the validation of the proposed configuration to soils with higher fines content, broadly graded sands, gravelly soils, and different particle morphologies. Quantitatively, morphology parameters such as roundness, sphericity, angularity, and surface texture should be considered in explaining the influence of particle shape on funnel spout response and repeatability. Inter-laboratory testing should also be conducted to assess the wider applicability and reproducibility of the proposed configuration.

Author contributions

CRediT: **B. Sai Laxman:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft; **P. Anbazhagan:** Conceptualization, Data curation, Formal analysis, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors reported there is no funding associated with the work featured in this article.

ORCID

B. Sai Laxman http://orcid.org/0000-0003-3360-8947
P. Anbazhagan http://orcid.org/0000-0001-9804-5423

References

ASTM International. 2016. *ASTM D4254-16: Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*. West Conshohocken, PA: ASTM International.

ASTM International. 2017, Reapproved 2025. *ASTM D2487-17: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*. West Conshohocken, PA: ASTM International.

Brand, E. W. 1973. "Some Observations on the Control of Density by Vibration." In *Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils, ASTM STP 523*, edited by E. T. Selig and R. S. Ladd, 121–132. West Conshohocken, PA: American Society for Testing and Materials.

Bureau of Indian Standards. 1983, reaffirmed 2020. *IS 2720 Part 14: Methods of Test for soils—Determination of Density Index (Relative Density) of Cohesionless Soils*. New Delhi: Bureau of Indian Standards.

Cubrinovski, M., and K. Ishihara. 2002. "Maximum and Minimum Void Ratio Characteristics of Sands." *Soils and Foundations* 42 (6): 65–78. https://doi.org/10.3208/sandf.42.6_65.

D'Appolonia, E. 1969. *Loose Sands-Their Compaction by Vibroflotation*, 138–160. West Conshohocken, PA: ASTM. Special Technical Publication 156.

Japanese Geotechnical Society. 2009. *JIS a 1224: Test Method for Minimum and Maximum Densities of Sands*. Tokyo: Japanese Standards Association.

Kolbuszewski, J. J. 1948. "An Experimental Study of the Maximum and Minimum Porosities of Sands." In *Proceedings of the 2nd International Conference on Soil Mechanics and Foundation Engineering*, 158–165. Vol. 1. Rotterdam.

Lade, P. V., C. D. Liggio, and J. A. Yamamuro. 1998. "Effects of Non-Plastic Fines on Minimum and Maximum Void Ratios of Sand." *Geotechnical Testing Journal* 21 (4): 336–347. https://doi.org/10.1520/GTJ11373J.

Mehdiratta, G. R., and G. E. Triandafilidis. 1978. "Minimum and maximum densities of granular materials." *Geotechnical Testing Journal* 1 (1): 34–40. https://doi.org/10.1520/GTJ10366J.

Mijic, Z., J. D. Bray, M. F. Riemer, M. Cubrinovski, and S. D. Rees. 2021. "Test Method for Minimum and Maximum Densities of Small Quantities of Soil." *Soils and Foundations* 61 (2): 533–540. https://doi.org/10.1016/j.sandf.2020.12.003.

Muszynski, M. R. 2006. "Determination of Maximum and Minimum Densities of Poorly Graded Sands Using a Simplified Method." *Geotechnical Testing Journal* 29 (3): 263–272. https://doi.org/10.1520/GTJ12591.

Oda, M. 1976. *Fabrics and their effects on the deformation behaviour of sand* [Special Issue].: Department of Foundation Engineering, Saitama University, Japan.

Walter, J. E., W. H. Highter, and R. P. Vallee. 1982. "Determining Maximum Void Ratio of Uniform Cohesionless Soils." *Transportation Research Record* 897:42–51.

Yoshimi, Y., and I. Tohno. 1973. "Statistical Significance of the Relative Density." In *Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils, ASTM STP 523*, edited by E. T. Selig and R. S. Ladd, 74–84. Philadelphia, PA: American Society for Testing and Materials.