New Criterion for Shutter Designing by Dry Pluviation Method

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Abstract

Dry pluviation is a technique applied for preparation of sandy soil samples for physical modeling. In this method, soil particles rainfall in the mold after passing through the mesh with certain opening sizes. In this study, a dry pluviation device was designed and manufactured to examine the effect of shutter properties including the hight of fall (HF), deposition intensity (DI), and gradation on relative density (RD). The results indicate that HF and DI have a direct and indirect relation with RD, respectively, but RD is constant for HF $\geq$ 1200 mm. In order to investigate the impact of shutter properties on DI and RD, α ratio (total area of the shutter holes to the area of the deposition surface) was defined and a linear relationship is proposed between DI and α. The results revealed an indirect relation between RD and α, but for $\alpha \geq$ 0.130 RD is constant. In order to assess the simultaneous effect of grain size and shutter properties on RD, an independent grain size variable (i.e., $\alpha/D50$) was defined and a linear relationship was established between $\alpha/D50$ and RD. The results showed that the variable $\alpha/D50$ can be considered as a useful criterion for designing a shutter to reconstitute sandy soils with different gradations.

1. Introduction

Physical modeling is one of the methods widely applied in laboratory studies. In this method, sample preparation is a critical step because of its effects on the outcomes of laboratory tests. Sample preparation methods should have the ability to reconstruct a natural soils fabric, a natural soil density, and a uniform void ratio (Arthur and Menzies 1972; Oda 1972; Yamamuro and Wood 2004; Amini and Qi 2000). Moreover, sample preparation techniques can affect the fabric and stress-strain response of the soil particles (Tabaroei et al. 2017). The most common methods for sample preparation in physical modeling in laboratory studies include dry and wet moist tamping, dry and wet pluviation, mist pluviation, slurry deposition, dry funnel deposition, water sedimentation, and vibration (Lade and Yamamuro 1997; Garga and Zhang 1997; Wood et al. 2008; Tatsuoka et al. 1986; DeGregorio 1990; Huang et al. 2015). Wichtman et al. (2020) investigated impact of the sample preparation method on the cumulative strains in sand under high-cyclic loading. Mahmudi et al. (2020) were prepared the samples using dry funnel pluviation and wet deposition at three selected relative densities and investigated impact of packing density and overconsolidation ratio effects on the mechanical response of granular soils. Wang and Brennan (2019) used the dry pluviation method for fibre-reinforced sand in centrifuge testing. Le et al. (2020) used the air pluviation and dry vibration methods for soil preparations that investigated effect inherent anisotropy on the shear strength and shear modulus of both saturated and unsaturated. Khari et al. (2019) using the pluviation method and produced loose and dense sand samples with relative densities of 30% and 75%.

Selecting the most suitable method for sample preparation is a difficult task because each method has unique characteristics (Raghunandan et al. 2012). Among the mentioned methods, moist tamping and dry pluviation are used more frequently than other methods for sand sample preparation in large-scale models (Been et al. 1987; Pournaghiazar et al. 2011; Lombardi and Bhattacharya 2014; Choi et al. 2010; Dave and Dasaka 2012; Gade and Dasaka 2015).

Vaid and Sivathayalan (2000) showed that reconstituted sandy soil samples retrieved by water pluviation closely mimic stress-strain behavior with undisturbed samples. Kuerbis and Vaid (1988) stated that the slurry deposition can produce a homogeneous sample with a fabric similar to that of natural fluvial sands. Sample preparation by wet pluviation produces the fabric of fluvial and hydraulic-fill sands (Oda et al. 1978; Vaid et al.1999). Wood et al. (2008) demonstrated the declining effect of sample preparation method on the undrained behavior by increasing the density. Dry pluviation and water sedimentation methods produce sand samples with homogeneous density (Vaid et al.1999). Also, it has been found that specimens reconstituted by moist tamping are less homogeneous compared to those prepared by dry pluviation. Dry pluviation is a sample preparation method based on the deposition of sand rained from a certain height. This method is widely used in physical modeling for reconstituting sand specimens with different size and widely adopted for preparation of large, uniform and repeatable sand beds of desired densities for laboratory studies to simulate in-situ conditions and obtain test results which are highly reliable (Dava and Dasaka, 2012). Jacobsen (1976) conducted comprehensive studies on dry pluviation technique for large-scale physical models. He suggested that this method is capable of creating soil layers with a relative density (RD) between 20% and 90%, large thickness (about 1m), and homogenous dry densities (between 0.8-1.2%) the top and bottom. This method is capable of preparing sand samples with 100% RD (Rad and Tumay 1987; Miura and Toki 1982). In this regard, Rad and Tumay (1987) confirmed that specimens formed by this method are homogeneous. Moreover, it has been found that using this method for well-graded sand samples containing significant amounts of fines, particle segregation occurs in the reconstituted specimens (Vaid and Negussey 1988; Wood et al. 2008). Overall, the dry pluviation method is suitable for reconstituting clean sandy soils with minimum particle segregation (Rad and Tumay 1987). The advantages of this method compared to the vibration (ASTM D 4253-83) are a higher dry density, no particle crushing, less effect of segregation, and better repeatability (Lo Presti et al.1993). Kim and Seo (2019) investigated void ratios of binary sand mixtures deposited by dry pluviation with various weight fractions of smaller particles and particle size ratios.

In the dry pluviation method, the density of the samples depends on the deposition intensity (DI), height of fall (HF), uniformity of raining sand, the opening width of the curtain in the curtain technique, the porosity of diffuser, particle size, and other parameters (Butterfield and Andrawes 1970; Rad and Tumay 1987; Vaid and Negussey 1988; Lo Presti et al. 1992 &1993; Fretti et al. 1995; Lagioia et al. 2006; Choi et al. 2010; Raghunandan et al. 2012; Dave and Dasaka 2012; Gade and Dasaka 2015; Hariprasad et al. 2016; Srinivasan et al. 2016; Tabaroei et al. 2017). In general, an increase in DI leads to a decrease in the density of the soil specimen because of with increase DI, The grains collision with each other increase and the grains farther apart so the density decreases. The DI depends on shutter porosity as a function of hole size and hole spacing (Rad and Tumay 1987). Height of fall (HF) is the distance between the lowest diffuser bottoms to the surface of the sand in the specimen (Choi et al. 2010, Gade and Dasaka 2015). Deposition intensity (DI) is the mass of soil falling in the container per unit of area to per unit of time (Lo Presti et al. 1993; Dave and Dasaka 2012; Gade and Dasaka 2015). Shutter porosity is calculated as the ratio of hole area to the total area for the sand raining hopper (Okamoto and Fityus 2006). The hole area includes a single or multiple circular or rectangular holes. Increasing the shutter porosity is accompanied by an increase in DI and decrease in RD. However, there is no statistically significant relationship between shutter porosity and DI (Okamoto and Fityus 2006). Previous studies have reported an increase in the density by increasing the HF and shown the limited effect of HF. This limitation has been reported 500 mm from top of the split mold sample (Okamoto and Fityus 2006). Vaid and Negussey (1988) showed the velocity of sand particles increases with an increase in HF until the critical velocity is reached, while further increase in HF certainly would not affect the RD of the specimen. For a certain HF, an increase in DI increases the void ratio and decreases RD of the sand sample (Rad and Tumay 1987; Miura and Toki 1982; Lo Presti et al. 1992 &1993; Fretti et al.1995).

The diffuser is utilized in order to uniform sand rain. Researchers have used one or more sieves for this purpose (Jacobsen 1976, Miura and Toki 1982) and shown that sieves with smaller openings provide a more dispersed sand rain. Moreover, the number of sieves used in a diffuser and distance between them has a negligible effect on the relative density (Rad and Tumay 1987).

Khari et al. (2014) designed mobile pluviator adopted the air pluviation method for deposition of sand samples. Zakir Hossain and Ansary (2018) developed of a portable traveling pluviator device and its performance to prepare uniform sand specimens.

The objective of this paper is to study factors effective on DI by controlling the shutter characteristics for three types of sandy soils with different grain size distributions. Also, it introduces a new criterion for designing shutter with the aim of reconstituting sample with desired relative density.

2. Material And Methods

In this study, three different gradations of sandy soils (S_1, S_2, and S_3) with less than 10% fine content were used. These sandy soils contain 97.5% SiO_2, 0.85% Fe_2O_3, 0.95% Al_2O_3, and 0.7% other oxides. Index properties of the soils used in this study are shown in Table 1.

Figure 1 presents particle size distribution curves of this soils compared with the size distribution curves of soils used by other similar researchers. The soil ranges used by other (not similar) researchers are represented by dashed lines. This figure illustrates that the three sandy soils used in the present study well cover all gradation range of soils used for sample preparation by dry pluviation method.

The dry pluviation apparatus used to prepare sand samples in this study is shown in Figure 2. This equipment includes a hopper with a height of fall (HF) up to 1200 mm, a shutter with triangular hole pattern, single diffuser screen, and a cylinder for uniform column sand raining. The diameter of holes and shutter porosity are between 8-15 mm and 0.4-13.9% separately (Table 2). The distance between shutter and diffuser screen is denoted by 'H_1' and the distance between the diffuser screen and bottom is shown with 'H_2' that is variable during pluviation as the soil surface moves up, the height of fall is $HF=H_1+H_2$. Detailed specifications of the apparatus are presented in Figure 2. In all tests, to achieve the maximum RD, the sand was rained from the hopper and through holes, passing a single diffuser screen placed at a distance of 600 mm (H_2=600 mm) from the bottom of the split mold. The Diameter of the shutter plate and mold (as shown in Figure 2 and Table 2) are between 120 - 150 mm and 101 mm separately so the ratio shutter diameter/mold diameter is between 1.2-1.5.

Deposition intensity (DI) was calculated by measuring the mass deposited in the split mold during a specified time. A change in DI resulted in the consequent changes in hole size, hole spacing, and the number of holes. Table 2 presents the values assigned to these variables.

The holes were arranged in a triangular pattern. Two diffuser screens with mesh numbers #4 (for sample S_1) and #8 (for samples S_2 and S_3) were used (ASTM E11:01). To avoid disperse of sand and provides a rout for precipitation, cylinders with 150 and 120 mm diameters were embedded in the distance between diffuser screen and split mold.

3. Test Results

3.1. The relation between 'HF' and 'RD'

To investigate the effect of HF on RD, sample S_3 was selected. In Figure 3, variations of RD with HF is plotted for three different DI. In these tests, H1= 600 mm and H_2 is variable. HF and RD have a direct relationship and as HF increases, RD increases as well but when HF ≥ 1200 mm, RD remains constant. Besides, for a specific HF, with an increase in DI, RD decreases. In this case, because HF is constant, the reason for the increase in DI may be the increase in shutter porosity. Therefore, with increasing shutter porosity, DI decreases. In this study, to investigate precipitation rate and eliminate the effect of HF on the RD, all tests were carried out with an HF ≥ 1200 mm.

3.2. The relation between 'HF' and 'DI'

The deposition intensity (DI) is defined as the mass of soil per unit time that passes through the mold surface unit. Figure 4 illustrates DI versus HF in two different conditions. In case 'a' there is a cylinder between diffuser screen and mold and in case 'b' there is no a cylinder between diffuser screen and mold. In the case 'a', with increase HF, DI is uniform and constant while in case 'b', with an increase in HF, DI starts to decrease. In case 'b', due to the absence of the cylinder, the sand grains are separated and dispersed after passing through the diffuser screen, so DI decreases and is variable.

Therefore, in all tests in this study, a cylinder was used with the goal of achieving a uniform deposition intensity. Figure 4 shows that DI is controlled by the deposition surface and hole size. In order to determine the simultaneous effect of the hole size and the deposition surface, parameter 'α' was defined by equation 1.

$$\alpha = \frac{\text{The total area of the shutter holes}}{\text{The area of the deposition surface}} = \frac{A_{SH}}{A_{DS}} \qquad (1)$$

The total area of the shutter holes (A_{SH}) is calculated from some holes existing in the area of the shutter. The deposition surface (A_{DS}) is described as sand passing through a cylinder embedded in the distance between the diffuser screen and split mold (i.e., the area of the cylinder). Deposition surface (A_{DS}) should be greater or equal to the mold surface. When the deposition surface is equal to the total area of the sand raining hopper and mold, this parameter will be the same as the shutter porosity.

For example, in Figure 2 there are 7 holes each with a 10 mm diameter in the surface area; so, A_{SH} = 791.28 mm^2, the cylinder diameter is 120 mm, and A_{DS} = 11304 mm^2. According to Eq. 1, α is calculated as follows:

$$\alpha = \frac{791.28\ \mathrm{mm2}}{11304\ \mathrm{mm2}} = 0.07 \qquad (2)$$

The experimental design of this study includes measuring DI in the specified shutter porosity calculated by equation 1. Table 2 presents the α ratio estimated using equation 1 for the whole tests.

Using the data presented in Table 2, Figure 5 illustrates the correlation between α ratio and the DI for various soil gradations. As can be seen in this figure, there are linear relationships between the α ratio and DI for all samples.

According to the determination coefficients (R^2) presented in Figure 5, it can be stated that the α ratio is a comprehensive criterion for estimating the DI. As the α ratio increases, the DI increases. Also, it has been shown that DI is variable at the constant α ratio for sandy soils with different gradations. Under the same conditions, sandy soil with smaller gradation shows a higher the DI. This effect is greater in a higher α ratio. In other words, the DI depends on soils gradation in the same conditions of the shutter.

In the tests conducted on sand S_1, it was observed that pluviation was stopped in the hole size 10 mm because the grain of soil accumulates in the shutter holes. Thus, it is suggested that the minimum hole size is 7 times more than the D_{50} of soils

3.3. The relation between 'RD' and 'DI'

The results in Table 2 were used to study the effect of DI on RD for sandy soils. Based on the data in Table 2, Figure 6 presents the RD plotted versus DI for three soil samples. These results confirm that RD decreases with an increase in DI. Also, it was observed that RD for the same DI depends on soil gradation. The influence of the DI on RD of sandy soil with larger grain size is more. In addition, for specified DI, the effect of DI on RD disappears. This value is a function of soil gradation. For example, for soil S_3, for DI ≥ 3200 (kg/min/m^2), an increase in the DI does not affect the RD.

Based on Figure 5, there is a significant relation between α ratio and DI. Moreover, based on Figure 6, there is a relation between DI and RD, so the α ratio can serve as a useful parameter for evaluating RD. Figure 7 depicts the relationships between the α ratio and RD for sandy soils. The results confirm that RD decreases with increasing the α ratio. The figure also presents the effect of soil gradation on the DI under the same device conditions. As can be noted, the α ratio greater than 0.130 has almost no effect on RD.

There is a limitation for α ratio as a device parameter such that for α ratios greater than 0.130 the DI does not affect the RD. For $\alpha \le 0.130$, it is suggested that samples with lower RD are obtained by adjusting the HF and increasing diffuser sieve opening. Sample S_1 shows unacceptable results at lower α ratios due to the particle size in this sample is larger than the other samples. The results show that RD depends on soil gradation, H_2 and the α ratio, as a device parameter (Figure 7). In order to remove the effect of soil gradation on the results, a new parameter (i.e., α/D_{50}) was used. Figure 8 shows a linear relationship (R^2 =0.94) between α/D_{50} and RD for two sand samples S_2 and S_3.

The most important feature of Figure 7 is the simultaneous assessment of soil gradation, holes area, and deposition surface on RD. This linear relationship can be used to design shutter properties to reconstitute a sample with desired relative density for different gradations of sandy soils. The results of this study are presented in a fall height of 1200 mm. Thus, it is possible to increase α/D_{50} ($\alpha/D_{50} \ge 0.6$) through reconstituting samples with a relative density of less than 40%.

4. Discussion

This research was conducted to evaluate some parameters affecting dry pluviation in three sand samples with different grain size distributions. Based on previous studies, the RD range of samples made with the dry pluviation method is 20% ≤RD ≤90% (Jacobsen 1976) and RD=100 (Rad and Tumay 1987; Miura and Toki 1982; Okamoto and Fityus 2006). In this research, samples were produced with 45%≤RD ≤100%, suggesting that it allows preparing samples with different RD values.

Homogeneous samples can be produced using this method (Jacobsen 1976, Rad and Tumay 1987). In this research, it was found that for HF≥1200 mm, RD is not dependent on the HF and then is constant throughout the sample. Therefore, to prepare uniform RD samples, the HF was considered to be 1200 mm.

In this study, similar to previous works, it was observed that RD of the samples depends on the deposition intensity (DI), the height of fall (HF), the porosity of diffuser, and particle size. Okamoto and Fityus (2006) showed that with an increase in the shutter porosity, DI increases while RD decreases. However, no statistically significant relationship was extracted between shutter porosity and the DI. In this research, the α ratio (A_{SH}/A_{DS}) was defined to assess the impact of shutter properties on DI and RD. A linear relationship between DI with α with $R^2 \ge 0.96$ was proposed for each particles size. The results revealed an indirect relation between RD and α. Moreover, it was found that for $\alpha \ge 0.130$, RD is constant. The range of α variations in the present study is between 0.003 and 0.19.

Several studies have shown that with an increase in the HF, velocity of sand particles increases until the critical velocity is reached while further increase in HF certainly would not affect the RD of the specimen

(Vaid and Negussey 1988). This limitation has been reported for a height 500 mm from top of the split mold sample (Okamoto and Fityus 2006). In this study, the direct relation between the HF and RD was established but for HF ≥ 1200 mm, RD is constant and independent of the HF.

In this study, similar to previous works (Rad and Tumay 1987; Miura and Toki 1982; Lo Presti et al. 1992 &1993; Fretti et al. 1995), we observed that for a certain HF, an increase in DI leads to a decrease in RD of the sand sample. The results of this study revealed that HF and DI have respectively direct and indirect relations with RD, and for HF ≥ 1200 mm RD is constant for a further increase in HF. In addition, RD was constant with DI. To analyze the simultaneous effect of shutter properties and grain size, we proposed a new parameter (α/D_{50}) and presented a linear relationship between RD and α/D_{50}.The range of D_{50} and α/D_{50} variations in the present study are $0.08 \leq D_{50} \leq 0.8$ and $0.005 \leq \alpha/D_{50} \leq 0.73$ separately.

5. Conclusion

In this study, a dry pluviation apparatus was fabricated. Then, three soils with various gradations were used and the effect of different factors such as shutter properties and gradation on the DI and relative density (RD) was investigated. Overall, the results of the present study can be summarized as follows:

-HF and RD have a direct relationship and as HF increases, RD increases as well but when HF ≥ 1200 mm, RD remains constant.

-The relationship between DI and HF as well as shutter properties are a function of the deposition surface. In order to investigate the simultaneous effect of these two variables, a new parameter (α ratio) was defined.

-There are direct linear relationships between the α ratio and DI for three samples studied this research. In addition, this relation is associated with soil gradation.

-With an increase in DI, RD decreased, but for a specified DI, with an increase in DI, RD is almost constant. In dry pluviation apparatus made in the present study, the specified DI for soil S_3 is equal to 3200 kg/min/m^2. Also, it was observed that in the same DI, RD depends on soil gradation.

-There is a relation between RD and α ratio. With an increase in α ratio, RD declines but exceeding a specified α ratio (i.e., 0.13), RD is almost constant. Moreover, it was observed that RD for the same α ratio depends on soil gradation.

-In order to remove the effect of soil gradation on RD, a new parameter (i.e., α/D_{50}) was defined. The main feature of this parameter is the simultaneous investigation of the shutter specification and soil gradation. There is a linear relation between RD and α/D_{50}. The results revealed the parameter α/D_{50} is a comprehensive criterion for estimating the DI required for sample preparation and shutter design.

-It is recommended preventing the accumulation of particles by considering the minimum hole size 7 times greater than the D_{50} of soils.

Abbreviations

HF: is the height of fall

DI: is the deposition intensity

RD: is the relative density

A_{SH}: is the total area of the shutter holes

A_{DS}: is the area of the deposition surface

α: is the total area of the shutter holes to the area of the deposition surface

D_{50}: is the median diameter or the medium value of the particle size distribution

A_{SH}: is the total area of the shutter holes

A_{DS}: is the area of the deposition surface

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Tables

Table 1. Index properties of sandy soils S_1, S_2, and S_3

Sample ID.	Gs	D_{50}	D_{10}	Cu	Cc	e_{min}	e_{max}
S_1	2.62	1.64	0.79	2.27	1.29	0.40	0.77
S_2	2.65	0.50	0.12	5.6	0.79	0.43	0.74
S_3	2.70	0.18	0.08	2.73	0.97	0.55	0.91

Table 2. The summary of the test designs and results

Sample ID.	Hole size (mm)	Number of holes	Column diameter rainfall (mm)	α ratio	Deposition intensity (DI, kg/min/m2)	Relative density (RD, %)
S_2	8	1	120	0.004	0.01	94
		2		0.009	0.01	93
		4		0.018	0.03	92
		7		0.031	0.04	94
	10	1	120	0.007	0.01	94
		2		0.014	0.02	94
		3		0.021	0.03	92
		7		0.049	0.09	93
		19		0.132	0.20	72
	12	1	120	0.010	0.02	95
		2		0.020	0.03	94
		3		0.030	0.05	92
		7		0.070	0.13	85
		19		0.190	0.36	67
	15	1	120	0.016	0.03	94
		2		0.031	0.03	92
		3		0.047	0.10	88
S_3	8	1	120	0.004	0.01	95
		1	150	0.003	0.00	96
		2	120	0.009	0.01	95
		4		0.018	0.03	93
		7		0.031	0.05	85
	10	1	120	0.007	0.01	93
		3		0.021	0.04	87
		7		0.049	0.08	65
		19		0.132	0.28	38

	12	1	120	0.010	0.02	91
		2		0.020	0.03	87
		3		0.030	0.05	84
		7		0.070	0.18	55
		19		0.190	0.42	37
	15	1	120	0.016	0.03	87
		2		0.031	0.06	75
		3		0.047	0.10	67
S_1	10	1	120	0.007	0.01	95
		2		0.014	0.01	91
		3		0.021	0.02	90
		7		0.049	0.06	83
		19		0.132	0.11	84
	12	1	120	0.010	0.01	90
		1	150	0.006	0.01	92
		2	120	0.020	0.02	86
		3		0.030	0.02	86
		7		0.070	0.08	85
		19		0.190	0.19	81
	15	1	120	0.016	0.02	87
		2		0.031	0.04	88
		3		0.047	0.05	84

Figures

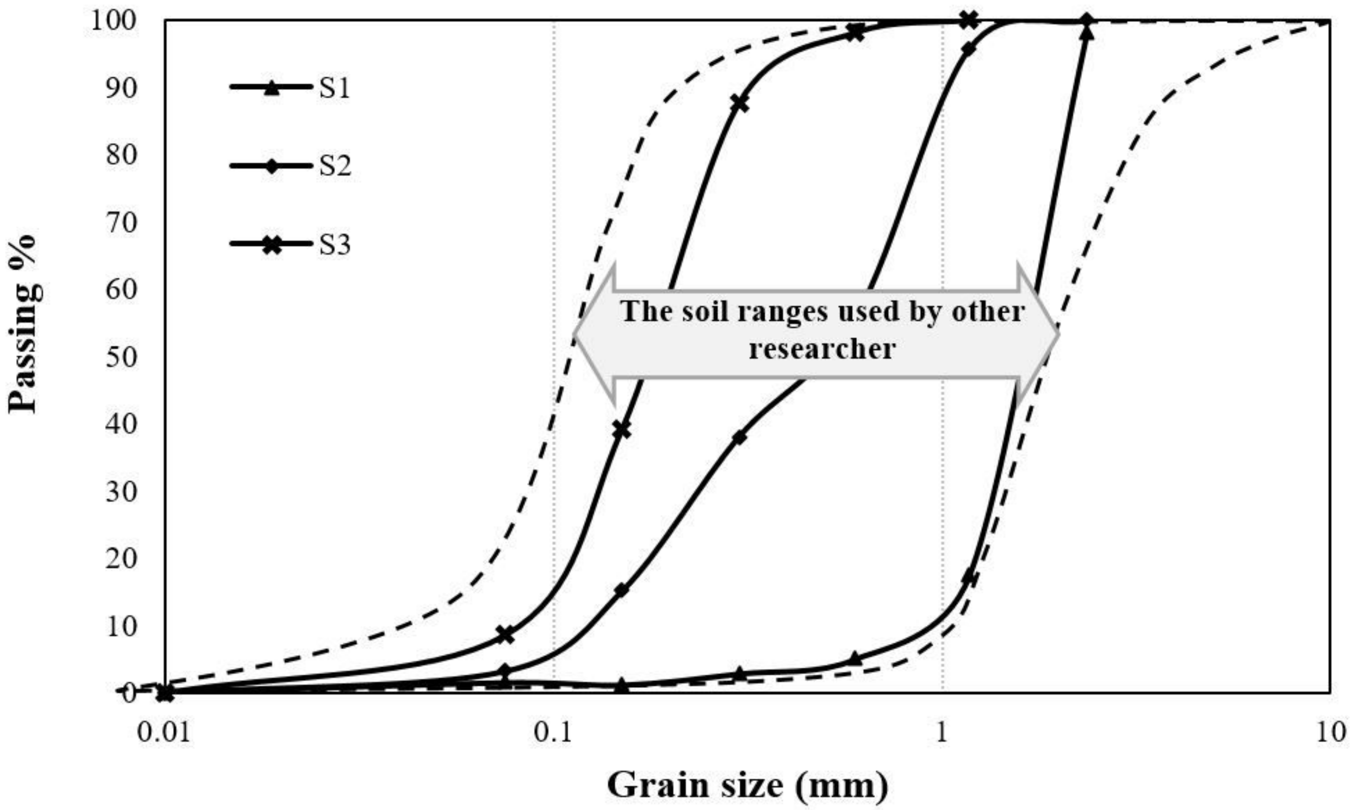

Figure 1

Particles size distribution of sandy soils in this study and soils used by some researchers

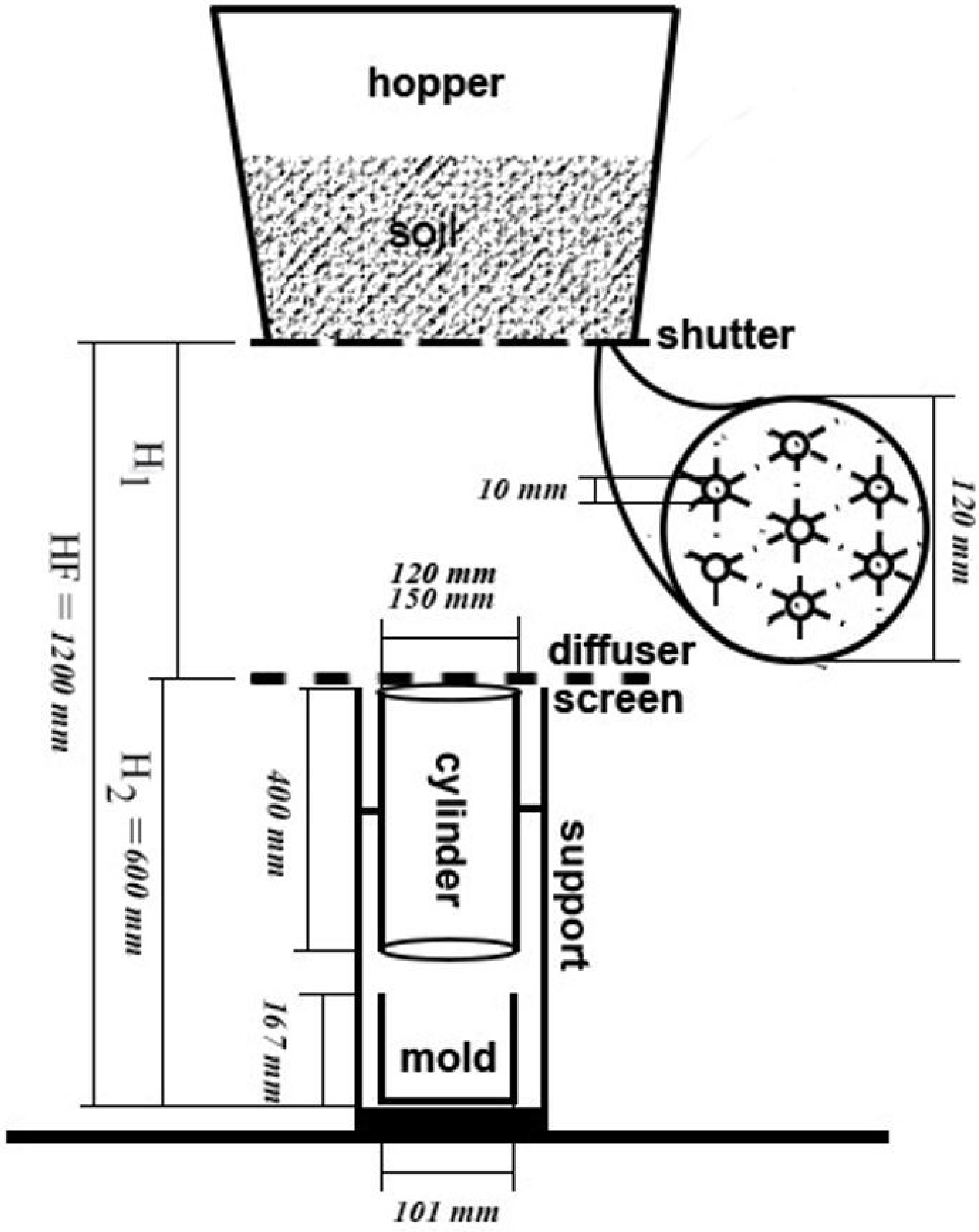

Figure 2

Details specification the pluviation apparatus used in this study

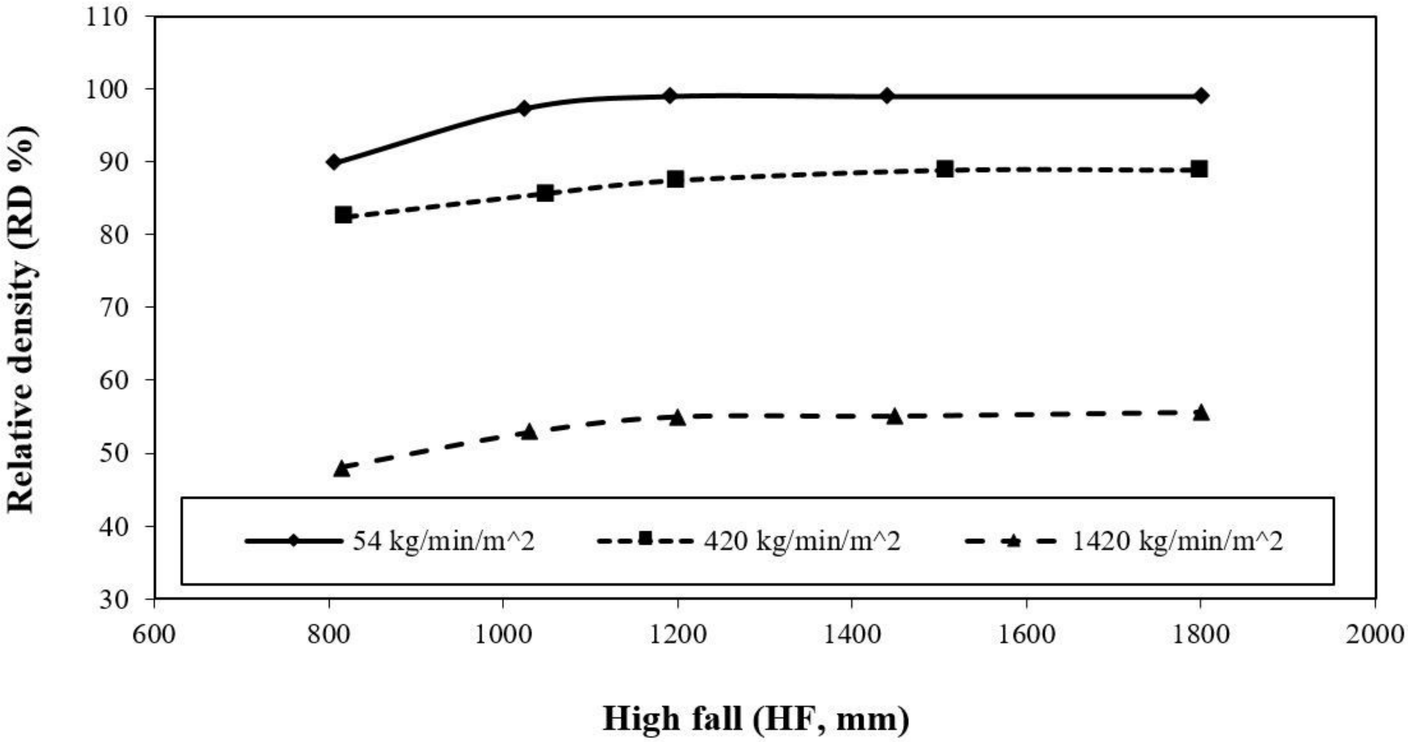

Figure 3

DR variations with HF for various DI.

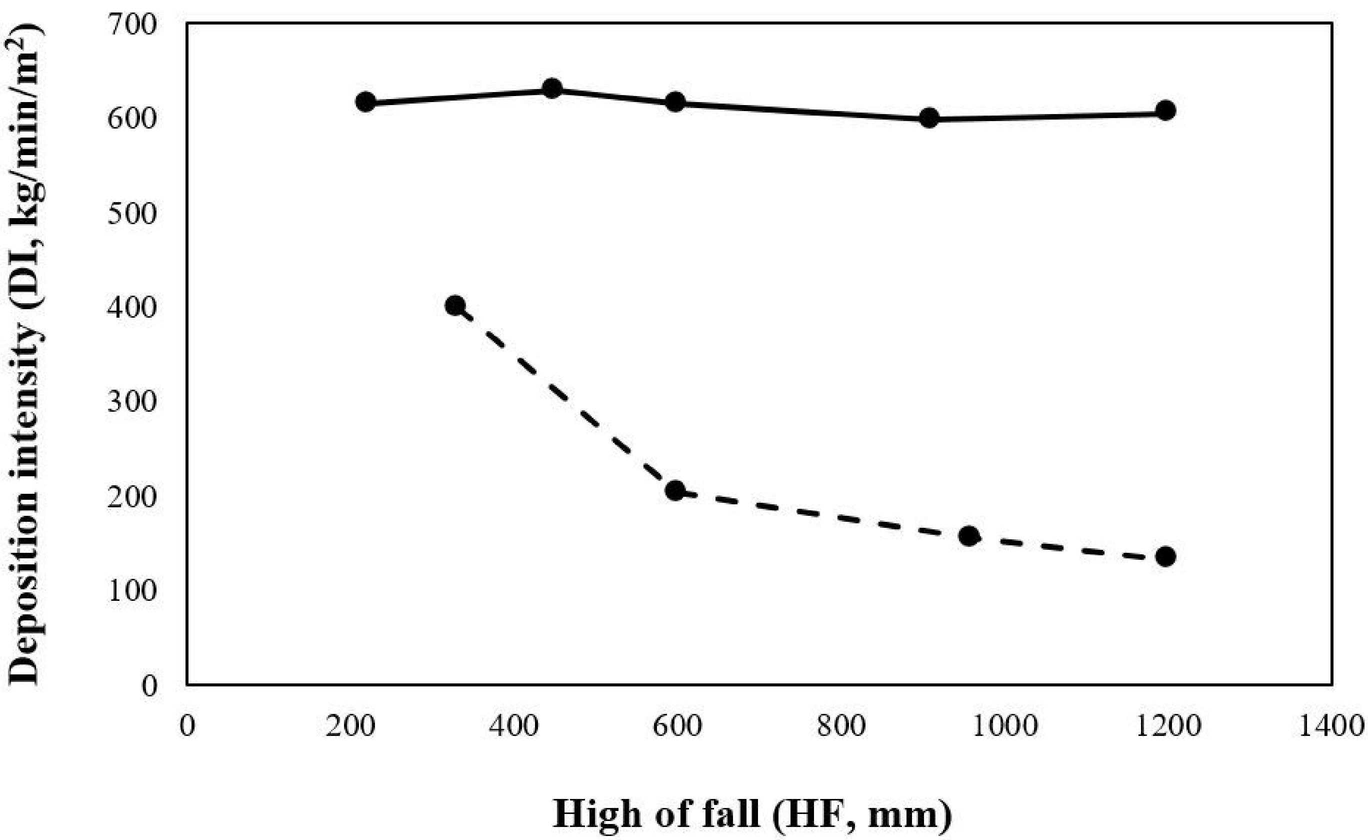

Figure 4

DI versus HF a) with the cylinder and b) without the cylinder

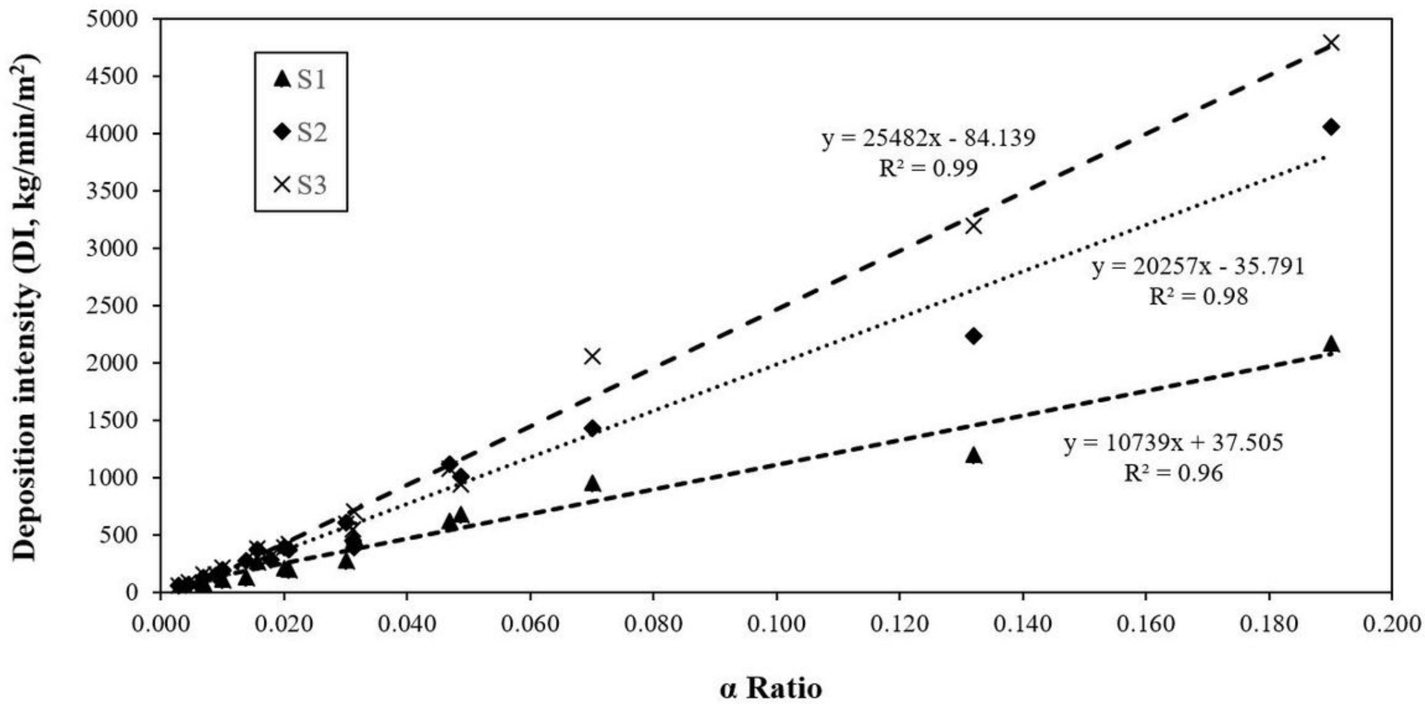

Figure 5

DI versus α ratio for 3 sand samples (S1, S2, and S3)

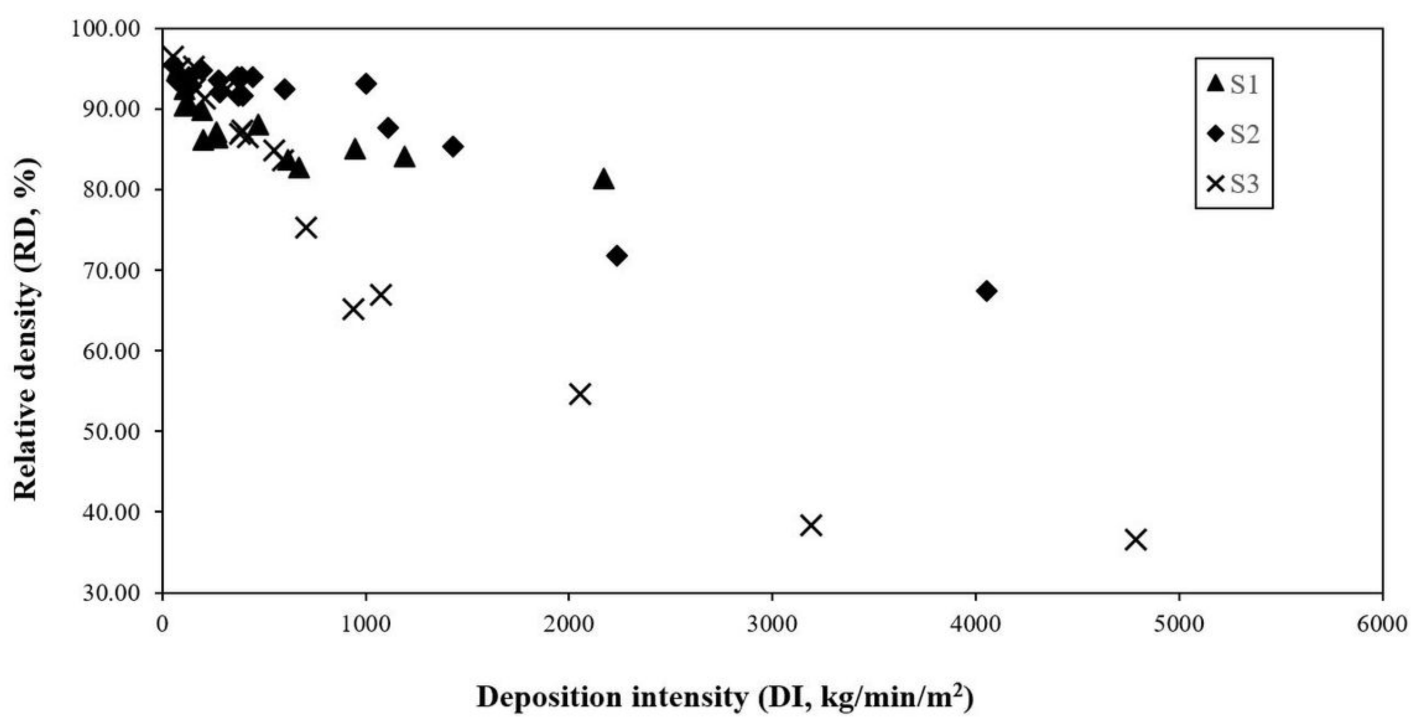

Figure 6

The relationships between DI and RD for sand samples (S1, S2, and S3)

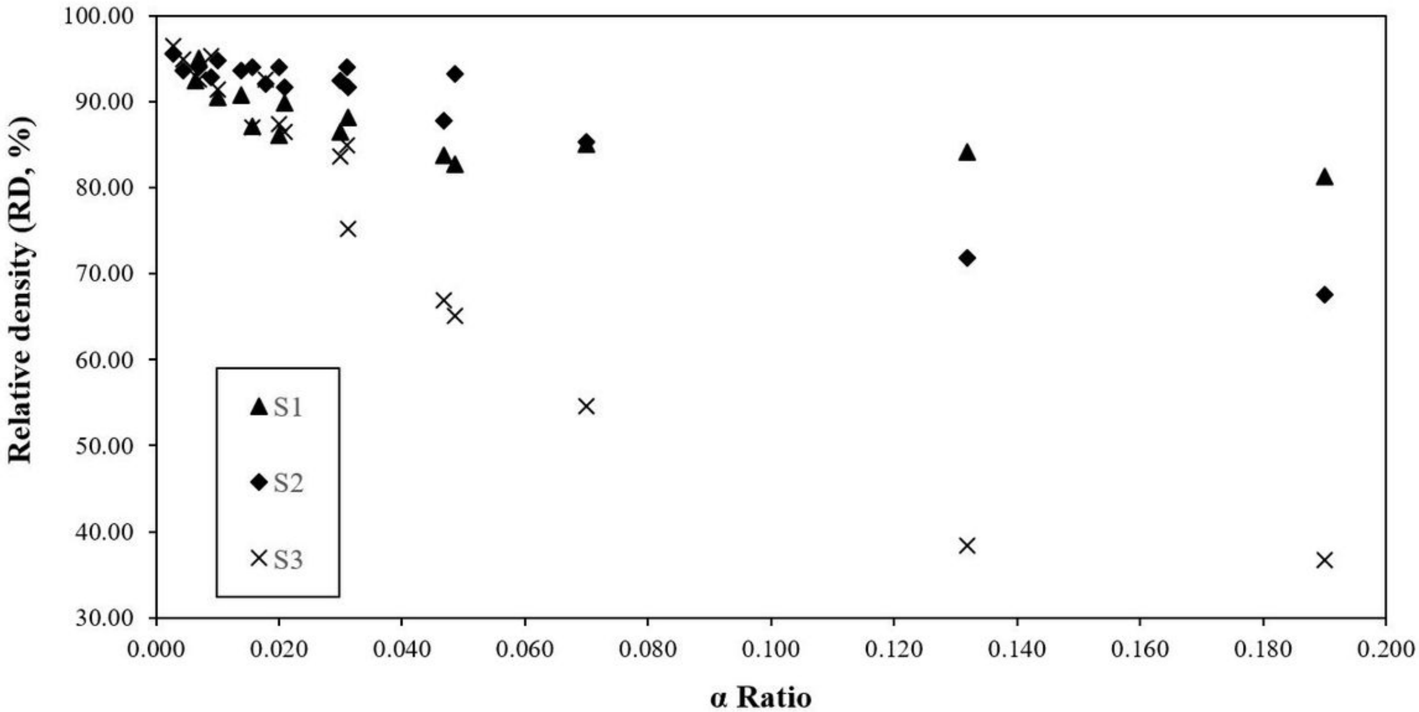

Figure 7

The relationships between the α ratio and RD for sand samples (S1, S2, and S3)

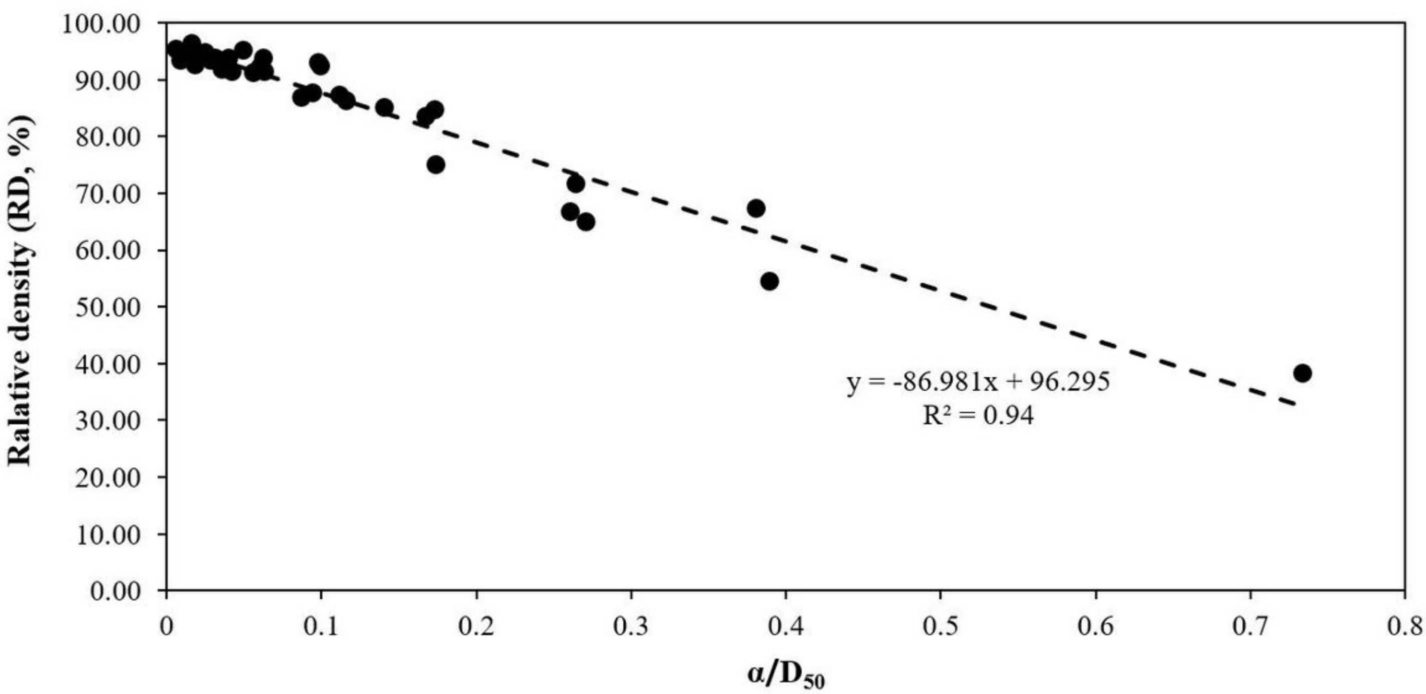

Figure 8

The relationships between α/D50 and RD for sand samples (S2 and S3)