

Research Article

Experimental Study of the Aggregate Shapes in Self-Compaction

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Compaction operations have a vital role in embankments or rock fills to avoid settlement, but in some projects, such as marine ones, it is hardly possible to accomplish compaction operations due to the problems and executive limitations. In situations with no possibility of compaction, it is recommended to use single-size or self-compacted materials. From a theoretical point of view, self-compacted materials consist of coarse aggregates with no vast domain of gradation. In this case, the porosity of the materials in the dense state is not significantly different from the loose one, and a relatively dense condition occurs after it is poured; thus, the mass of materials will undergo lower volumetric changes in the future. In this study, the self-compacted characteristic of materials has been investigated using real aggregates with different gradations (the ratio of the largest to the smallest aggregate size of 1, 2, 4, and 8). The gradation and shape of aggregates are the main variables examined in the research. Real aggregates have been used in order to compare the study of self-compacted idea with ideal aggregates and the effects of sphericity and angularity of them. According to the experiments carried out on samples in the present work, it was observed that, without compaction operations, even ideal materials would not be in fully self-compacted state. However, relatively denser conditions can be achieved by observing the necessary points. Moreover, aggregates with high sphericity have better self-compacted property. Furthermore, the more uniform gradation and bigger size of materials lead to more self-compacted pile of materials.

1. Introduction

Compaction operations are performed on structures to prevent soil subsidence. If the compaction is not done well, excessive sitting can cause many problems [1]. Self-compacting materials are materials that, firstly, their porosity ratio in the compacted state is not much different from the loose state, and secondly, when poured in place, they are automatically closer to the compacting state, so the material mass will change volume and settle less [2]. In all earthen structures, compaction operations are very important to prevent the aggregation of materials because the aggregation of materials causes many problems in the use and operation of the structure during its life [3]. Due to the geographical location of the country and the high importance of maritime transport, the construction and maintenance of marine structures is essential. In some operating conditions, especially in offshore structures, it is not possible to compact granular materials in order to prevent excessive subsidence

and increase the load-bearing capacity for the construction of the structure [4]. For example, it is not very difficult, and sometimes impractical to pound pebbles behind the walls of parallel beach docks or composite breakwater rocks. Examples of these environmental conditions are shown in Figure 1.

The compaction operations are not practically possible or face many problems in many conditions, especially at sea [6]. In these conditions, the problems related to compaction operations can be solved to a large extent using self-compacting materials. In the present study, laboratory studies have been used to test the hypothesis of self-compacting materials. The testing process is simple and usable for small, laboratory-grade aggregates. In previous research works of Shabanpour [2] and Torabi [3], real rock fragments were used first, so the results were influenced by the properties of aggregates. Keshtpour [4] then conducted his research to investigate the idea of self-compacting materials regardless of the effect of the shape of the material on completely

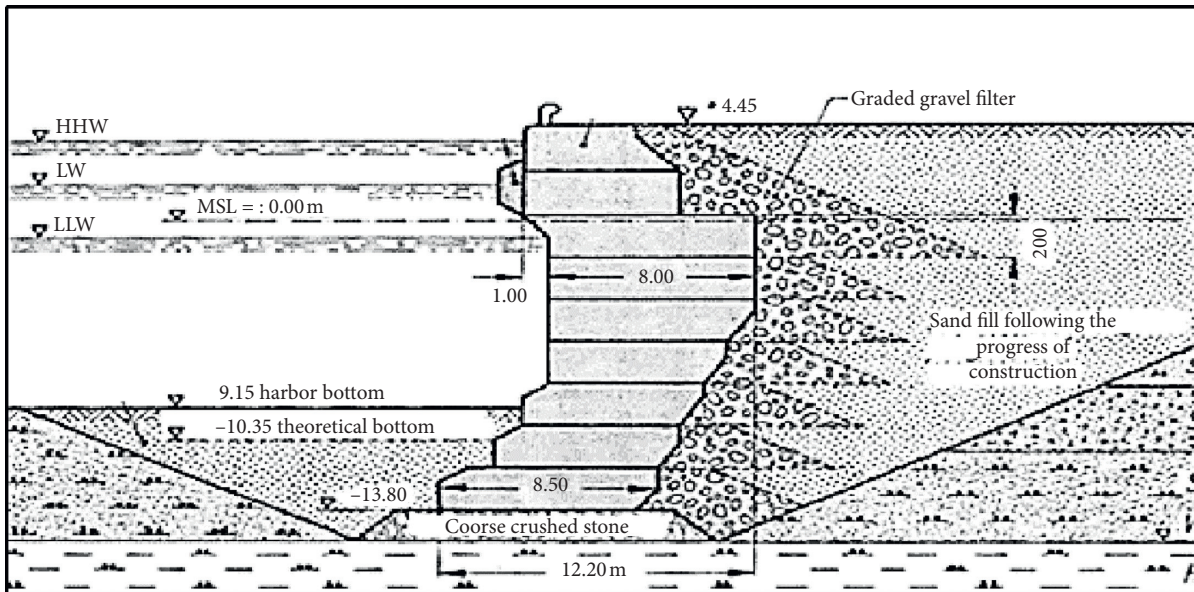


FIGURE 1: Granular materials used behind block piers [5].

spherical grains [7]. Also, the materials were precipitated in three different ways so that the appropriate precipitation method could be selected [4]. In this study, in order to approach the real conditions, Keshtpour experiments have been performed with round and sharp corner stone materials.

1.1. Technical Literature. In noncohesive soils with grain structure, sand and silt particles with a diameter of more than 0.02 mm are deposited singly and independently of other particles when deposited in water [5]. The weight of these particles causes them to precipitate rapidly and to equilibrium among other particles, in which the weight force is the only effective force [8]. Depending on the position of the particles on top of each other, the degree of compaction of the soil mass will change [9]. If these particles are assumed to be spherical and of exactly the same diameter, their degree of density will have two final limits (Figure 2). One is the highest density limit at which the particles are placed in a position where the porosity ratio is minimized (densest state) and the other is the lowest density limit at which the porosity ratio is maximum (weakest state) [5].

The idea of self-compacting materials is based on the idea of self-compacting concrete. In self-compacting concrete, the aggregates are well granulated, and in these conditions, the aggregates are the same size and move easily between each other and fill the empty spaces [6]. This idea is based on the experimental use of self-compacting materials by engineers. The initial placement of materials after rainfall is very important [11]. In the case of materials with uniform granulation, the materials are in a relatively denser condition after precipitation; in fact, the uniformity of the materials will reduce their pores [12]. The noteworthy point about the uniformity of materials is that, with increasing the grain size

range and the nonuniformity of the grains, the porosity ratio of the materials decreases, but in this case, the difference between the maximum and minimum porosity ratios is large [7]. In 2002, a study was conducted at the University of Tokyo, Japan, on the ratio of maximum and minimum porosity of materials under ideal conditions and in real life [4]. With the help of mathematical relations, the maximum porosity ratio and the minimum porosity ratio of the ideal materials were calculated equally [13]. They concluded that the maximum and minimum porosity ratios as well as the “maximum and minimum porosity ratio difference” depend on the grain size, grain size curve, and fine grain percentage [4] (Figure 3).

In 2009, a study on the calculation of maximum and minimum porosity ratios as well as the fine-grained effect on these variables was conducted by Ilmaz at the University of Krikale in Turkey. Therefore, it seems that the fine-grained percentage between 30 and 70% reduces the difference between the maximum and minimum porosity ratios [5]. Shabanpour research was conducted in two parts: laboratory and numerical. In this research, first a view was considered about the granulation mechanism of self-compacting materials, and this view is in the form of considering the uniform granulation of materials. According to these hypotheses, a suitable method was considered to perform the experiment, and its shortcomings were eliminated by trial and error during various experiments [2]. Figure 4(a) shows an example of Shabanpour experiments.

The results of these experiments showed that, first, the more uniform the materials, the less the compaction is needed and the materials are closer to self-compaction. Second, it was observed that the “maximum and minimum porosity ratio difference” in the saturated medium increased at a slower rate than in the dry medium, and the grain self-compaction conditions in the saturated medium were better

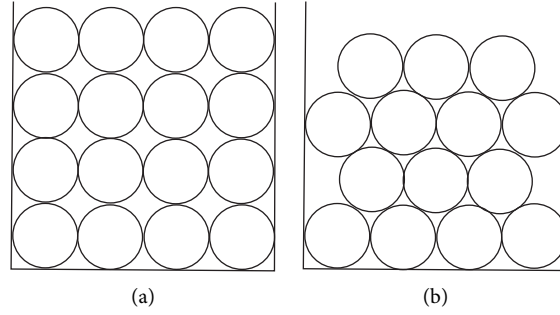


FIGURE 2: How to place uniform granulation after precipitation considering spherical grains of the same size. (a) Placement of materials with a high probability of occurrence after falling. (b) Placement of materials with low probability of occurrence and after shedding [10].

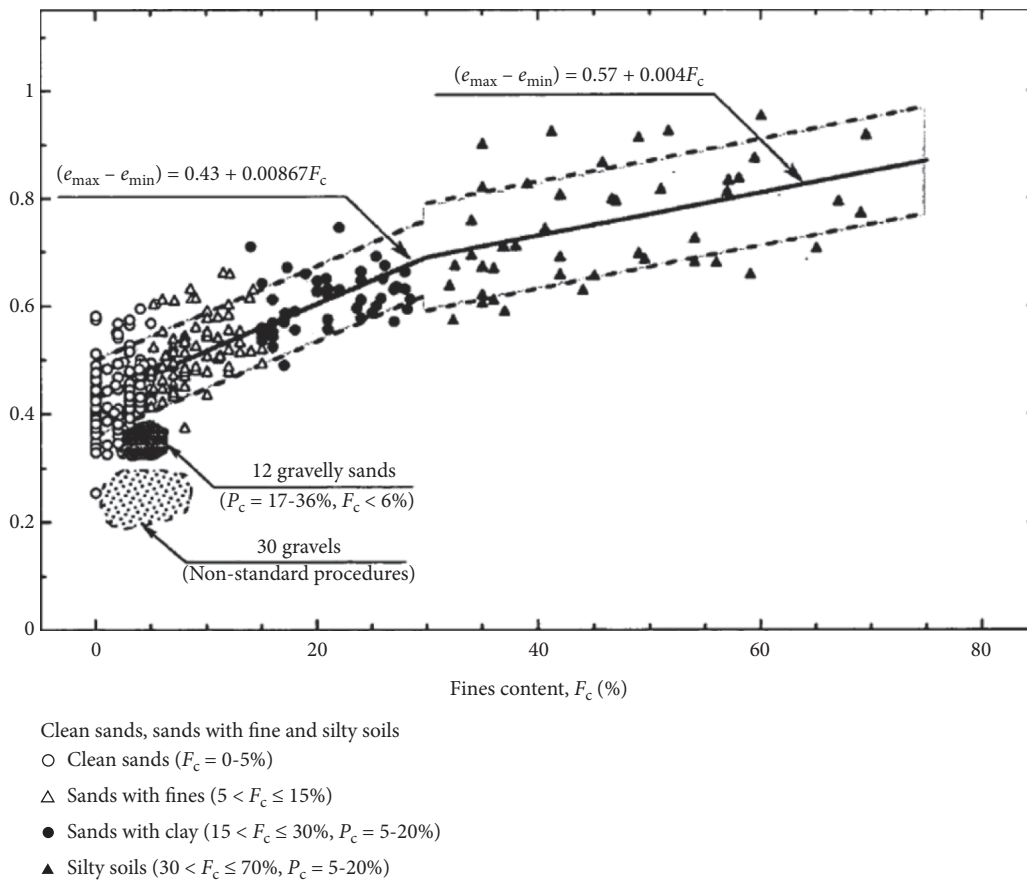


FIGURE 3: Difference between maximum and minimum porosity ratios in terms of fine-grained percentage [5].

than in the dry medium [14]. As a result, the results of the experiment in a dry environment can also be used for reliability in a saturated environment [2]. As shown in Figure 4(b), the laboratory results and the numerical modeling results are approximately the same. The difference in results is also due to laboratory errors as well as simplifying assumptions in modeling [2]. Finally, Shabanpour presented the relationship between the variables “maximum to minimum grain size ratio” and “settling coefficient” to use the results of his research in practice:

$$\Delta e = 0.0111 \left(\frac{D_{\max}}{D_{\min}} \right) - 0.0053, \quad (1)$$

$$\frac{\Delta e}{1 + e} H \leq \Delta H_{\text{allowable}}. \quad (2)$$

Then assume that an embankment with a definite granulation and without any compaction operation could not have a specific gravity of less than γ_{\min} and a higher e_{\max} porosity ratio [15]. Such an embankment can reach its

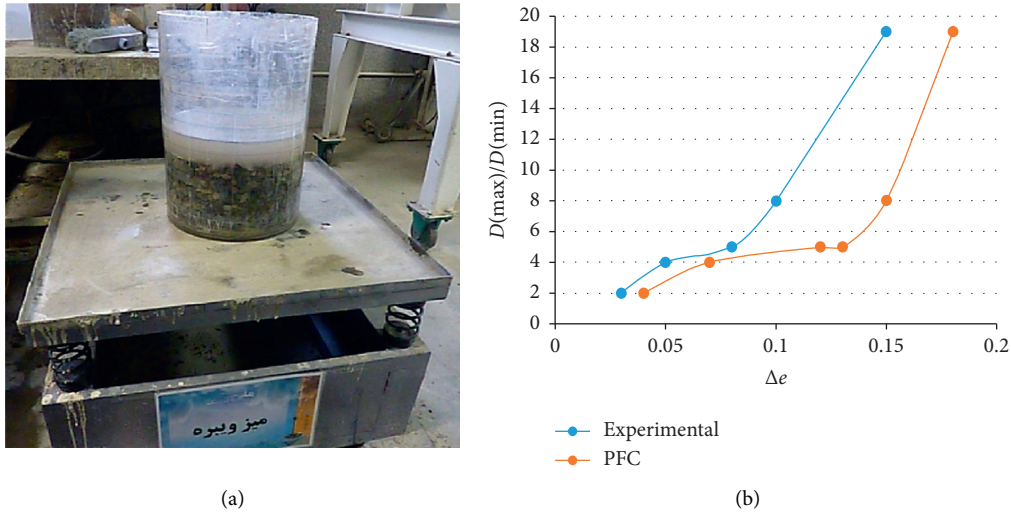


FIGURE 4: (a) Comparison of laboratory results and numerical modeling of Shabanpour and (b) Shabanpour experiment with vibrating table.

maximum specific γ_{\max} gravity and porosity ratio e_{\min} due to vibration and deformation. The smaller the e_{\max} , e_{\min} difference or less, the less γ_{\min} , γ_{\max} congestion will occur. This amount of settling is equal to the product of the “settling coefficient” ($\Delta e/1 + e$) at the height of the embankment, that is, we will have, in equation, the left side of the inequality is equal to the maximum possible subsidence for the embankment due to compaction and the right side of the inequality is equal to the allowable subsidence value of the embankment. The desired allowance was calculated. Torabi research [3] was performed in the continuation of Shabanpour research and in a laboratory (Figure 5). In Torabi research, the flowability, ease of application of self-compacting materials, and the effect of granulation of self-compacting materials were investigated (Figure 6). Experiments similar to self-compacting concrete flow tests were selected and performed on several different types of granulation [11].

Torabi investigated the effect of granulation on the self-compacting properties of materials using compaction experiments. His aim was to investigate the self-compaction of materials with different granulations. Material grading was selected from Shabanpour grading [2, 3]. He found that, in addition to the aggregation of aggregates, the performance requirements for self-compacting aggregates need to be considered because the execution conditions can cause the materials to be in a very loose or very dense state [16]. In other words, the aggregation of the materials may be such that the difference between the maximum and minimum porosity ratios is small, but the way the materials are poured can cause the materials to be in a loose state. After the studies of Shabanpour [2] and Torabi [3] as well as the results of Kobrinovski and Ishihara [4], Keshtpour [4] research was carried out in order to eliminate the variable of aggregate shape and to study the behavior of self-compacting materials with ideal materials (metal balls). The materials used in this study were metal spheres with diameters of 2.5, 5, 10, and 20 mm and an example of cultivation experiments is shown



FIGURE 5: An example of Torabi L-Box experiment.



FIGURE 6: An example of “Keshtpour” experiments.

in Figure 5 [4, 8, 9]. He found that, in ideal materials, regardless of how the material precipitates, the relative settlement of the material increases with the nonuniformity of the granulation, and the more uniform the granulation, the denser the material itself. In ideal materials, the larger the grain size, the denser the material itself [17]. In ideal

materials, the more uniform the granulation, the smaller the difference between the loose and dense porosity ratios, and as a result, the self-compacting materials. In ideal materials, the larger the grains, the smaller the difference between the loose and dense porosity ratios and the denser the self-compacting materials [4].

2. Material and Methods

As mentioned earlier, extensive research has not been conducted on self-compacting materials. Laboratory studies are a good way to start exploring new topics. In this research, laboratory studies using round and sharp-grained grains have been used to investigate the hypothesis of self-compacting materials in reality to study the effect of grain shape on self-compacting properties [18]. As mentioned in previous sections, this study examines cultivation experiments with real materials and compares the results of ideal and real materials. Due to the fact that there is no method developed in the existing standards for laboratory study of self-compacting materials, the study and laboratory study of ideal materials were performed according to ASTM standard tests. With the help of these experiments, loose and dense porosity ratios were calculated. The full description of these experiments, materials, tools, and methods of their implementation is the subject of this section.

2.1. Selection of Tests and Materials. As mentioned in the previous section of this study, self-compacting materials in theory are materials in which the difference in porosity ratio in the densest and weakest state is small. The experiments of this study were performed similar to the standard experiments of ASTM (D-4253-93 and D-4254-91) [12, 13] because, with the help of these experiments, the maximum and minimum porosity ratios can be calculated. Therefore, in this study, loose and dense porosity ratios are investigated in this way. In Shabanpour and Torabi research studies, despite the importance of grain shape on compaction operations, these variables were not studied [2, 3]. In Keshtpour research, using completely spherical grains as ideal materials, the hypothesis of self-compacting materials regardless of the shape of the grains was investigated so that the variables “sharpness” and “sphericity” have no effect on compaction operations. This study showed that even assuming that the materials (metal spheres) are completely ideal, the initial and small compaction energy is still needed to achieve the densest state of the materials [4]. This study was conducted to compare the results of cultivation with ideal materials and sharp and round aggregates.

2.2. Materials Used. In this research, two types of materials are used: round and sharp. The round materials of this research are alluvial and river materials from around Tehran. Sharp-angle materials are also broken materials in Sangshahr Rey mine. Sharp and round materials are divided into 4 groups in terms of dimensions. These 4 groups have the same cultivation granulation for ideal materials [4], which can be seen in Figures 7 and 8.



FIGURE 7: Round corner materials used.



FIGURE 8: Sharp corner materials used.

2.3. Testing Tools. In this study, it is very important to observe the placement of materials after precipitation and the trend of their volume change during the vibration period, so the materials were poured into two cylindrical containers made of Plexiglas sheet with a thickness of 5 mm and diameters of 100 and 150 mm (Figure 9). To create a dense state, according to ASTM D-4253 standard, 14 kPa of overhead is required [8, 9].

3. Analysis of Results

3.1. Effect of Grain Size on Relative Settlement. Figure 10 shows the relative settlement of materials for each experiment for funnel precipitation and sudden precipitation, respectively.

As can be seen from Figure 10, in uniform granulation, the relative settlement of the aggregates decreases with increasing grain diameter, which means that as the aggregate diameter increases, the aggregates have less settling and more self-compacting properties. Also, by comparing the diagrams of round and sharp materials in each precipitation method, it can be seen that roundness has a positive effect on the self-compacting properties of materials, and the more rounded the materials are, the more self-compacting properties. Another conclusion that can be seen from Figure 11 is that the sudden precipitation method causes initial self-compaction in the materials due to the initial energy from the precipitation that the materials apply to themselves. The precipitation method will be fully explained as follows.



FIGURE 9: Cylindrical Plexiglas containers used.

By comparing Figures 12(a)–12(d), it can be seen that the more nonuniform the grain size of the materials, the further away from the self-compacting materials. In other words, the greater the distance between the composite grains, the lower the self-compaction. In general, it can be said that materials with completely uniform granulation have the highest self-compacting properties. Another result that can be seen from Figure 12 is that the higher the ratio of the largest to the smallest aggregate in the granulation, the shorter the relative settling distance between the round and sharp corners. In other words, the higher the ratio of the largest to the smallest aggregate in the aggregation, the less the aggregate shape variable plays a role in self-compaction, and that aggregation has a non-self-compacting property.

3.2. Effect of Grain Size on the Amount of Porosity. Figure 13 shows the difference in porosity ratios between loose and dense materials for each experiment for funnel precipitation and sudden precipitation, respectively.

As can be seen in Figure 13, in uniform granulation, with increasing grain diameter, the difference in porosity ratio between loose and dense materials decreases, which means that as the aggregate diameter increases, the materials settle less and have more self-compacting properties. Also, by comparing the diagrams of round and sharp corners in each precipitation method, it can be seen that roundness has a positive effect on the self-compacting properties of the materials, and as observed in the relative settling diagrams of materials, the more rounded the materials are, the more self-compacting. Another conclusion that can be seen from Figure 14 is that the sudden precipitation method causes initial self-compaction in the materials due to the initial energy from the precipitation that the materials apply to themselves. The precipitation method will be fully explained as follows. A noteworthy point from Figure 14 is that, in experiments with 20 mm grains, the amount of porosity ratio increased, which indicates the effect of the role of the size on the ratio of the diameter of the test vessel to the grain diameter. According to Figure 14 and according to dimensions of utensils, it can be said that to achieve the desired results and eliminate the factor affecting the size of the container, the ratio of container diameter to maximum grain size of materials should be at least 15 (container diameter 150 mm and grain size 10 mm) so that the grains do not get stuck to be.

By comparing Figures 15(a)–15(d), it can be seen that the more nonuniform the grain size of the materials, the difference in the porosity ratio in the loose and dense states increases and the materials move away from self-compaction. In other words, the greater the distance between the composite grains, the lower the self-compaction. In general, it can be said that materials with completely uniform granulation have the highest self-compacting properties. Another result that can be seen from Figure 15 is that the higher the ratio of the largest to the smallest aggregate in the granulation, the smaller the difference in the ratio of porosity in the loose and dense states of round and sharp materials. In other words, the higher the ratio of the largest to the smallest aggregate in the aggregation, the less the aggregate shape variable plays a role in self-compaction, and that aggregation has a non-self-compacting property.

3.3. The Effect of Precipitation on Relative Subsidence. Comparing the results of Table 1, due to the lower coefficient of variation in the method of sudden rainfall, this method will have better reproducibility. Also, by comparing the results in different precipitation methods, it can be said that, in most results, the sudden precipitation method has helped the self-compaction of materials and has reduced the amount of settling after the test.

Larger aggregates have less self-compaction than smaller aggregates. Of course, it should be noted that this difference in the amount of sitting is not significant, and there is a possibility of error. In general, for the reasons listed below, the sudden precipitation method is more appropriate for conducting experiments and achieving greater self-compaction.

3.4. Energy Required for Final Compaction. Experiments 1 to 40 showed that the materials reached their maximum density in much less than 8 minutes. For this purpose, the experiment in Figure 16 is performed to study about the relative settling over time considering uniform granulation. The experiments were performed in the previous conditions with the method of sudden precipitation, but after the start of the experiment, the VB device was turned off every 4 seconds and the amount of settling was measured. The results of these experiments and their diagrams are as follows. Table 1 lists the amount of time required for the final density of each sample.

From Figure 16, it can be concluded that the larger the aggregate size, the more time is needed for the material to compact. In other words, according to Keshtpour results, where the hypothesis of fully self-compacting materials does not exist and the initial energy is required to achieve ideal self-compaction [4], the larger the aggregate size, the more initial energy is required to achieve maximum compaction. Another noteworthy thing that can be seen from Figure 16 is that sharpness increases the amount of time required to reach the final density (Figure 17). In the following, compaction time diagrams for mixed granulation materials will be presented (Figure 18).

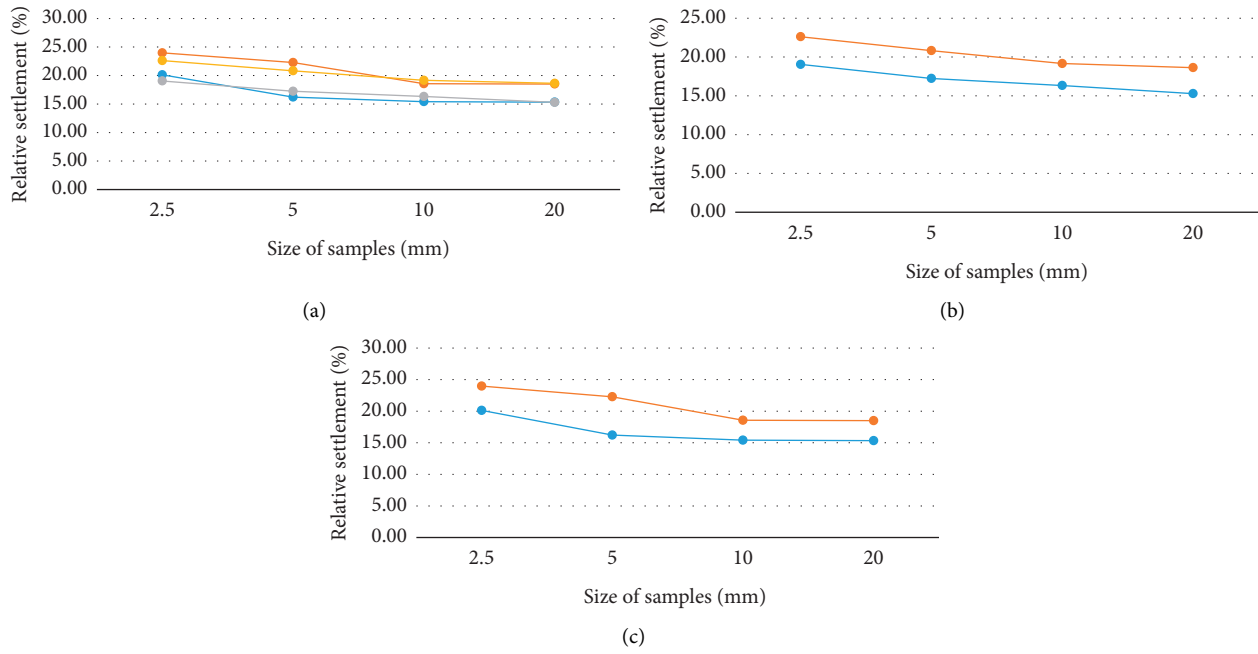


FIGURE 10: Relative settlement of uniform granulation materials by funnel and spoon precipitation method, sudden precipitation, and comparative precipitation.

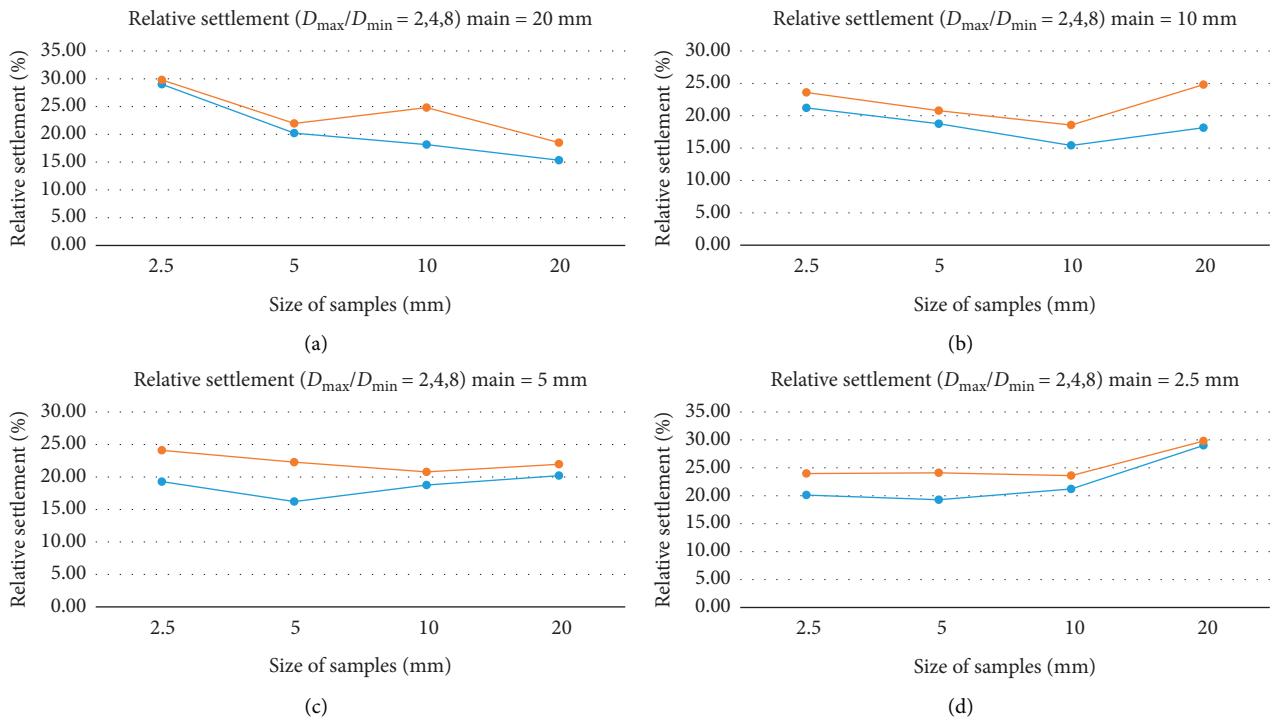


FIGURE 11: Relative settlement of aggregates for different granulations by funnel and spoon precipitation method (half weight of materials, aggregates with sizes of 2.5, 5, 10, and 20 mm).

3.5. Calculation of Energy Required for Density. To better understand the amount of energy applied to the samples in the experiments, the amount of energy per unit volume of materials is calculated in this section. Using equation (3),

energy is calculated for each oscillation. In this regard, W and f , the motor power and frequency of the VB table, are used in the University of Tehran, respectively [14]. In this regard, v is the volume of materials. Using equations (3) to

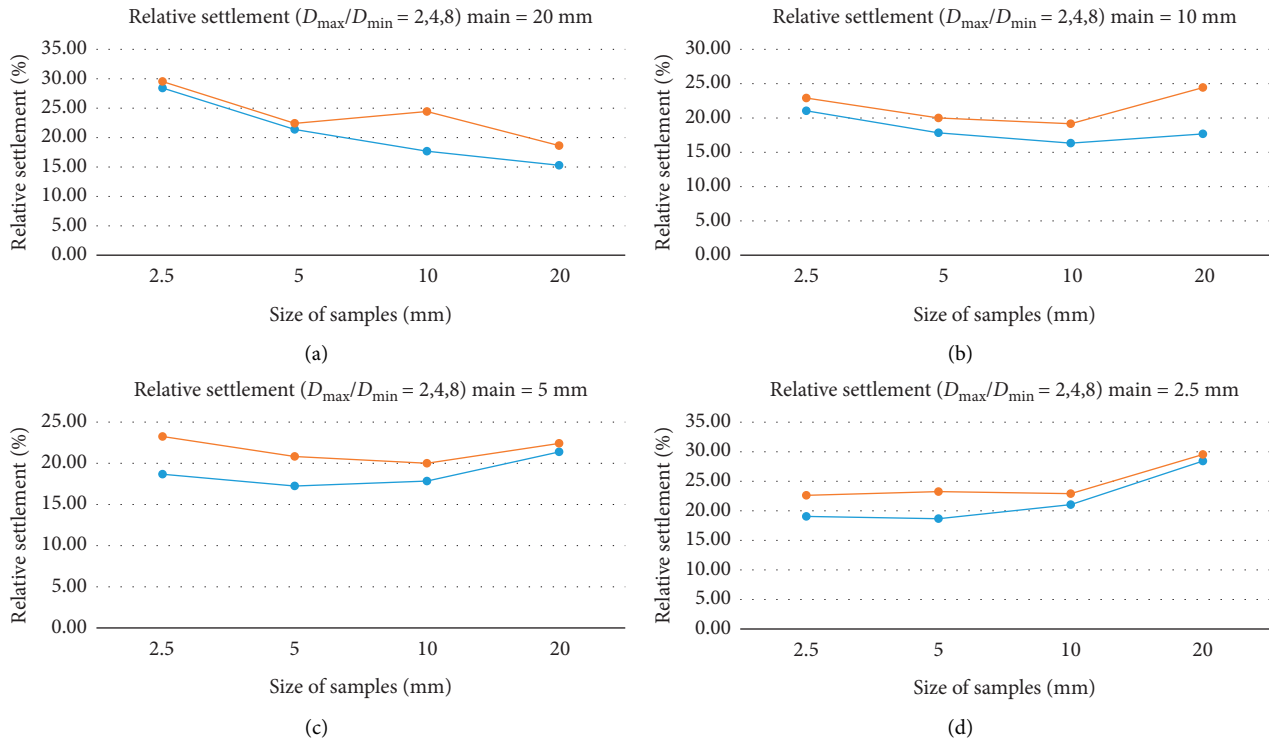


FIGURE 12: Relative settlement of materials for different granulations by sudden precipitation method (half weight of materials, aggregates with sizes of 2.5, 5, 10, and 20 mm).

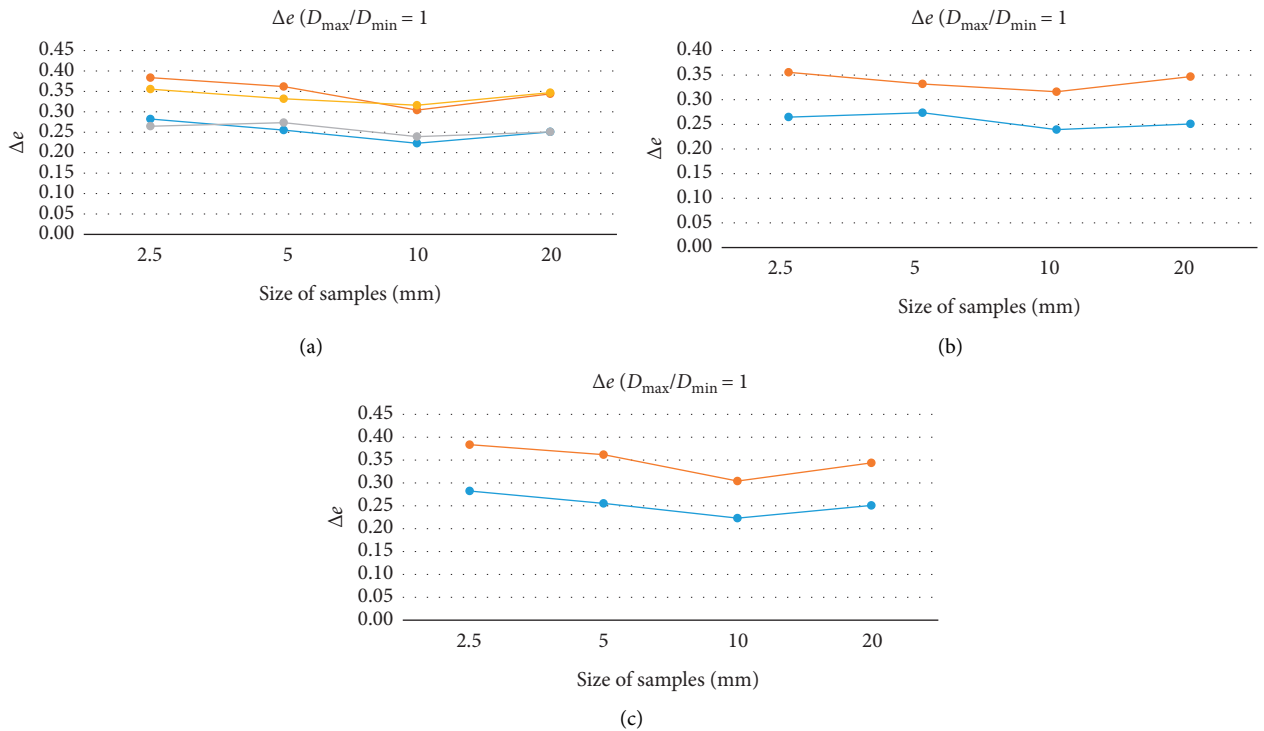


FIGURE 13: Difference in porosity ratios between loose and dense materials with uniform granulation by funnel and spoon precipitation, sudden precipitation, and comparative precipitation.

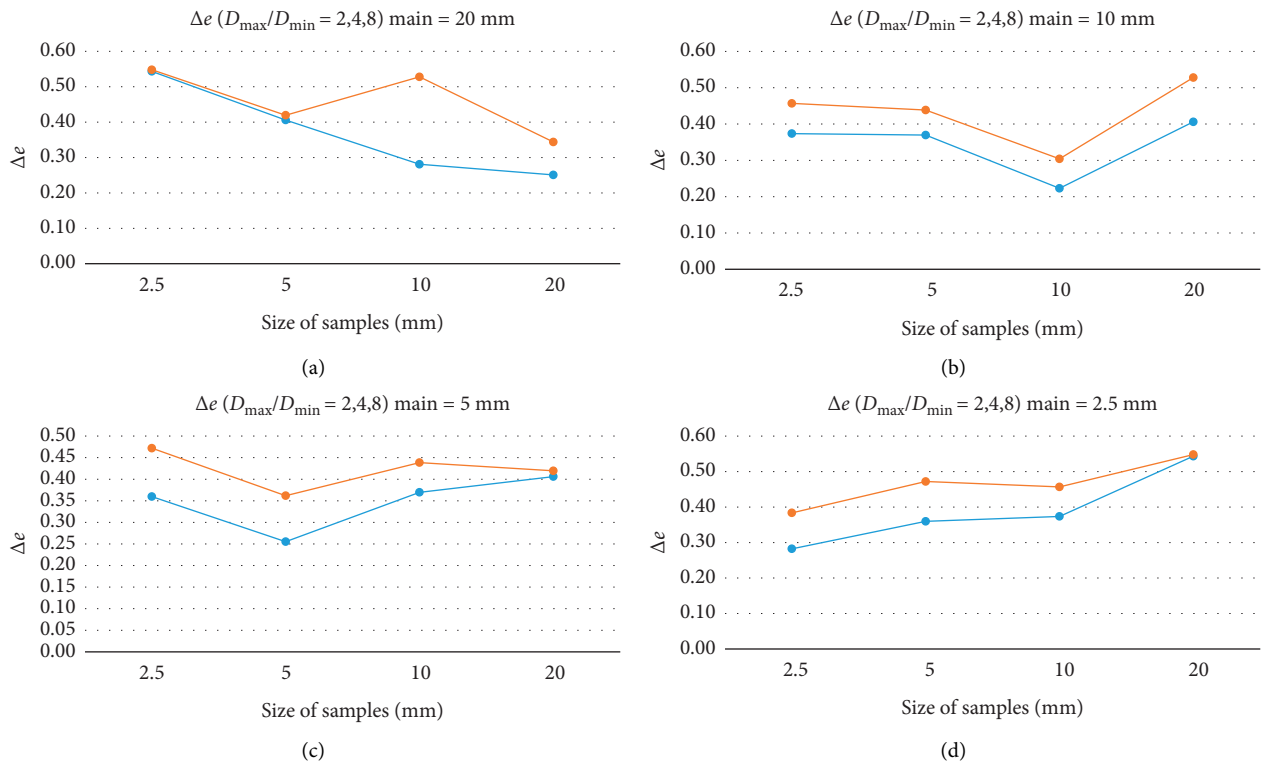


FIGURE 14: Difference in porosity ratio between loose and dense materials with different granulations by funnel and spoon precipitation method (weight installation of aggregates, aggregates with sizes of 2.5, 5, 10, and 20 mm).

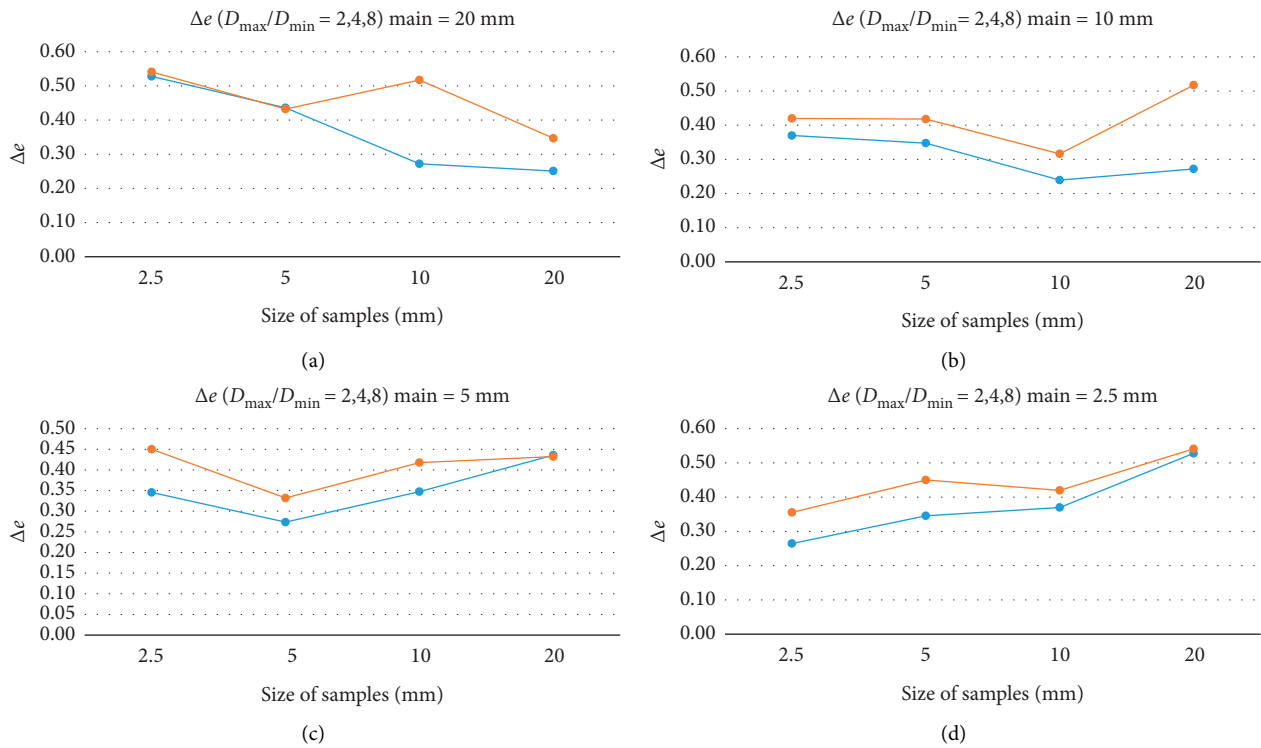


FIGURE 15: Difference in porosity ratio between loose and dense materials with different granulations by sudden precipitation method (weight installation of aggregates, aggregates with sizes of 2.5, 5, 10, and 20 mm).

TABLE 1: Relative settling difference in two precipitation modes.

Grading	Relative meeting amount		The size of the relative meeting difference
	Funnel	Sudden	
2.5	20.13	19.05	1.08
5	16.22	17.24	1.03
10	15.41	16.33	0.91
20	15.34	15.29	0.05

(5), the total energy per unit volume of the material is calculated. In this regard, t is the duration of vibration and T is the period of rotation is vibrational motion.

$$\text{energy}_{(\text{cycle})} = 1000 \times \left(\frac{W}{f} \right) = 4.17 \text{ Joules}, \quad (3)$$

$$\frac{E}{V} = 5635.14 (\text{J}/\text{m}^3), \quad (4)$$

$$\left(\frac{E}{V} \right)_{\text{total}} = \frac{E}{V} \times \frac{t}{T} = 4057.3 (\text{kJ}/\text{m}^3). \quad (5)$$

By comparing Figures 19(a)–19(d), it can be concluded that the larger the aggregate size, the more energy is required for the compaction of materials. Sharp-angle specimens also require more energy than round specimens to achieve final density (Figure 19).

3.6. Description of Tombak Port Project. Tombak service port is located near Tombak village on the northwest coast of the Persian Gulf and at the coordinates of 52,203 easts and 27,702 wests. This port has been constructed about 250 km southeast of Bushehr port. Figures 20 and 21 show a view of Tombak port and the location of Tombak port on the shores of the Persian Gulf, respectively.

3.7. LPG1 Dock. Figure 21 shows the location of the LPG1 and LPG2 wharves, which are located in the western breakwater of Tombak port, as well as the sulfur wharf, which is located in the eastern part of the port. The length and width of the LPG1 pier are 90 and 21 meters, respectively. The structural system of this pier includes 3 caissons with a length and width of 30 and 21 meters. Figure 20 shows the plan and cross section of the LPG1 wharf [16]. Also, the geotechnical profile of the berths is presented in Table 2.

3.8. Limitations of Choosing Land Improvement Method for Kisoni Wharves in This Project. As mentioned above, the berths studied in this project consist of a number of quays. The method of improvement in each project should be selected according to the executive and economic issues. Tombak port improvement project has been carried out at a depth of 15 meters of sea water. As mentioned before, in marine work, due to operational and noneconomic problems, as well as the lack of access to heavy-duty compact machinery, there are several limitations in choosing the

method of improvement. Improvement at a depth of 15 meters of sea water has been one of the main limitations of land improvement in the land improvement project in Tombak port, which is discussed in the following about the method of improving the pier land in this port.

3.9. Density of Alternative Stone Materials. As mentioned above, alternative materials must be compacted with little energy. The compaction of stone materials was done by hammering metal piles using a vibrating hammer (Figure 22). Piles with a diameter of 48 inches were inserted into the alternative material and pulled out at low speed [16, 17]. Figure 23 shows a schematic of the piling and a view of the piling operation at the port of Tombak, respectively [18].

After pouring the alternative materials, 48-inch candles were vibrated at a distance of 8 meters (center to center) within the caisson installation area and exited at low speed. The time of sinking and pulling out the candles was also recorded. Secondary piling was also plunged into 5 candles under vibration and pulled out to evaluate the density in the initial stage. Figures 24 and 25 show the plan of piling in the first and second stages, respectively [19].

The sinking times of the primary piles in the caisson range (R5-8) and secondary piles in the caisson (R5-8) are shown in Figures 26 and 27, respectively. Increasing the sinking time of secondary piles compared to primary piles (approximately twice) indicates an improvement in the density of alternative materials due to the pounding of primary piles (Figures 26 and 27). Also, comparing the sink time of 5 secondary piles with each other shows that the values are not much different from each other, which indicates a relatively equal density of the replacement layer [19].

Table 3 shows the average time of sinking and pulling out the piling in both stages [16]. Increasing the sinking time of the piling in the second stage compared to that in the first stage and also increasing the total vibration time (total sinking and pulling out the piling) in the second stage indicate an improvement in the compaction condition of the alternative materials.

3.10. The Results of Measuring the Meeting of the Caissons. After installing the LPG1 dock quays, four points of the quill (R5-8) were selected as monitoring points. The plan of caisson and its monitoring points are presented in Figure 28. Monitoring data including cumulative sessions on 12 different days are presented in Figure 28. It can be seen that the daily sitting of the caisson at the monitoring points was initially high but gradually decreased (Figure 28). On the eighth day of the measurement (September 22), the daily meeting was almost zero and then very small (Figure 29). The caisson summit also had an upward trend in the early days but did not increase after 9/21.

3.11. Discussion on Compaction and Settling of Alternative Materials at LPG1 Docks. The compaction of the materials was sufficient to withstand the design loads of both berths [19, 20] but an examination of the LPG1 berth cumulative

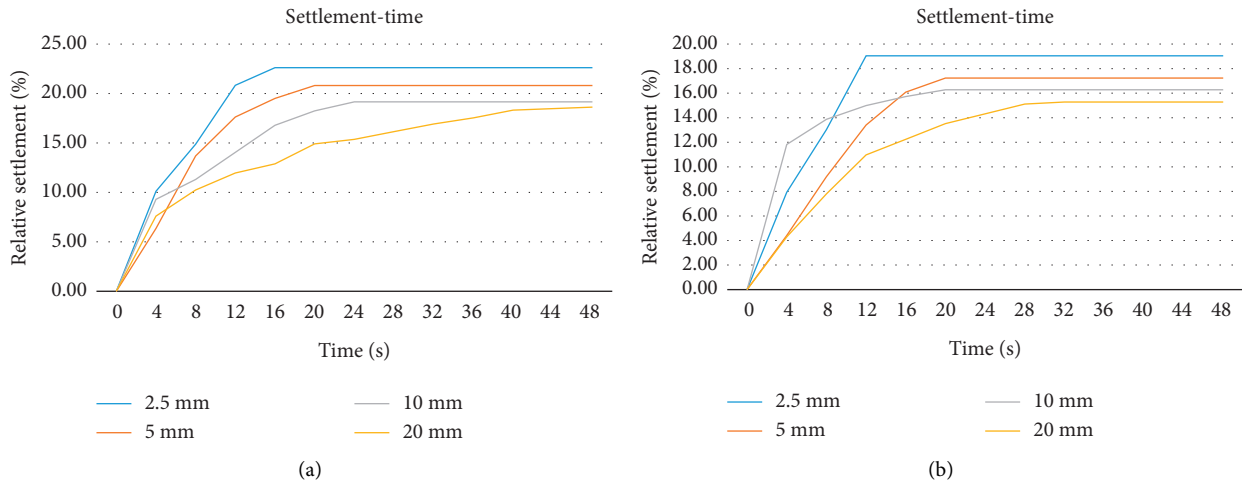


FIGURE 16: Percentage of relative settlement over time for round and sharp corner aggregates with uniform granulation.

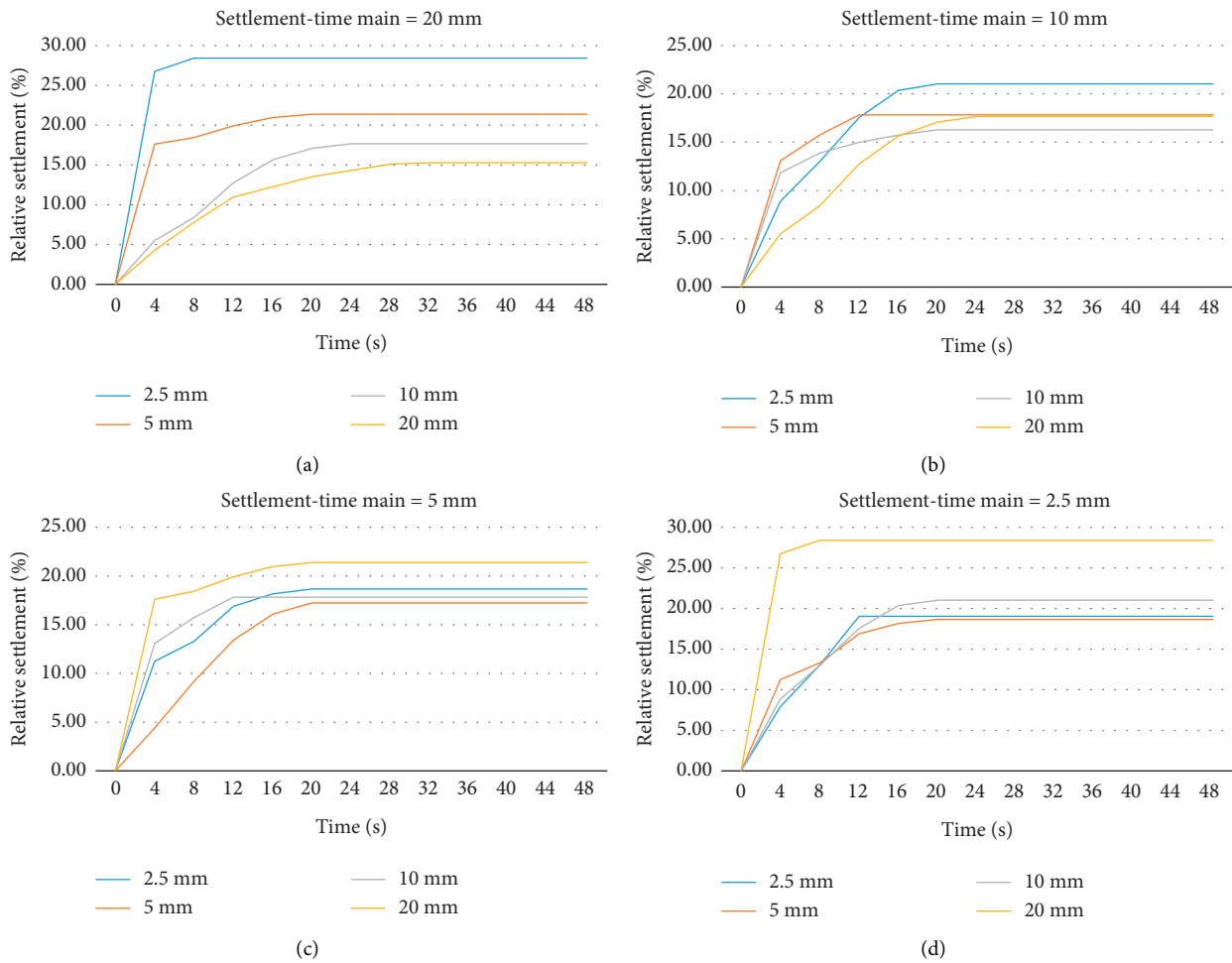


FIGURE 17: Percentage of relative settlement over time for rounded aggregates with a weight mixture equal to 2.5, 5, 10, and 20 mm.

diagram shows that some subsidence occurred at the LPG1 berth due to abnormal loads such as piling on the berth or other work. Therefore, it was decided to increase the density

of vibrating materials at the sulfur pier. By doing this, the aggregation of materials in the sulfur pier was less than that in the LPG1 pier. It can also be seen that the assembly of

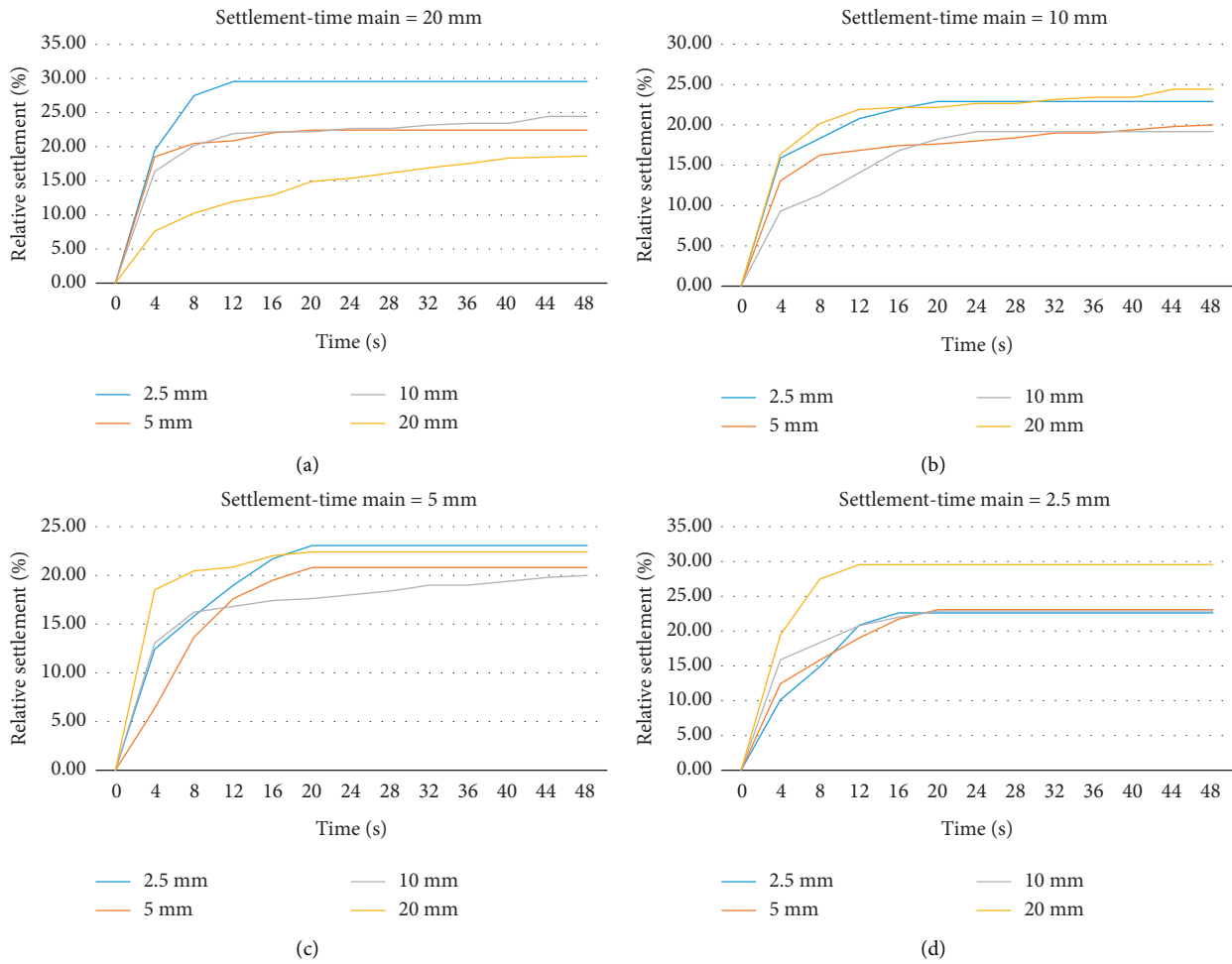


FIGURE 18: Percentage of relative settlement over time for sharp corner aggregates with a weight mixture equal to 2.5, 5, 10, and 20 mm.

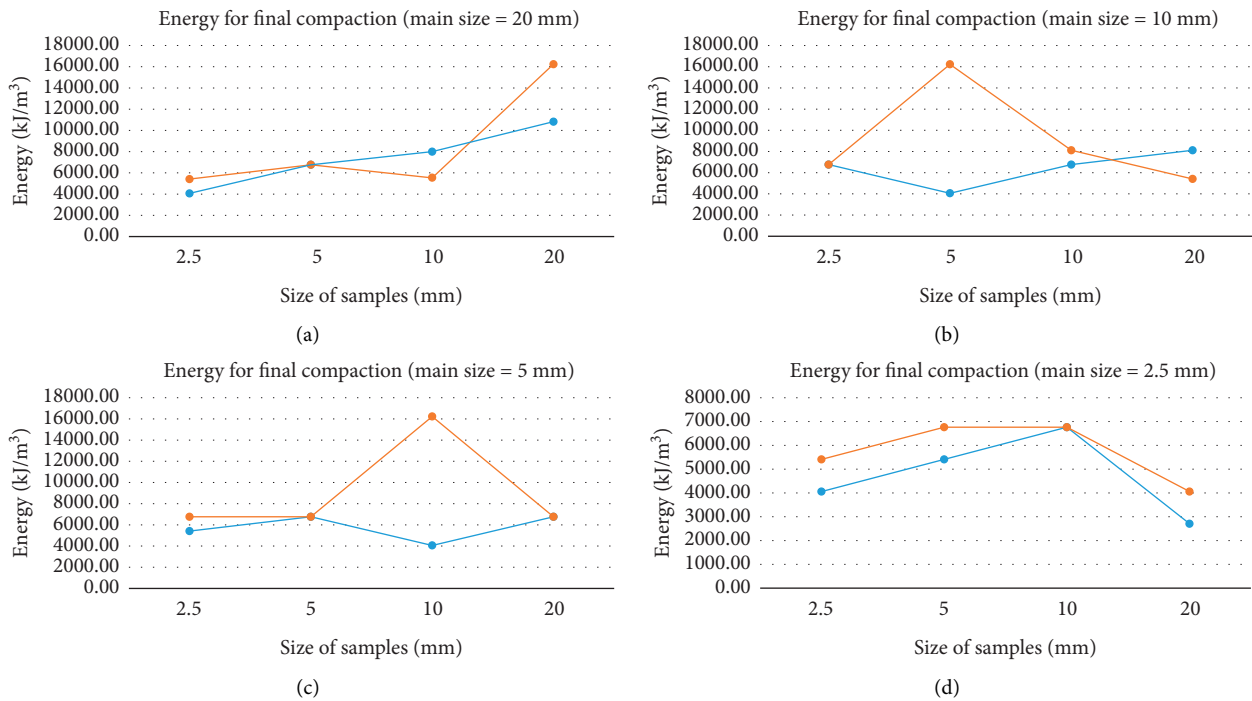


FIGURE 19: The amount of energy required for mixed materials with a weight ratio equal to 2.5, 5, 10, and 20 mm.



FIGURE 20: View of the current Tombak export port.

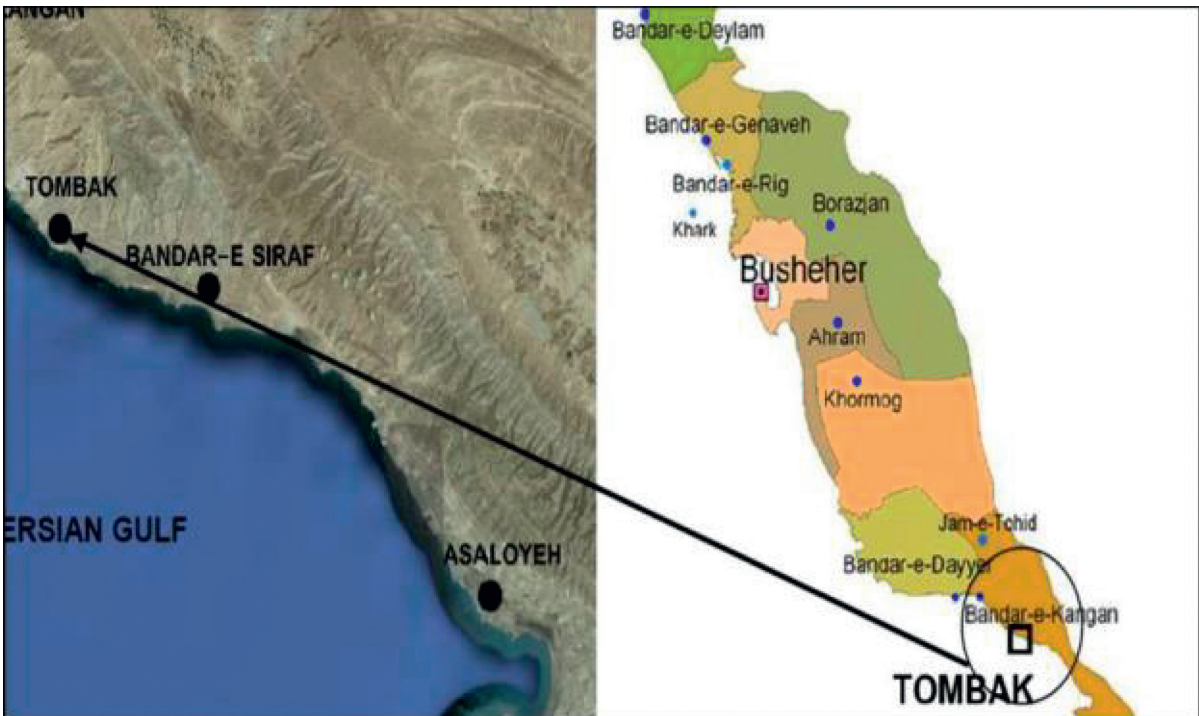


FIGURE 21: Location of Tombak port on the shores of the Persian Gulf.

sulfur pier materials has stopped after about 2 months. The compaction of rock materials over time is caused by vibrations and machinery and the like and possibly waves. Of course, the deposition of fine materials under stone materials also causes subsidence.

3.12. Comparison of Energy Requirements for Tombak Project Density and Laboratory Results. As previously explained, improvements in Tombak service port projects have not been easily possible due to maritime operating conditions. Therefore, by combining the use of alternative and relatively

TABLE 2: Geotechnical profile of LPG1 wharf.

Layer thickness (m)	Layer type	Φ' (deg)	Cu (kPa)	E (MPa)
1.5	Rubble mound	—	—	—
7.5	SM/SC	33	—	12
14	CL/CL-ML	—	125	29
18	SM/SC	37	—	94
4	CL	—	400	45
6	SM/SC	34	—	88



FIGURE 22: View of the piling at the docks of Tombak port.

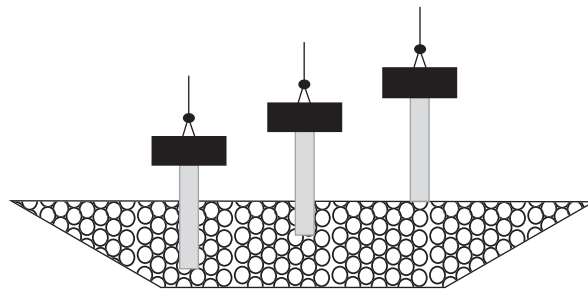


FIGURE 23: Schematic diagram of the density of alternative materials by piling and vibrating operation.

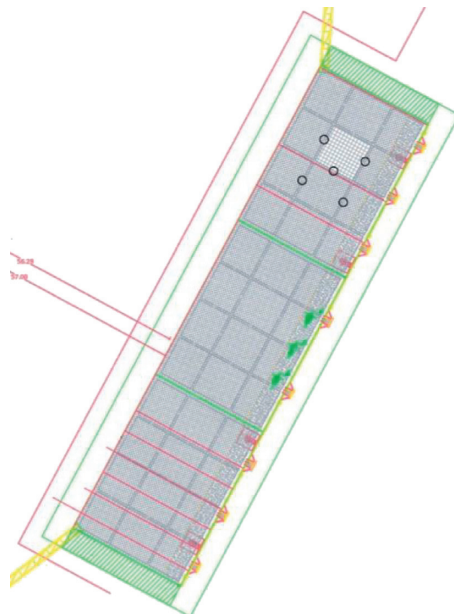


FIGURE 24: Plan of the first-stage piling.

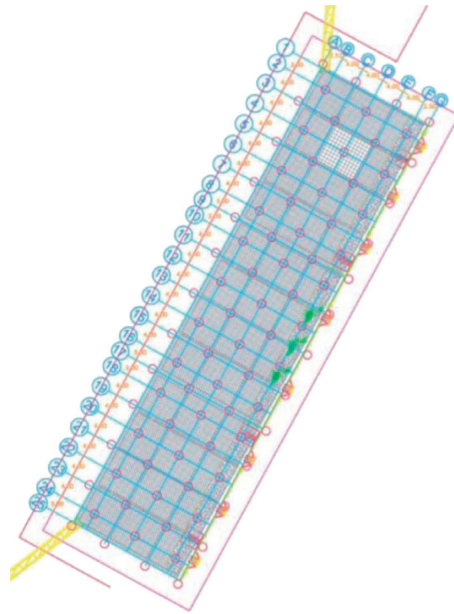


FIGURE 25: Plan of the second-stage piling.

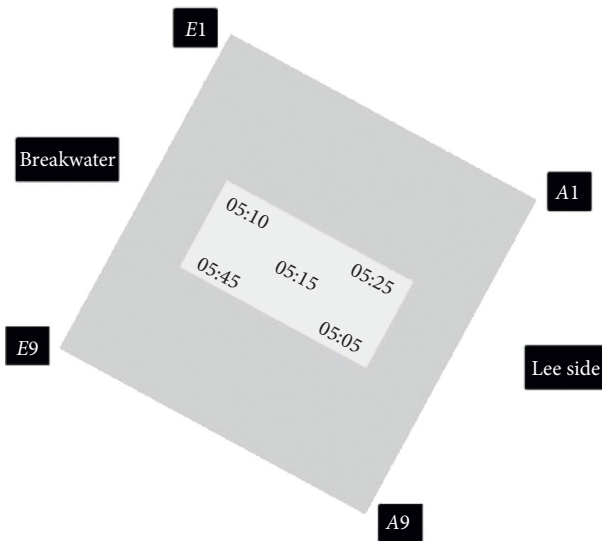


FIGURE 26: The sinking time of the first-stage piling in the range of caisson R5-8 in minutes.

self-compacting materials and compaction operations, improvements were made in this project. In the operation of compacting the alternative materials of LPG1 wharf, the energy per unit volume was equal to 349 kJ/m^3 , which was not enough to place the alternative materials in a completely dense condition. Although the amount of material density was sufficient for the pier, knocking the pile near the pier caused a slight subsidence. Comparing the results of Table 4 and the energy required for sulfur dock compaction, it can be seen that the energy applied to the alternative materials in the sulfur dock is in accordance with the minimum energy required to reach the self-compacting material, to its final density, and as expected with increasing the diameter of the aggregates, the energy required for compaction per unit

volume has also increased. A comparison of the results of energy calculation from the laboratory method and the docks of Tombak port is given in Table 4.

As can be seen in Table 4, it can be seen that the energy required for the compaction of alternative materials at the sulfur dock was close to the laboratory results and, as expected, the amount of sulfur dock settlement was much less than at the LPG1 dock. A noteworthy point in laboratory samples is that some laboratory conditions can affect the results. For example, the size of the test vessel can affect the results of the energy test because as the diameter of the aggregates increases and the diameter of the vessel remains constant, the space available for the aggregates to move decreases and they may lock together after a while. Also, by

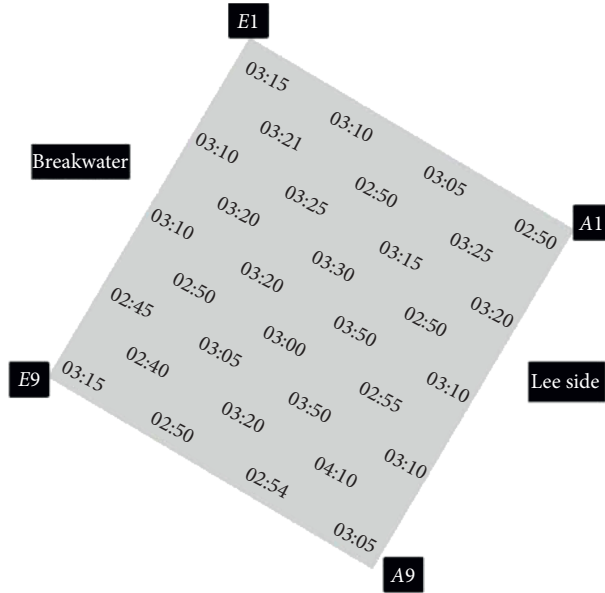


FIGURE 27: The sinking time of the second-stage piling in the range of caisson R5-8 in minutes.

TABLE 3: The average time of sinking and pulling out the piling in the alternative materials in the first and second stage.

The level	Submerged (seconds)	Pull out (seconds)	Submerged and pull out (seconds)
First stage	196	400	596
Second stage	320	350	670

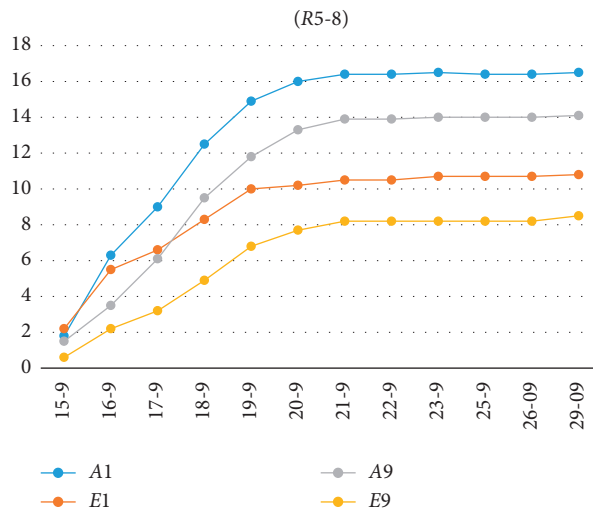


FIGURE 28: Caisson cumulative meeting on different monitoring days in centimeters.

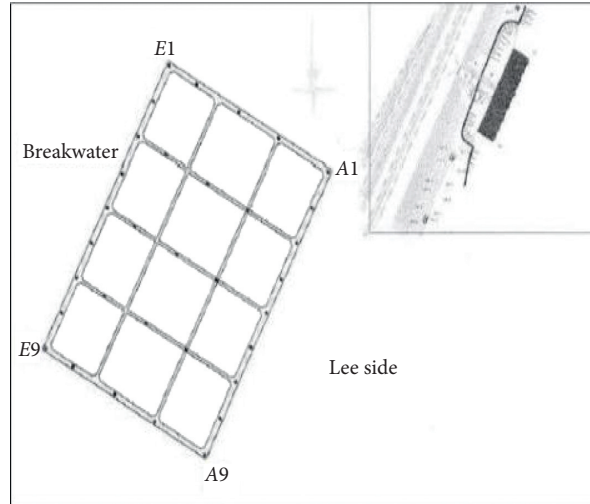


FIGURE 29: Caisson plan location of monitoring points.

TABLE 4: Energy results per unit volume for compaction in laboratory samples and Tombak port docks.

Test number	Energy per unit volume (Kilojoules per cubic meter)	The name of the pier	Energy per unit volume (Kilojoules per cubic meter)
46	10819	Sulfur	9486
56		LPG1	

comparing the results of Table 4 and the energy required for sulfur dock density and the energy results per unit volume of cultivar [4], it can be seen that the energy required per unit volume to achieve the maximum density of ideal metal spheres is much higher than the energy required per unit volume. The aggregates are round and sharp. The reason for this is the very high weight of metal spheres compared to aggregates, which affects the results.

4. Conclusion

The main purpose of this study is to investigate the idea of self-compacting materials in real materials and the conditions affecting these materials, including the effect of grain shape, and also to compare the results of ideal and real materials. The more uniform the aggregation of the stone material or the lower the “maximum to minimum grain size ratio,” then the relative aggregation of the material decreases due to vibration and the more compact the material is. The dimensions of the grains affect the placement and compaction of the materials in the loose state. As the grains get bigger, the energy that the grains give to each other when they are emptied increases, so the materials become denser. Therefore, the larger the seeds, the denser they become after being in place. Materials that are cast quickly are, firstly, self-compacting and, secondly, their results are more reproducible. During the experiments, observing the materials, it was found that the materials reach the densest possible state in a maximum time of 48 seconds and with an energy of 4 to 16 thousand kJ/m^3 on a web table with a frequency of 60 Hz. Observing the results of additional experiments (precise picking of the grains in the container by hand), it became

clear that even in these conditions, it is not possible to place the ideal size of materials in completely dense conditions. In general, experiments on real materials of equal roundness and sharpness have shown that even these materials do not become completely self-compacting after casting, and some energy is required for their compaction. Of course, this energy is much less than materials with different grains. The energy required to reach sharp corners is self-compacting, more than round materials. Due to the necessity of performing compaction operations due to the lack of fully compacted materials, it is better to use the term “semi-self-compacting materials.” The results of experiments on round and sharp-grained aggregates regarding the effect of maximum to minimum grain size ratio and the effect of grain size were in good agreement with ideal materials. In other words, there is no real self-compacting material in practice, but the idea of semi-self-compacting material is also applicable.

Symbols

S :	Standard deviation
\bar{X} :	Average data (X)
V_v :	The volume of empty space between the aggregates (m^3)
V_s :	The volume of aggregates (m^3)
ω :	Angular velocity (rad/s)
A :	Oscillation range (m)
e :	Porosity ratio
D_{\max} :	The diameter of the largest aggregate (mm)
γ_{\max} :	Maximum specific gravity (kg/m^3)
H_1 :	Initial height of materials before vibration (mm)

W_s : Weight of materials (kg)
 C_v : Coefficient of variation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request via m.mohaddespour@ut.ac.ir.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

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