

One-dimensional compression and consolidation parameters of soil-quarry dust mixtures

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ABSTRACT: Quarry dust is the finest stone material formed by the mechanical crushing of rocks, such as dolomite, basalt, marble, granite, or melaphyre. The grain size distribution of the crusher dust is directly related to the source of origin and depends on the crushing process used. Due to its specific gradation, stone dust is frequently classified as a solid waste material, which requires expensive and problematic disposal. Considering the purposes of sustainable engineering, such as minimizing the depletion of natural resources, utilizing environmentally friendly materials, and preventing waste, the implementation of quarry dust becomes a highly beneficial and desirable practice. An example of a stone dust application that perfectly meets the objectives of sustainable engineering is its use as a substitute for mineral soils. The one-dimensional consolidation test is one of the typical tests conducted for soils. It enables the determination of compression and consolidation parameters, such as compression and recompression indexes (C_c and C_r), or coefficient of consolidation (c_v), which are crucial to estimating the magnitude and duration of settlement. The study aims to investigate the effect of admixing granite, melaphyre, and basalt dust on the compression and consolidation parameters of mineral soil. A series of oedometer tests were performed. Samples of untreated non-cohesive soil and specimens containing 5%, 10%, and 15% quarry dust by dry mass of soil were tested. The laboratory research enabled the selection of the most beneficial amount and type of crusher dust, considering one-dimensional characteristics.

KEYWORDS: Sustainable engineering, waste materials, quarry dust, oedometer tests.

1 INTRODUCTION

Quarry dust, also known as crusher dust or stone dust, is the finest material formed by the mechanical crushing of rocks, such as dolomite, basalt, marble, granite, or melaphyre. The mineral and chemical composition of the crusher dust is the same as the composition of the rock from which it originated. Whereas its grain size distribution is directly related to the source of origin and depends on the crushing process used. Due to the specific gradation, stone dust is frequently classified as a solid waste material, which requires expensive and problematic disposal.

The use of quarry dust is a highly beneficial and desirable practice, especially considering the purposes of sustainable engineering, which is one of the biggest challenges of recent years. Generally, the primary goals of sustainable engineering include protecting the natural environment and securing future generations. The mentioned purposes can be achieved by developing and improving natural geosystems, applying life-cycle thinking, using environmentally friendly materials and energy, preventing waste, minimizing the depletion of natural resources, and implementing innovative solutions (Abraham, 2006).

Stone dust, though categorized as a waste material, has a variety of applications. In construction engineering, it is used in the production of bituminous and concrete mixtures (Silva et al. 2023; Sutradhar et al. 2015). It functions as a fertilizer and nutrient in horticulture and agriculture (Silva et al. 2005). Additionally, the possibility of the application of quarry dust in soil stabilization is also widely reported. Numerous studies presented in the literature indicate that the addition of stone dust positively affects the physical and mechanical properties of various soil types, reducing plasticity and hydraulic conductivity and increasing the maximum dry density, unconfined compressive strength, and California bearing ratio (Agarwal & Kumar 2015; Okagbue & Onyeobi 1999; Öncü & Bilsel 2018). Furthermore, Öncü & Bilsel (2018) and Sivrikaya et al. (2020) demonstrated that the stone dust admixture influences the reduction of soil compressibility. The researchers analyzed the marble dust inclusion and found that soil-dust mixtures are characterized by a lower primary compression index (C_c) compared to untreated soil. Moreover, studies of

Cabalar & Alosmar (2021) have shown that the dust addition also affects consolidation parameters by increasing the consolidation coefficient (c_v). The encouraging research results presented in the literature motivated the investigations presented in this paper.

The study examined the effect of granite, melaphyre, and basalt dust on the one-dimensional compressibility of mineral non-cohesive soil. The tests were performed on untreated soil and soil with dust contents of 5%, 10%, and 15%. The tests performed in oedometers enabled the determination of compression parameters, including compression and recompression indexes (C_c and C_r , respectively), as well as consolidation characteristics measured by the coefficient of consolidation (c_v). Research was conducted to explore the possibility of using stone dust as a partial substitute for the medium sand, thereby contributing to the development of sustainable engineering.

2 MATERIALS AND METHODS

2.1 Materials

The soil analyzed in this study was collected from deposits located in northeastern Poland. Based on the results of the grain size distribution analysis, it was classified as medium sand. The origin of the tested material is typical of non-cohesive soils formed in Poland, related to the activity of glacial meltwater. Considering the mineral composition, the tested sand predominantly consists of quartz.

Three types of quarry dust were tested in the study: granite, melaphyre, and basalt (Figure 1), sourced from quarries in southern and southwestern Poland. The properties and mineral composition of the considered stone dust are closely related to the characteristics of granite, melaphyre, and basalt rocks. Considering the chemical components, all types of analyzed quarry dust primarily consist of calcium oxide (CaO), silicon dioxide (SiO₂), and aluminum oxide (Al₂O₃).

The grain size distribution curves of the considered soil (S) and granite (GD), melaphyre (MD), and basalt (BD) dust are shown in Figure 2. Figure 2 also presents the values of graining parameters: coefficient of uniformity (C_u) and coefficient of curvature (C_{cu}).

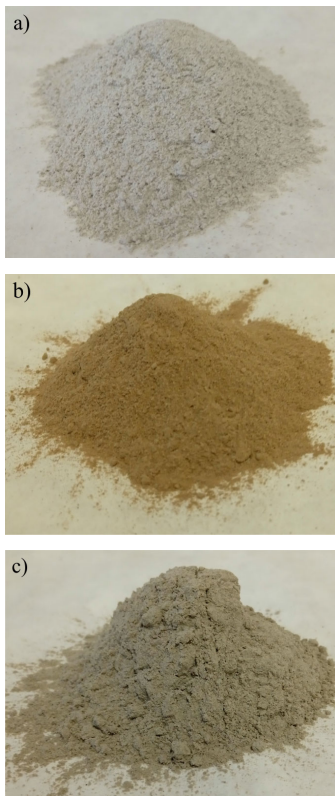


Figure 1. Considered quarry dust: a) granite, b) melaphyre, c) basalt.

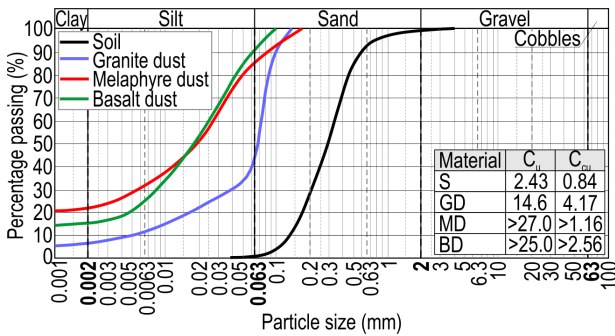


Figure 2. The grain-size distribution curves determined for the tested materials.

According to ISO 14688-1 standard, the gradation of the granite, melaphyre, and basalt dust corresponds to the particle distribution of sandy clayey SILT (saclSi), silty CLAY (siCl), and clayey SILT (clSi), respectively. The values of C_u and C_{cu} coefficients obtained for medium sand classify it as poorly graded. The granite dust is characterized by medium gradation. Meanwhile, the melaphyre and basalt dust can be classified as well-graded.

2.2 Methods

Compression tests were performed on unsaturated samples of medium sand without admixtures and with the addition of 5%, 10%, and 15% granite, melaphyre, and basalt dust to the dry soil mass. Only one type of quarry dust was added at a time. The tested samples were characterized by the maximum dry density (ρ_{dmax}) and optimum water content (w_{opt}). The ρ_{dmax} and w_{opt} parameters were determined using the standard Proctor compaction method. The obtained values of the maximum dry density (ρ_{dmax}) and optimum water content (w_{opt}) are presented in Table 1. Additionally, Table 1 contains the specific dry density (ρ_s) and initial void ratio (e_0) of compacted untreated non-cohesive soil and soil-quarry dust mixtures.

Table 1. Parameters of tested materials.

Material	Parameter			
	ρ_{dmax} (g/cm ³)	w_{opt} (%)	ρ_s (g/cm ³)	e_0 (-)
S	1.722	13.61	2.65	0.539
S+5%GD	1.766	12.90	2.65	0.501
S+10%GD	1.828	11.94	2.65	0.450
S+15%GD	1.832	11.35	2.66	0.452
S+5%MD	1.797	12.46	2.65	0.475
S+10%MD	1.856	11.52	2.66	0.433
S+15%MD	1.880	11.05	2.66	0.415
S+5%BD	1.810	11.96	2.66	0.470
S+10%BD	1.867	11.38	2.66	0.425
S+15%BD	1.920	11.00	2.67	0.391

Compression tests were conducted on cylindrical samples with an initial height of 20 mm and a diameter of 63.5 mm, using oedometers equipped with automatic recording of displacement sensor readings. The specimens were placed in non-deformable rings with porous stones on the top and bottom. The soil and soil-quarry dust mixtures were protected from moisture loss throughout the compression test. The research program included the implementation of the following vertical stresses σ_v : 16, 32, 64, 128, 256, and 512 kPa. The testing process contained the primary loading, unloading, and secondary loading sequences. Based on the test results, the compression and recompression indexes (C_c and C_r , respectively) and coefficient of consolidation (c_v) were determined.

The C_c and C_r parameters were obtained using the dependence of the void ratio (e) on the vertical effective stress plotted in the logarithmic scale ($\log \sigma_v'$), considering the primary loading (C_c index) and unloading (C_r index) sequences. Whereas, the coefficient of consolidation (c_v) was calculated using the square-root-time method (Taylor's method) from the formula given below (Head, 1994).

$$c_v = T_v h^2 / t = T_{90} h^2 / t_{90} \quad (1)$$

where: T_v (T_{90}) is theoretical time factor for 90% of primary consolidation, $T_{90} = 0.848$, h is the length of the maximum drainage path, t (t_{90}) is the time corresponding to 90% primary consolidation, determined from the graph describing the relationship between the settlement of a soil sample and square root of time.

3 RESULTS

Figure 3 illustrates the dependence of the void ratio (e) on vertical stress (σ_v') obtained for the considered non-cohesive soil (S) and the mixtures of soil and granite (GD), melaphyre (MD), and basalt (BD) dust.

The admixture of each of the considered quarry dust influenced the decrease in void ratio, which is directly related to the results of the compaction tests (the obtained ρ_{dmax} values) presented in Table 1. The most significant impact on the e parameter can be observed for a 15% addition of basalt dust (a decrease of void ratio by an average of 27% compared to untreated soil, considering all compression test sequences). Meanwhile, a 15% admixture of melaphyre and granite dust caused a reduction of the void ratio by an average of 23% and 15%, respectively. In comparison, the addition of 5% granite, melaphyre, and basalt dust resulted in a decrease in e values of 4.5%, 8.8%, and 11%, respectively. The effect of quarry dust addition on the compressibility of soil-dust mixtures is even

more clearly evident, considering the values of compression and recompression indexes summarized in Table 2.

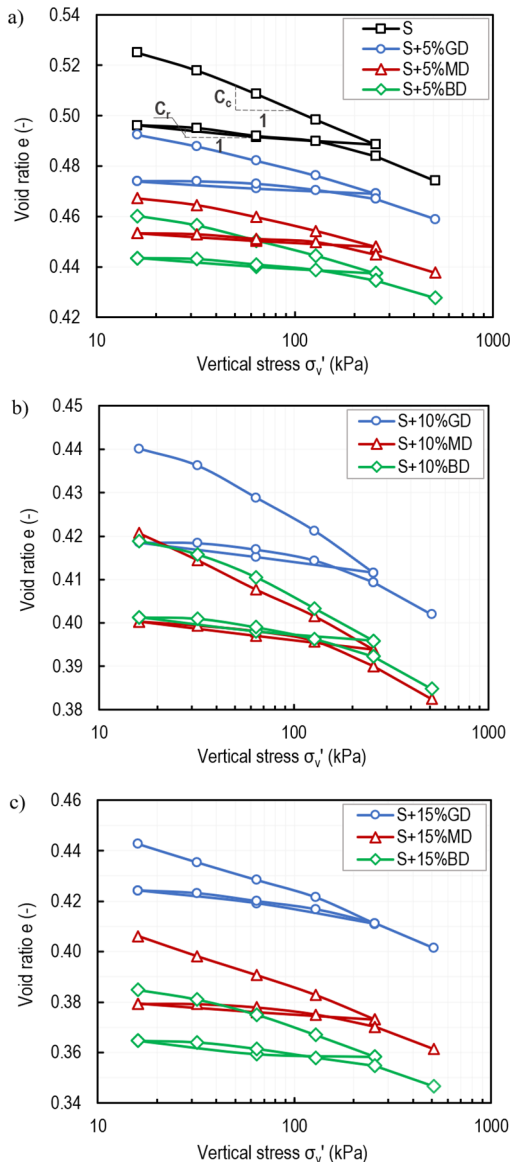


Figure 3. The $e-\sigma_v'$ relationships obtained from one-dimensional compression tests for soil and soil-dust mixtures: a) 5% dust addition, b) 10% dust addition, c) 15% dust addition.

Table 2. The obtained values of the compression and recompression indexes (C_c and C_r , respectively).

Material	Parameter		
	C_c (-)	C_r (-)	C_c/C_r
S	0.0326	0.00699	4.66
S+5%GD	0.0205	0.00382	5.36
S+10%GD	0.0269	0.00457	4.88
S+15%GD	0.0260	0.00820	3.10
S+5%MD	0.0196	0.00418	4.68
S+10%MD	0.0230	0.00500	4.60
S+15%MD	0.0291	0.00491	5.94
S+5%BD	0.0207	0.00521	3.98
S+10%BD	0.0225	0.00552	4.07
S+15%BD	0.0255	0.00739	3.45

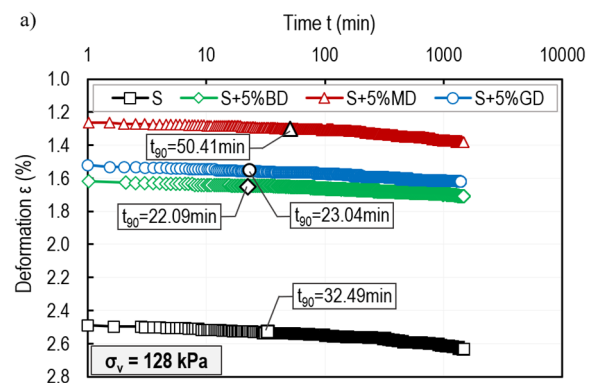
According to the data presented in Table 2, the untreated non-cohesive soil is characterized by the highest primary compression (C_c equals 0.0326). The addition of 5% melaphyre dust resulted in a reduction of the compression index by approximately 40%, representing the most significant difference in C_c value comparing untreated soil and soil with admixtures. Generally, considering all percentage dust contents and dust types, the medium sand with the addition of basalt dust is characterized by the lowest primary compression (the average C_c value equals 0.0229).

As shown in Table 2, the highest recompression index (C_r) was determined for the non-cohesive soil with a 15% granite dust content, whereas it was the lowest for the medium sand with the addition of 5% granite dust (C_r values of 0.00820 and 0.00382, respectively). Analyzing all the tested materials, the lowest recompression is characteristic of sand mixed with melaphyre dust, with an average C_r value of 0.00470, which is 33% lower than that determined for the untreated soil. According to Table 2, the C_c/C_r ratio falls within a relatively wide range, from 3.10 to 5.94.

Overall, the determined values of the compression and recompression indexes are comparable to those reported in the literature for sands (Hough, 1969; Zheng et al. 2017). However, the analysis performed revealed no evident correlation between the dust percentage content and the C_c and C_r values.

The results of the consolidation analysis are presented in Figure 4. The graphs illustrate the relationship between the deformation (ϵ) of the sample and the time plotted in the logarithmic scale at $\sigma_v = 128$ kPa, including information on the 90% consolidation time (t_{90}). Only the results obtained for one stress level are presented because the consolidation process for the remaining analyzed σ_v values was similar to that shown in Figure 4. In general, based on the consolidation test findings, it can be concluded that the medium sand without any admixtures exhibited the highest deformation, which is associated with the maximum dry density of the tested samples.

Analyzing the time corresponding to 90% primary consolidation, the t_{90} values determined at a vertical stress of 128 kPa ranged from 19.36 to 50.41 minutes. Meanwhile, the t_{90} time considering all σ_v values was in the range of 16.00-62.41 minutes. In general, t_{90} values are characterized by high variability. No correlation was found between the time corresponding to 90% consolidation and the content of the tested dust. In some cases, the t_{90} values determined for non-cohesive soil with admixtures were even higher than those specified for the untreated soil. The high irregularity of the t_{90} time determined for the tested materials is evidenced by the values of the consolidation coefficient (c_v) presented in Table 3.



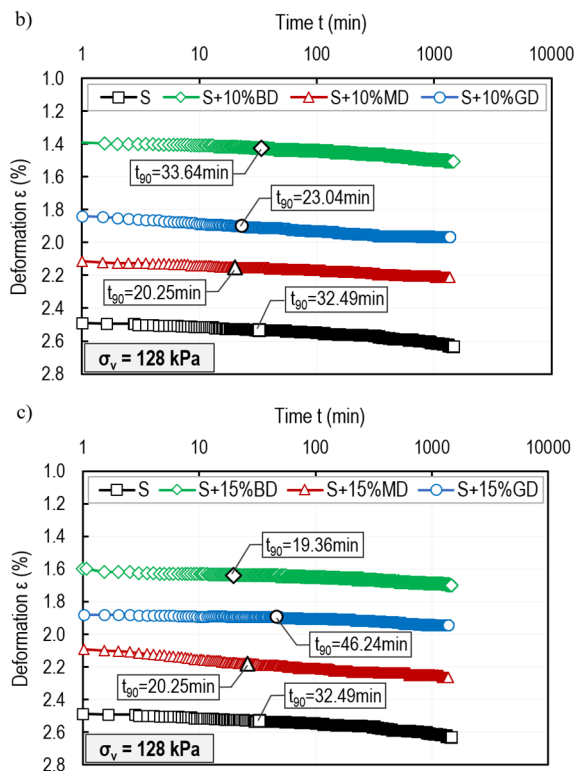


Figure 4. Sample deformation versus time for soil and soil-dust mixtures: a) 5% dust addition, b) 10% dust addition, c) 15% dust addition.

Table 3. Determined values of the coefficient of consolidation (c_v).

Material	Coefficient of consolidation $c_v \times 10^{-8}$ (m ² /s)					
	at the vertical stress σ_v (kPa)					
	16	32	64	128	256	512
S	2.48	3.16	8.08	4.13	5.75	6.14
S+5%GD	5.38	5.79	6.25	5.94	5.22	6.91
S+10%GD	4.30	3.19	7.43	5.90	6.08	5.51
S+15%GD	5.39	6.58	5.93	2.94	2.39	2.48
S+5%MD	2.31	2.24	7.17	2.73	3.23	6.95
S+10%MD	7.54	2.90	6.74	6.68	4.96	5.72
S+15%MD	4.17	3.85	5.26	5.20	5.33	6.47
S+5%BD	5.39	6.57	8.61	6.19	6.69	6.59
S+10%BD	2.79	6.61	7.16	4.09	8.09	8.36
S+15%BD	2.50	2.42	8.64	7.06	6.10	5.30

The data shown in Table 3 indicate that the lowest c_v values, averaging the results obtained for considered vertical stresses, were found for medium sand with a 5% melaphyre dust content (4.11×10^{-8} m²/s), whereas the highest were for soil with 5% basalt dust addition (6.67×10^{-8} m²/s), which indicates the longest and shortest times corresponding to 90% consolidation, respectively. For the remaining tested materials, the average c_v was in the range of 4.29×10^{-8} to 6.18×10^{-8} m²/s. In connection with the high variability and irregularity of the determined t_{90} times, the correlation between the percentage content of dust and the c_v coefficient cannot be found.

4 CONCLUSIONS

Based on the research performed, the following general conclusions may be derived:

1. The addition of each tested quarry dust at every considered percentage content has a positive effect on reducing the primary compression of the tested soil. The addition of 5% melaphyre dust resulted in an approximately 40% decrease in the compression index compared with the C_c value obtained for the untreated medium sand.
2. The admixture of the considered stone dust reduced the recompression index of the tested sand, except for a 15% content of granite and basalt dust. The most significant, 45%, reduction in the C_r parameter was found for a 5% granite dust content.
3. The determined t_{90} values, and consequently the c_v values, were characterized by high variability and irregularity. In general, the highest average consolidation coefficient was obtained for soil with a 5% basalt dust addition (approximately a 27% increase compared to untreated soil).
4. The analysis performed revealed no evident correlation between increasing dust percentage content and the C_c , C_r , and c_v parameters.
5. Overall, the quarry dust can be considered as a potential substitute for non-cohesive mineral soils, positively affecting sustainable engineering development.

5 ACKNOWLEDGEMENTS

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