



ORIGINAL PAPER

CORRELATION OF SAND FABRIC AND CONSTRAINED ELASTIC MODULUS (EC)

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ARTICLE INFO

Article history:

Received 17 July 2025

Accepted 26 September 2025

Available online 7 October 2025

Keywords:

Consolidation

Mineralogy

Sand

Constrained elastic modulus (Ec)

ABSTRACT

The Constrained Modulus of Soil (Ec) is a key parameter for assessing soil compressibility and calculating consolidation settlements. The Ec values obtained from laboratory and in-situ tests are influenced by various factors. This study investigates the variations in Ec with respect to selected sample characteristics. To this end, four sand samples were utilized: three of marine origin and one collected from a riverbed. Only clean sands were considered in the testing program. In order to evaluate the influence of mineralogy, the samples were chosen to represent magmatic, metamorphic, and sedimentary origins. Their mineralogical compositions were identified through X-Ray Diffraction (XRD) analyses. To better examine the effects on the elastic modulus, loose specimens representing shallow deposits and dense specimens representing deeper layers were prepared. Accordingly, the physico-mechanical properties of the sands were also determined. The metamorphic sand, rich in mica, exhibited the lowest specific gravity (2.74) and the highest void ratio, whereas the magmatic sand containing iron compounds showed the highest specific gravity (3.44) and the highest minimum void ratio.

In this study, oedometer tests were conducted on sand specimens prepared at different relative densities under applied stresses of 200, 400, 800, 1600, and 3200 kPa, and the Constrained Modulus (Ec) values were calculated. The experimental results indicated that the sands exhibited similar behavior up to 3200 kPa, but differences emerged at this stress level. The lowest Ec values were obtained in sands with high mica content. The findings reveal that the genetic and mineralogical differences of sands have a significant influence on the constrained modulus.

1. INTRODUCTION

The Constrained Modulus is a key parameter widely used to evaluate soil compressibility and to calculate consolidation settlements (Dhimitri and Powell, 2023). It plays a critical role in the estimation of both total and differential settlements. However, in cases where undisturbed samples of granular soils are difficult to obtain for laboratory testing, various in-situ tests may also be employed from which the constrained modulus can be empirically derived (Massarsch, 2024a). The geotechnical literature further suggests several empirical methods to estimate the constrained modulus based on one-dimensional oedometer tests (Massarsch, 2024b). In constrained modulus studies involving sands, the cleanliness of the sand, grain shape, void ratio, and density are important factors. Sand grains can occur in a wide range of forms depending on various influences (Işık and Çabalar, 2022).

In research involving the constrained modulus, the specific properties of the sand being used should be carefully considered, as sands with different characteristics can produce variations in experimental results. The relative density of the soil (loose or dense state) also affects the modulus. The modulus of elasticity tends to yield relatively lower values near the

surface but increases with depth. This difference arises from the looser condition of surface sands and the increased sensitivity at greater depths (Demiröz and Tan, 2008). The presence of fines filling the voids between sand particles may also influence density (Karakan et al., 2020). Finer particles tend to occupy the intergranular voids between larger grains, leading to higher density and lower void ratios compared with a structure formed solely by uniform spherical particles.

Another factor affecting studies on the constrained modulus is the cleanliness of the sand sample. Clean sand introduces a different distribution and changes the nature of the experiment (Karakan, 2022). The removal of silt and clay ensures that the soil remains fully cohesionless, which significantly influences relative density and looseness. In the literature, ranges of drained modulus of elasticity have been defined for sands: loose sands yield the lowest modulus values, while dense sands produce the highest (Turan et al., 2006; Akbaş and Tekin, 2013). According to previous studies, water has an adverse effect on the modulus of elasticity. As the ratio of compressibility to horizontal permeability increases, the development of consolidation slows down (Tian et al., 2023). In clean sands, an increase in permeability

is associated with a reduction in the modulus of elasticity (Demiröz and Tan, 2008).

Sand mineralogy is another factor influencing experimental results on the constrained modulus. Although platy minerals such as mica may not constitute a significant proportion of the total weight, even small amounts can affect sand behavior. Experimental findings indicate that the presence of fines can influence multiple aspects of soil behavior, including compressibility, strength, and stability (Çellek, 2019). The presence of mica increases the compressibility of sandy soils (Karakan, 2022). Particularly in clean sands, the removal of silt and clay results in a relative increase in the SiO₂ content, due to both the reduction in finer material and the relative enrichment in SiO₂. This ratio is even higher in marine sands, where high quartz content accounts for elevated SiO₂ percentages. Sands with high SiO₂ content are therefore considered clean and of high quality.

Grain structure is another factor influencing the constrained modulus. The structural behavior of granular materials is strongly dependent on their elastic and morphological characteristics as well as inter-particle interactions at contact points (Zhao et al., 2020; Wiebicke et al., 2020).

In studies on the constrained modulus, microscopic analysis of granular sands can provide better insight into their macroscopic behavior (Çinicioğlu, 2006). Therefore, the use of binocular microscopes is important in such experimental studies. However, this method alone is not sufficient and should be complemented with X-ray Diffraction (XRD) analyses (Işık and Çabalar, 2022).

In the present study, consolidation tests were conducted to determine the constrained modulus. A review of the literature showed that oedometer tests generally begin with the determination of specific gravity and grain size distribution (Çabalar and Hasan, 2013). Therefore, all relevant parameters of the sands used in the tests were first identified. Subsequently, XRD analyses were performed to determine the mineralogical composition. The physical and mechanical properties of the sands were characterized through laboratory tests and empirical formulas. Finally, oedometer experiments were carried out on sand specimens prepared at different relative densities and subjected to various loading conditions.

2. METHODS

In this study, four different sand samples were used: three collected from coastal areas and one from a riverbank. The mineralogical properties of the sands were first identified, followed by the determination of their stress–strain behavior and elastic moduli. Grain size distributions were obtained through sieve and hydrometer analyses, and the classification of the sands was established according to ASTM standards.

The sands were prepared at different relative densities in accordance with ASTM D4254-00e1. For this purpose, the specific gravity (G_s) and maximum and minimum dry unit weights (γ_{dmax} and γ_{dmin}) of the

sands were determined experimentally. Oedometer tests were then conducted on samples prepared at varying densities under vertical stresses of 200, 400, 800, 1600, and 3200 kPa.

The fundamental physical and mechanical properties of the sands were determined through a series of laboratory tests, including sieve analysis, density measurements, and consolidation tests. The sieve analysis was performed in accordance with the American standard ASTM D2487-98. Based on the results, grain size distribution curves (granulometry curves) were plotted for each sand sample.

$$\% P = \frac{\text{Amount of Sand Passing Through the Sieve}}{\text{Sieved Sand}} * 100 \quad (1)$$

The particle size distribution of silts and clays was determined by the hydrometer test, which is based on Stokes' Law (ASTM D7928-17). Initially, the grain size distribution of the sands was obtained through sieve analysis. For this purpose, the soil fraction passing the No. 200 sieve was soaked in solution for 24 hours. Prior to testing, the suspension was mixed with a mechanical stirrer, and hydrometer readings were taken at specific time intervals. The values calculated using the following equation were incorporated into the grain size distribution (granulometry) curves.

$$D = \sqrt{\frac{18}{1}} - \frac{n}{\gamma_s - \gamma_w} * \frac{L}{T} \quad (2)$$

The grain size distribution curve was plotted, and the characteristic diameters D_{10} (effective size), D_{30} , and D_{60} were obtained from the curve. The coefficient of uniformity (C_u) was calculated using Equation (3), while the coefficient of curvature (C_c) was determined using Equation (4).

The coefficient of curvature (C_c) typically ranges between 1 and 3 for well-graded soils. If $C_c < 1$ or $C_c > 3$, the soil is classified as gap-graded. In general, the coefficient exceeds 4 for gravels and 6 for sands. Regarding the coefficient of uniformity (C_u), soils with $C_u < 4$ are composed of uniformly sized particles, while $C_u = 1$ indicates particles of identical size. Conversely, $C_u > 4$ corresponds to well-graded soils (Çellek, 2016).

The specific gravity values were determined according to the British Standards. BS 1377: Part 2:1990 recommends the use of a 100 mL density bottle for determining the specific gravity of particles smaller than 2.00 mm. Approximately 15–20 g of material was used in each test, which was repeated three times for each sand sample.

The maximum dry density, or equivalently the minimum void ratio, of the sand samples was determined using a small mold and a hand compaction device (ASTM D4254-00). The modified Proctor test was not applied. Instead, both large and small molds were employed, and the results were evaluated comparatively. In the small mold tests, sand samples were placed in layers and compacted with 21 blows of a hand rammer. In the large mold (compaction mold)

Table 1 Typical Void Ratio Values (Genç, 2011).

Soil Type	e_{min}	e_{max}
Uniform spherical particles (theoretical values)	0.35	0.91
Clean fine-medium sand	0.40	1.00
Uniform inorganic silt	0.40	1.10
Silty sand	0.30	0.90
Sandy soil with mica	0.40	1.20
Silty sand with gravel	0.14	0.85

Table 2 Relative density class (Genç, 2011).

Relative Density (%)	Describing
0-15	Very Loose
15-35	Loose
35-65	Moderately Firm
65-85	Firm
85-100	Very Firm

tests, dry sand was placed in five layers, each compacted by dropping a 4.5 kg rammer freely from a height of 45 cm. The maximum dry unit weight (d_{max}) was then calculated using Equation (5).

$$d_{max} = \frac{M_S}{V} \quad (5)$$

Using the experimental results, the minimum void ratio (e_{min}) was calculated with the aid of the empirical Equation (6).

$$e_{min} = \frac{G_S}{d_{max}} - 1 \quad (6)$$

The minimum dry density (corresponding to the maximum void ratio) of the sands was determined in accordance with ASTM D4253-00 using three alternative methods. In Method A, the sand was placed into the mold in its loosest state. In Method B, the sand was poured into a graduated cylinder in its loosest state. In Method C, the sand sample was first placed into a cylindrical container positioned within the mold; the cylinder was then quickly withdrawn, allowing the sand to fall freely into the mold in its loosest condition. The test results were calculated using the following equation;

$$d_{min} = \frac{M_S}{V} \quad (7)$$

Based on the results obtained from Equation (7), the maximum void ratios (e_{max}) were empirically determined using Equation (8).

$$e_{max} = \frac{G_S}{d_{min}} - 1 \quad (8)$$

In order to determine the relative density values, the void ratios must first be established. Typical void ratio values are presented in Table 1.

The sands used in the study were prepared based on the density values given in Table 2 and the relative density values were calculated using Equation (9).

$$Dr = \frac{e_{max} - e}{e_{max} - e_{min}} \quad (9)$$

After determining the physical properties of the sand, oedometer tests were conducted to evaluate the constrained modulus. Since the samples consisted of sand, all tests were completed in approximately two hours. The constrained modulus (E_c) was calculated using Equation [10].

$$E_c = E_{cref} \left[\frac{\sigma'_v}{\sigma'_{ref}} \right] \quad (10)$$

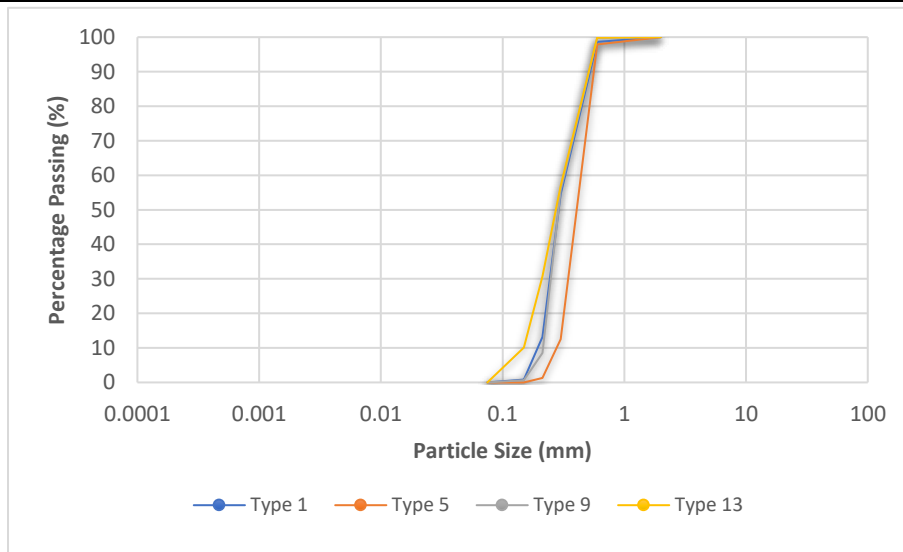
The primary objective of this study is to compare the test results obtained from samples with different structural characteristics. To highlight these differences, sand samples were collected from distinct lithological units. The sands used in the study are labeled as Type 1, 5, 9, and 13.

The principles of mineralogical identification using X-ray diffraction (X-RD) or electron diffraction are the same: both rely on the characteristic diffraction of X-rays or electrons due to the unique atomic arrangement within each crystal. X-RD is a widely used method to identify the minerals and crystal structures in cohesive soils. X-ray diffractograms reveal the types of materials present in a sample, as each crystalline substance produces distinct peaks at specific positions. In geotechnical studies, scanning electron microscopy (SEM) is more commonly employed than optical microscopy or X-RD (Karakan, 2022; Işık and Çabalar, 2022).

In the present study, the sands were analyzed using X-RD to investigate their mineralogical composition. Each mineral exhibit characteristic peaks at defined positions. Minerals in the samples, prepared by grinding in a porcelain mortar, were identified based on these analyses. The distribution of mineral contents shows that Type 1 sand possesses a distinctly different mineral composition compared to the others, while the remaining three sands exhibit similar mineral combinations.

Table 3 Mineral distributions of clean sands.

Mineral and Formula	Type 1	Type 5	Type 9	Type 13
Quartz SiO ₂		X	X	X
Anorthite CaAl ₂ Si ₂ O ₈		X	X	X
Muscovite KAl ₂ Si ₃ AlO ₁₀ (OH) ₂		X		X
Anorthoclase (Na, K)(Si ₃ Al)O ₈	X			X
Augite Ca (Mg, Fe) Si ₂ O ₆	X			
Augite Ca (Mg, Fe, Al) (Si, Al) ₂ O ₆	X			
Hedenbergite CaFe ⁺² Si ₂ O ₆	X			
Diopside Ca (Mg, Al) (Si, Al) ₂ O ₆	X			
Fayalite Fe ⁺² SiO ₄	X			

**Fig. 1** Grainometry curves of Type 1-5-9-13 sands.**Table 4** Clean sands used in the study, grain distribution.

	Type 1	Type 5	Type 9	Type 13
Fine	% 94	% 88	94	56
Medium	% 6	% 12	% 6	% 44

3. RESULTS

To evaluate the influence of mineralogy on the elastic constrained modulus, the sands were analyzed using X-ray diffraction (X-RD) to determine their mineral composition (Table 3).

The mineral composition of Type 1 sand includes iron-bearing components due to its magmatic origin. The specific gravity of Type 5 sand is 2.74, while that of Type 9 and Type 13 sands is 2.75. Types 5 and 9 sands are derived from sedimentary local rocks, whereas Type 13 sand originates from metamorphic rocks. Type 1 sand, in contrast, is derived from magmatic local rocks. The particle shapes of Type 13 sand, collected from a riverbed, are less angular due to increased transport and its mineralogical composition.

A series of tests were conducted to determine the physical and mechanical properties of the sands. Initially, grain size distribution curves were plotted (Fig. 1). The characteristic diameters D_{10} , D_{30} , D_{60} , as well as the coefficients of curvature (C_c) and

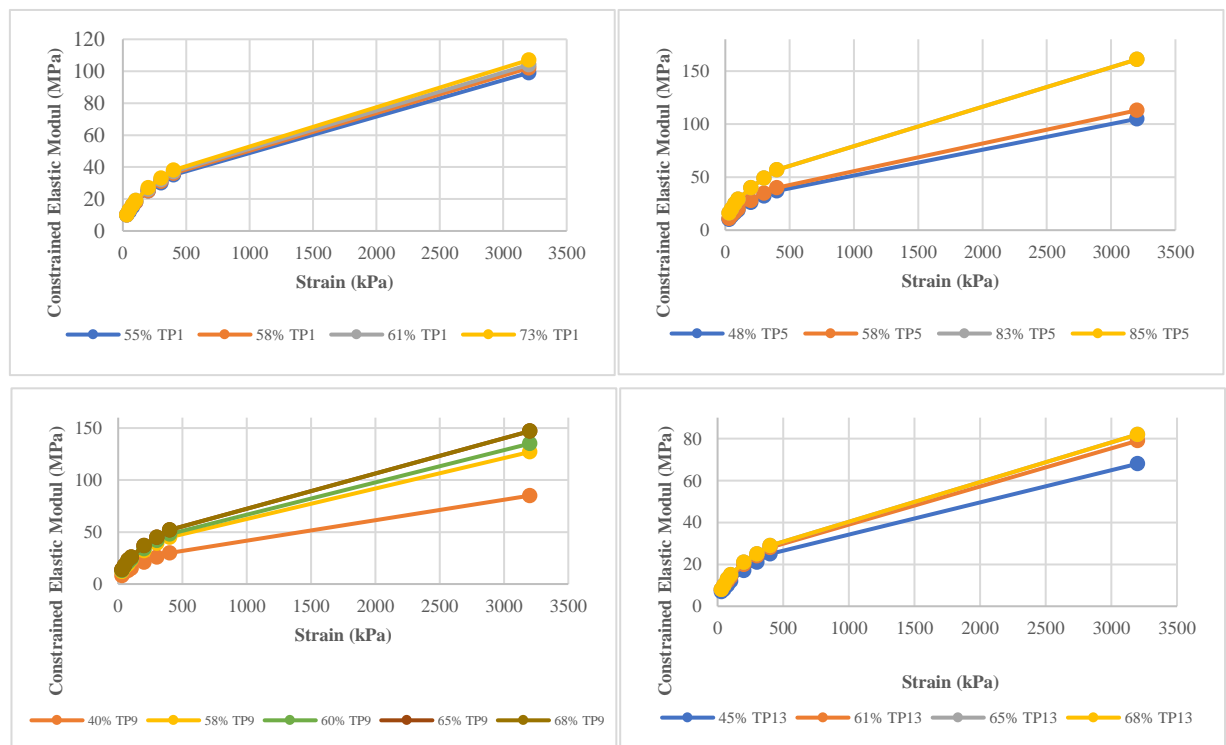
uniformity (C_u), were obtained from the granulometry curves. The sands used in this study were generally composed of coarse and medium-sized grains, with very few fines (Table 4).

As shown in the figure, all four sand samples exhibit approximately a single-grain distribution. The uniform sands produced relatively steep granulometry curves, indicating that the grains are mostly uniform or dominated by one or two sizes, with very similar particle compositions. The proportion of fine particles is less than 5%. All four sands are classified as poorly graded soils (SP), a category typically encountered in deltas, coastal dunes, or sand dunes (Çellek, 2016). The four sands used in this study share this characteristic.

In the minimum dry density determination test, the minimum dry density of the soil sample, corresponding to the maximum void ratio, was obtained in accordance with ASTM D4254. This standard acknowledges that other methods may exist that could yield slightly lower minimum dry densities

Table 5 G_s , e_{min} , e_{max} , D_{60} , D_{50} , D_{10} , C_u , C_c values of some sands used in the experiment and included in the literature.

Sand	Referance	G_s	e_{min}	e_{max}	D_{60}	D_{50}	D_{10}	C_u	C_c
Babolsar	Datta (2005)	2.78	0.56	0.81		0.24		1.8	
Brown Mortar	Cerato and Lutenegger (2006)	2.69	0.58	0.91		0.6	0.3	2.1	1.1
Ottawa Sand	Lee and Seed (1967)	2.62	0.49	0.8	0.76	0.5	0.65	1.9	1
Toyoura	Yoshimine and Ishihara (1998)	2.65	0.59	0.98		0.17		1.7	
Yamuna	Basudhar (2008)	2.66	0.57	0.91		0.48		2.6	
Type 1		3.44	0.91	0.66	0.6	0.55	0.43	1.68	0.11
Type 5		2.74	0.85	0.55	0.73	0.67	0.54	1.72	0.21
Type 9		2.75	0.85	0.60	0.6	0.55	0.45	1.52	0.10
Type 13		2.75	0.93	0.60	0.36	0.32	0.2	3	0.19

**Fig. 2** Constraint Elastic Modulus (E_c) vs. Stress (σ) values of Type 1, 5, 9, 13.

(ASTM D4254). Therefore, the obtained minimum dry density values are based on this standard. According to ASTM D4254, the minimum dry density can be determined using three alternative methods. Both the minimum and maximum dry densities were established, and the corresponding maximum and minimum void ratios were calculated using empirical equations. A literature review was conducted, and the physico-mechanical properties of the tested sands—including G_s , e_{min} , e_{max} , D_{60} , D_{10} , C_u , and C_c —are presented alongside the values of the sands used in this study (Table 5).

In this study, the constrained elastic modulus values were determined using empirical formulas (10), and the corresponding graphs were plotted. These calculations were performed for all sand samples prepared at different relative densities (Fig. 2). Additionally, the sands were graphed at the same relative density values. For Type 1 sand, the modulus was calculated at 55 %, 58 %, 61 %, and 73 % relative

densities; for Type 5 sand at 48 %, 52 %, 83 %, and 85 %; for Type 9 sand at 40 %, 58 %, 60 %, and 65 %; and for Type 13 sand at 45 %, 61 %, 65 %, and 68 % relative densities.

4. DISCUSSION AND CONCLUSION

This study was conducted to investigate the relationship between the constrained elastic modulus and sand structure. The results indicate that the grain characteristics of the sands used in the experiments are critical, with the two most influential factors being the mineralogical composition and the origin (formation environment) of the sand.

The experiments showed that the mineralogical origin of the sand particles is the primary factor affecting particle strength and deformation, followed by the transport history of the sand. However, sand grains from regions with different energy levels exhibited variations in particle shape. Another key finding of this study is that sands with different

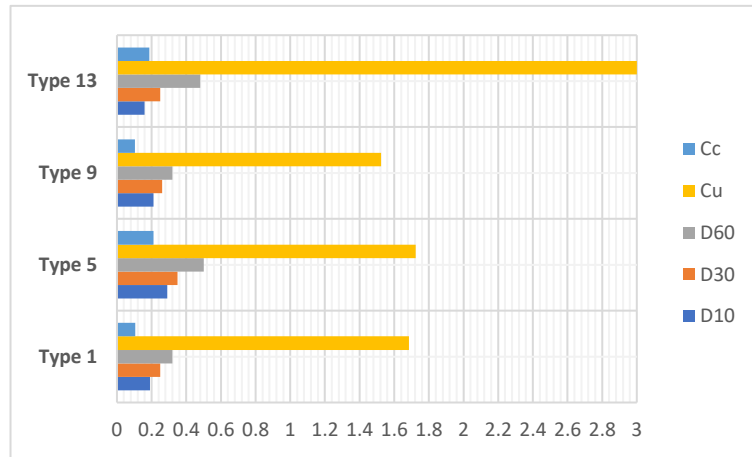


Fig. 3 Comparison of D_{10} , D_{30} , D_{60} , C_c , and C_u values of the sands used in the experiment.

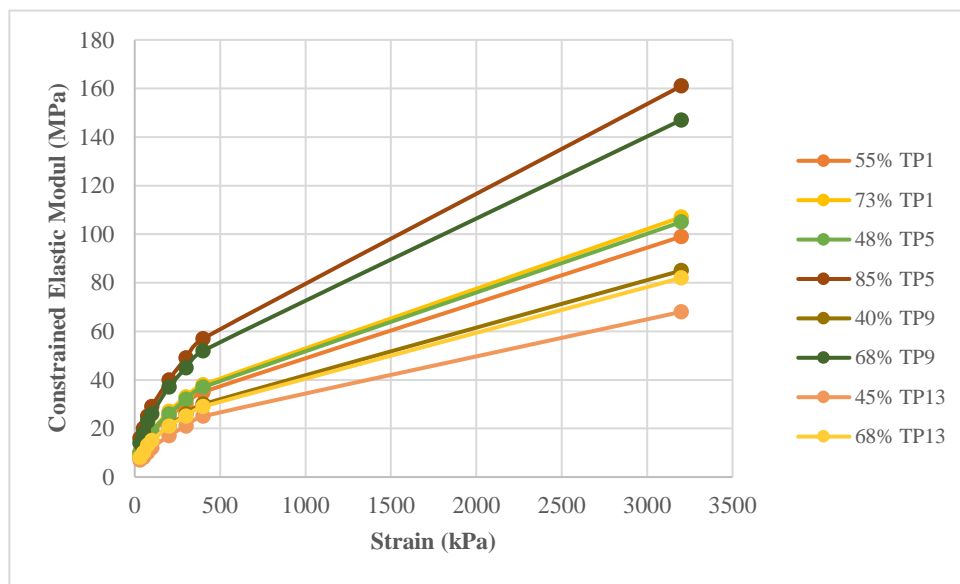


Fig. 4 Comparison of restricted elastic modulus behavior of sands according to low and high compactness values.

mineralogical compositions yield different specific gravity values. Literature indicates that the dominant minerals in most soils are quartz and feldspars, whereas mica and iron-bearing minerals are less common. Consequently, the specific gravity of most soils ranges between 2.60 and 2.75. In this study, the specific gravity values of Type 5, 9, and 13 sands were close to standard values, while Type 1 sand exhibited a significantly higher value of 3.44, deviating from typical literature values.

Specific gravity is influenced by mineral content and grain size. As the mica content increases, void ratios tend to rise, and shear resistance decreases. Type 13 sand contains more mica compared to the other sands. While the grain size distributions varied among the sands, Type 1 and Type 9 exhibited similar distributions. Overall, all sands except Type 1 produced values consistent with the literature. The distribution curves of Type 1, 5, and 9 sands were similar, whereas Type 13 sand, collected from

a riverbed, showed a slightly different distribution (Fig. 3).

Although the sands exhibited similar constrained elastic modulus (E_c) values under different densities, variations were observed below a vertical stress of 3200 kPa. Despite Type 13 sand displaying a different grain size distribution compared to the others, it showed the lowest E_c values. In particular, at 3200 kPa, Type 13 sand yielded lower E_c values than the other sands. The reduced E_c values are attributed to the influence of mineralogy and the fact that coarser, harder grains undergo less crushing. This indicates that grain size distribution has little effect when mineralogy differs. In sands with similar mineralogy, grain size was found to influence E_c values.

For example, Type 5 sand samples prepared at 65% and 68% relative density exhibited the same E_c values. It is evident that E_c values vary for each sand sample and at each compaction level. Type 1 and Type

13 sands demonstrated more stable behavior under a 30 kPa load compared to Type 5 and Type 9 sands. Type 1 sand exhibited consistent E_c values across all prepared compaction levels, while Type 13 sand showed uniform E_c values except at the lowest density. Type 5 and Type 9 sands displayed higher E_c values than the others and also exhibited variations depending on density changes (Fig. 4).

SYMBOLS

E_c	Constrained Elastic Modulus
XRD	X-Ray Diffraction (XRD) analyses
%P	Percent Passing
D_{10}	Effective Grain Size
D_{30}	30 % Passing Grain Size
D_{50}	Mean Grain Size
D_{60}	60 % Passing Grain Size
C_u	Coefficient of Uniformity
C_c	Coefficient of Curvature
SP	Poorly Graded
D	Particle Diameter
e_{max}	Maximum Void Ratio
e_{min}	Minimum Void Ratio
d_{max}	Maximum Dry Unit Weight
d_{min}	Minimum Dry Unit Weight

ACKNOWLEDGEMENTS

This study was conducted during my postdoctoral research at the Soil Mechanics Laboratory, Middle East Technical University. I sincerely thank Prof. Dr. Kemal Önder Çetin for his encouragement and for providing the opportunity to conduct this work under his guidance

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