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ORIGINAL PAPER

Comparison of Grain Size Distribution and Grain Shape of Various Sand Samples

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Abstract This study aimed to compare grain size distribution and grain shape of sands with different mineralogies and origins. Also, we attempted to investigate the changes in the physical properties of sands with different mineralogical properties. Four different sand samples taken from the Black Sea and Aegean regions were selected for experiments. Sands were named Type 1, Type 5, Type 9, and Type 13. A washing process was applied because clean sand was preferred for the experiments. Grain distributions were determined with wet mechanical analysis, and unwashed and washed samples were compared. The samples were classified as "poorly graded sand." Mineralogical properties were determined by binocular microscope, X-ray, and SEM. When the samples were chosen, attention was given to selecting those with different source rock properties. Their origins were determined to be sedimentary, magmatic, and metamorphic. It was determined that Type 1 sand is volcanic, Types 5 and 9 sands are sedimentary, and Type 13 sand is metamorphic in origin. Additionally, Types 1, 5, and 9 sands were taken from the seashore, and Type 13 sand was taken from the riverside. Also, it was determined that Type 5 is a mixture of river and sea sand. It was understood that different mineralogical properties result in different physical properties. Besides, not only the mineralogy but also the origin (marine or the river) affects the grain distribution and shape. Marine or the river origin has more effect on grain distribution and shape than does mineralogy. However, mineralogy is important in determining specific gravity.

Keywords Sand · Mineralogy · Sinop · Grain size distribution · Grain shape

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1 Introduction

A continuous rock formation and erosion cycle has existed from the formation of Earth and continues even today. Sand is a product of the decomposition and transportation of pre-existing quartz-bearing magmatic, sedimentary, or metamorphic rocks. Sand grains are composed of minerals that have been separated from solid rocks. During transportation, the weaker minerals are separated from the rocks, and the resistant granules shrink in size, become more even or rounded, and have their surfaces modified by continuous abrasion or by chemicals. As the grains move greater distances, they become more rounded. The farthest-transported sands are the purest chemically, the most rounded, and generally the best sand deposits. When alluvial and sandy quartz sands are rolled during transportation, some weak sand particles, such as volcanic ash, may exhibit higher angularity due to breakage during transport. However, during transportation, the weak grains wear excessively, leading to a decrease in grain size. The sizes of the particles that accumulate to form geological deposits are influenced by currents that carry fragments and tend to be in balance with the sedimentological environments. It has long been observed that there are differences between the sands in rivers, sand dunes, and sandy beaches. Scientists have examined mineral compositions, grain size distributions, grain rounding measurements, classification statistics of particles, and other details to reveal the histories of the sediments (Altuhafi et al. 2011; Carr 1971; Zdunczyk and Linkous 1994; Shaffer 2006; Santamarina and Cho 2004; Ramsey 1999; Nyembwe et al. 2016). Particle size is one of the most important parameters in materials science and technology, as well as in many fields such as construction, chemistry, food, agriculture, medicine, ammunition, electronics, mining products, medicine, pharmacology, biology, ecology, energy technology, and geology (Ramsey 1999; Pabst and Gregorová 2007; Nyembwe et al. 2016; Santamarina and Cho 2004; Dodds 2003). Traditionally, soil behavior studies have focused on either clean sand or soft clay material. Most of the time, geotechnical engineers adapt the behavior of transitional geomaterials to those classifications (Murthy 2010). Numerous experimental studies have shown that two sands with similar fine grain content may still have significantly different deformation and strength characteristics. Therefore, it is necessary to allow the best possible display of the character of the sand and the effects of various material properties (Selig and Ladd 1973; Aberg 1992; Miura et al. 1997; Cubrinovski and Ishihara 2002). Experimental results have shown that the proportion of fine grains can affect many aspects of soil behavior, such as compressional behavior, strength, steady-state line, static liquefaction, undrained fragility, and instability (Edil et al. 1975; Zelasko et al. 1975; Salgado et al. 2000; Fourie and Papageorigou 2001; Thevanayagam et al. 2002; Monkul and Ozden 2007; Cabalar et al. 2013; Cabalar and Mustafa 2015; Chang et al. 2016). It is known that the behavior and properties of granular soils are controlled by the properties of the particles, such as shape, roundness, particle size, surface roughness and specific gravity and the distribution of the particle sizes that make up the soil (Green 2001; Greene et al. 1994; Ceylan 2015). It is shown in the literature that the maximum and minimum void ratios are affected by grain size, diameter, and distribution characteristics and that e_{max} and e_{min} decrease due to increases in D_{50} and C_u. Vacancy rates increase with increasing angulartity, with both void ratios increasing but with the maximum void ratio increasing more than the minimum (Arasan et al. 2010).

2 Materials and Methods

Particulate materials are examined by geotechnical engineers, materials scientists, physicists, and geologists. Ground mechanics, or particle size analysis (PSA), is required to link soil texture to soil performance or behavior. Particles of sand size (0.05–2.00 mm) are usually determined by sieving. Standard methods for determining grain size distribution of soils are sieve analysis and sedimentation (hydrometer and pipette) methods. Sieve analysis is used for soils having grain sizes larger than 0.075 mm, and soils with particles smaller than 0.075 mm are analyzed by hydrometer experiments (Özer 2006). Particle size is measured by passing the samples through a series of sieves with various-sized gaps (Santamarina and Cho 2004; Buurman et al. 1997; Zobeck 2004; Arasan et al. 2011; Ramsey 1999; Pabst and Gregorová 2007; Nyembwe et al. 2016; Dodds 2003). Determination of grain size distribution by the mechanical method (sieving) is the most time-consuming and difficult. For that reason, image analysis methods have been used by several researchers to determine grain size distribution (Arasan et al. 2011). Various methods are used to determine particle shape and distribution. Some of them can be listed as X-ray, SEM, binocular microscope, and washing screen analysis. X-ray diffraction is a widely used method to identify minerals of cohesive soils and to determine crystal structures. The kind of material of which the sample is made is determined from the X-ray diffractograms. Each crystalline material has its own peaks, and those peaks are located in certain positions. The scanning electron microscope (SEM) has the ability to analyze selected point locations on the sample. This approach is particularly useful in determining chemical compositions, crystallizing, and crystal orientations, either qualitatively or semi-quantitatively. The binocular microscope makes it possible to examine features of thin sections with magnification up to 1600 ×, comfortable handling, and clear image reproduction, thus allowing the minerals to be seen in detail. Washing screen analysis is performed to determine particle size distribution of material having different-sized particles. The washing process removes the clay particles adhering to the sand particles.

3 Results

The samples were taken from Sinop, Trabzon, Zonguldak, and (Çine) Aydın. Samples of 10 kg were taken from each area (Fig. 1). During the field studies, geological maps were used in addition to observations previously made. Before the experiments, clays were removed with wet mechanical analysis. Mineralogical evaluations were also made by using XRD, optical microscope, and SEM views of the samples.

3.1 Sample Points

The changes in the mineralogical properties of the sand samples from different regions and their engineering properties were investigated. In addition, the mineralogical properties of the sands were determined in terms of the engineering behaviors of the marine- or river-origin sands.

Type 1 sand was taken from the place called Akçakale in Trabzon (Fig. 2).

The sample was taken from the Upper Cretaceous aged Kabaköy Formation, which has volcanic rocks. The formation usually consists of gray-colored andesite lavas and pyroclasts with sandstone-sandy limestone-tuff intermediate levels and black-to-greenish gray basalt lavas and pyroclasts.

Fig. 1 Sample points

Type 5 sand was taken from the place called Sarıkum (İncekum) in Sinop (Fig. 3).

The sample was taken from a yellow sandstone named the Sarıkum Formation, of Late Pliocene–Early Pleistocene age (Fig. 3).

Type 9 sand was taken from the place called İnkum in Zonguldak (Fig. 4).

The sample was taken from the Devonian aged Yılanlı Formation. It consists of limestone, dolomitic limestone, dolomite, and chert.

Type 13 sand was taken from the place called Çine in Denizli (Fig. 5).

The sample was taken from a Precambrian-aged formation which name is Menderes Massif that has metamorphic rocks. The formation usually consists of gneiss, fine-grained schist, and quartzite.

3.2 Mineralogy

Quartz sand consists of silica granules with grain sizes of 0.06–2 mm. It originates from the alteration of silica-rich rocks. The samples of sands used in the study were washed so that clean sands were obtained. The mineral names and percentages were determined as a result of the analyses made on the sands. It is preferable to wash the sand before the experiment, because the SiO_2 ratio is higher if the sand is of good quality and clean. The SiO_2 ratio is higher after washing due to the relative decrease in fine materials and the relative increase in SiO_2. The SiO_2 ratio also is higher in samples taken from the sea. Character changes were observed in the materials under load during the experiments. It is a clay size that falls 2 mm below the material, but it does not behave like clay mineralogically. To understand the mineralogy of the sands investigated in the study, SEM, X-ray diffraction (XRD analysis), epi-illumination, and binocular optical microscopes were used for analysis. XRD was used to determine the SiO_2 values of the sand. If the amount of SiO_2 is high, this is the amount of quartz contained in the sample. Those values were compared with those of XRD and binocular microscope studies.

3.2.1 Type 1

The X-ray diffractogram of the Trabzon sand and the percent values of minerals are shown in Table 1. As a result of mineralogical and petrographic studies made of basalts and andesites, it was determined that

Fig. 2 Trabzon sample point (41°4′48″N, 39°30′3″E)

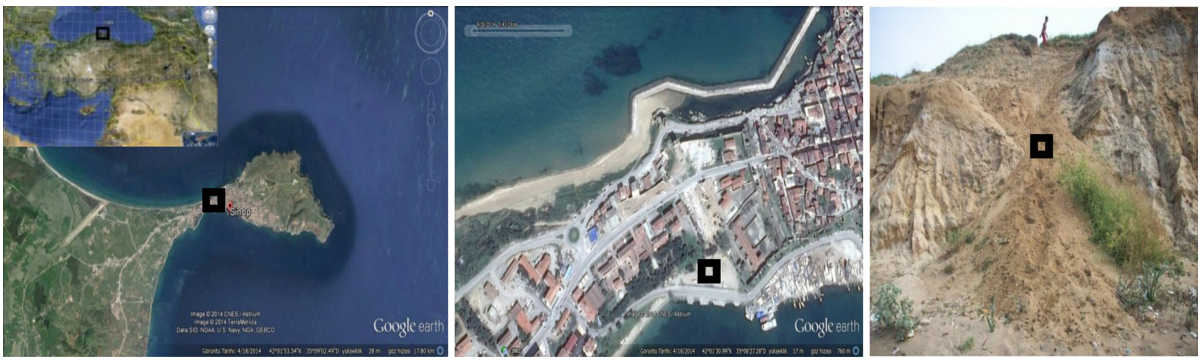


Fig. 3 Sinop sample point (42°01′29″N, 34°55′22″E)

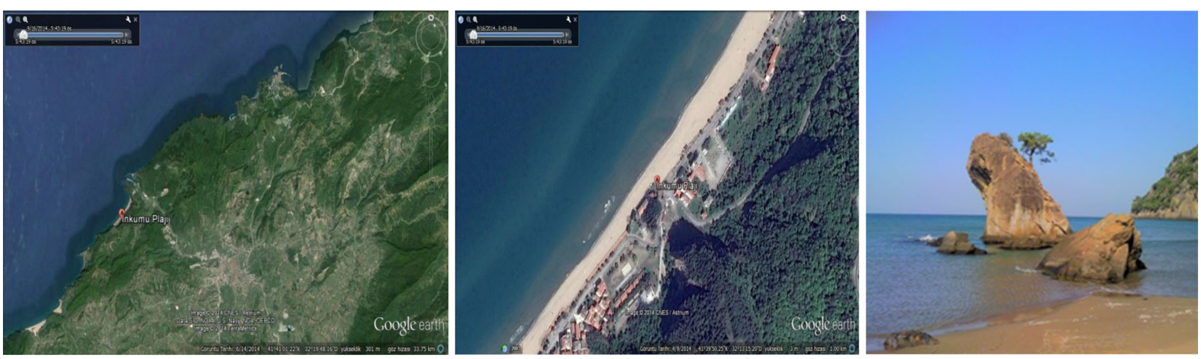


Fig. 4 Zonguldak sample point (41°37′54″N, 32°20′2″E)

plagioclase minerals account for about 60% of the minerals forming the parent rock and that augite (pyroxene) is present in the rock at about 20–25%.

SEM images were taken to examine the shapes of the scales forming the sand sample (Fig. 6).

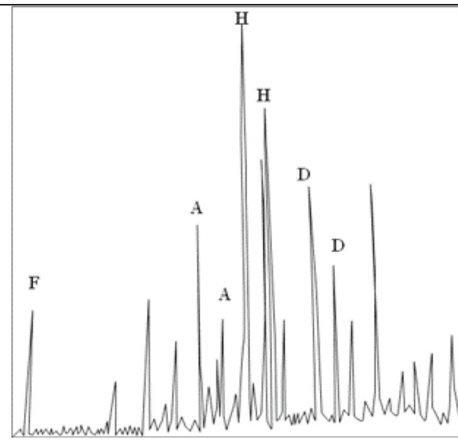
3.2.2 *Type 5*

The mineral content of the Type 5 quartz sand is seen in the sea in places, but this sample is alluvial. The sand was investigated by XRD analysis. The original sample consisted of quartz, anorthite, and muscovite. Muscovite was removed by washing (Table 2).

The old beach sand with quartz grains has been formed as a result of accumulation on the shore by the

Fig. 5 Çine sample point (37°36′42″N, 28°03′41″E)

Table 1 X-ray results of unwashed and washed Type 1 sand sample (*F* fayalite, *An* anorthite, *H* hedenbergite, *D* diopside, *A* augite)

Percentage	Type 1 (Unwashed)		
	Mineral	Formula	
26	Augite	$Ca(Mg,Fe)Si_2O_6$	
32	Augite	$Ca(Mg,Fe,Al)(Si, Al)_2O_6$	
16	Hedenbergite	$CaFe^{2+}Si_2O_6$	
21	Anorthite	$CaAl_2Si_2O_8$	
Percentage	**Type 1 (Washed)**		
	Mineral	**Formula**	
53	Augite	$Ca(Mg,Fe) Si_2O_6$	
20	Diopside	$Ca(Mg,Al)(Si,Al)_2O_6$	
20	Hedenbergite	$CaFe^{2+}Si_2O_6$	
7	Fayalite	$Fe^{2+}SiO_4$	

removal of the clay and other additives from the crushed material transported to the sea by alluvial processes at Sinop Beach. Accumulating these sand, the active westerly winds of the coast to 2.5 km from the inside up to the inside moved to this quartz sandy quarters have formed. SEM images were taken to examine the shapes of the scales forming the sand sample (Fig. 7).

3.2.3 Type 9

The X-ray diffractogram of the Type 9 sand is shown in Table 3. The sand consists of anorthite and quartz and has a similar appearance to the Type 5 sand.

The same minerals were obtained at different percentages before and after washing in the Type 9 sand used in the study.

SEM images were taken to examine the shapes of the scales forming the sand sample used in the study (Fig. 8).

3.2.4 Type 13

XRD analysis was performed on Type 13 sand (Table 4). It was determined that the sand is of metamorphic origin. Muscovite was found, especially in phyto-silicates, in the sand.

SEM images were taken to examine the shapes of the scales forming the sand sample used in the study (Fig. 9).

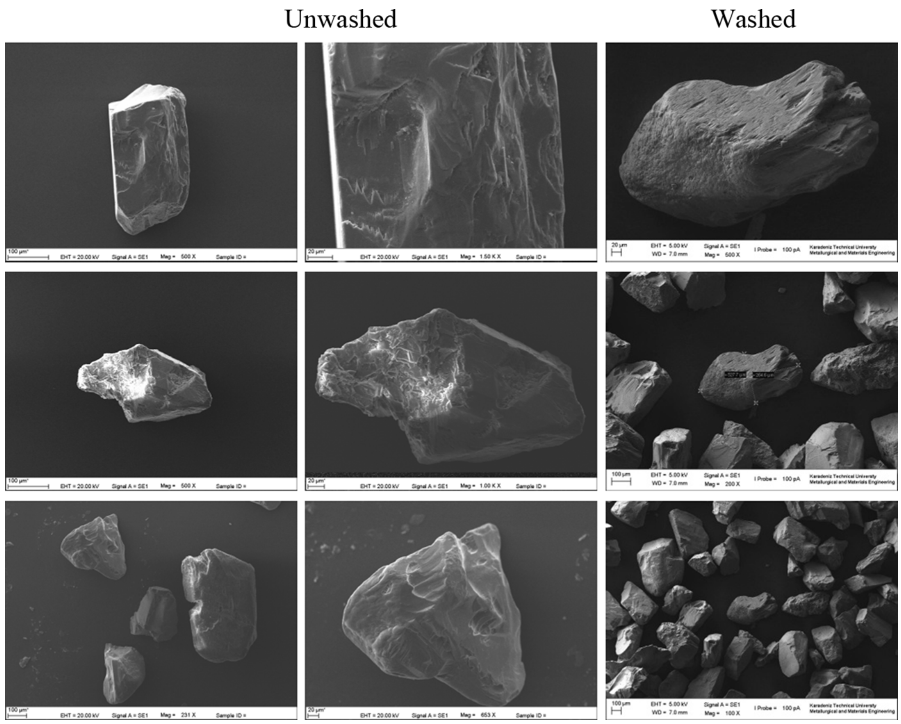
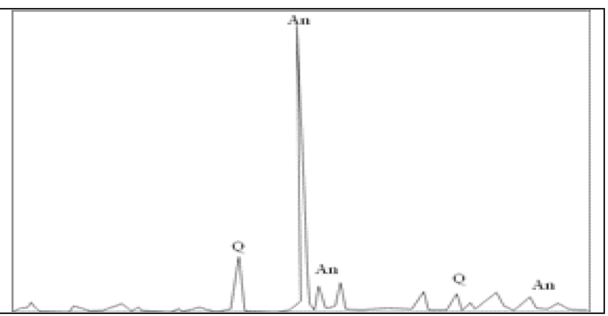


Fig. 6 SEM images of Type 1 sand sample

Table 2 X-ray results of unwashed and washed Type 5 sand samples (*Q* quartz, *An* anorthite)

Type 5 (Unwashed)		
Percentage	**Mineral**	**Formula**
38	Quartz	SiO_2
58	Anorthite	$CaAl_2Si_2O_8$
4	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$
Type 5 (Washed)		
Percentage	**Mineral**	**Formula**
57	Quartz	SiO_2
43	Anorthite	$CaAl_2Si_2O_8$



4 Comparison of Sands

SEM images of the sands were taken to examine the grain structure. According to the figure classification, Types 5 and 9 have angular grains, Type 13 generally consists of semi-angular and semi-rounded granules, and Type 1 generally consists of shaped corners and small angular corners (Fig. 10). Comparisons of the XRD results used in the study are given in Fig. 11 and Table 5. Types 5, 9, and 13 have similar mineralogical contents, but Type 1 has a different mineralogical structure. Quartz and anorthite minerals were detected in those three sand types. Muscovite was removed from the Type 5 sand by washing, whereas muscovite in the Type 13 sand showed only a proportional change. Anorthoclase occurs in Type 1 and Type 13 sands, but it was removed from the Type 13 sand by washing. Unlike the other sand types, Type 1 sand contains augite, hedenbergite, diopside, and fayalite minerals.

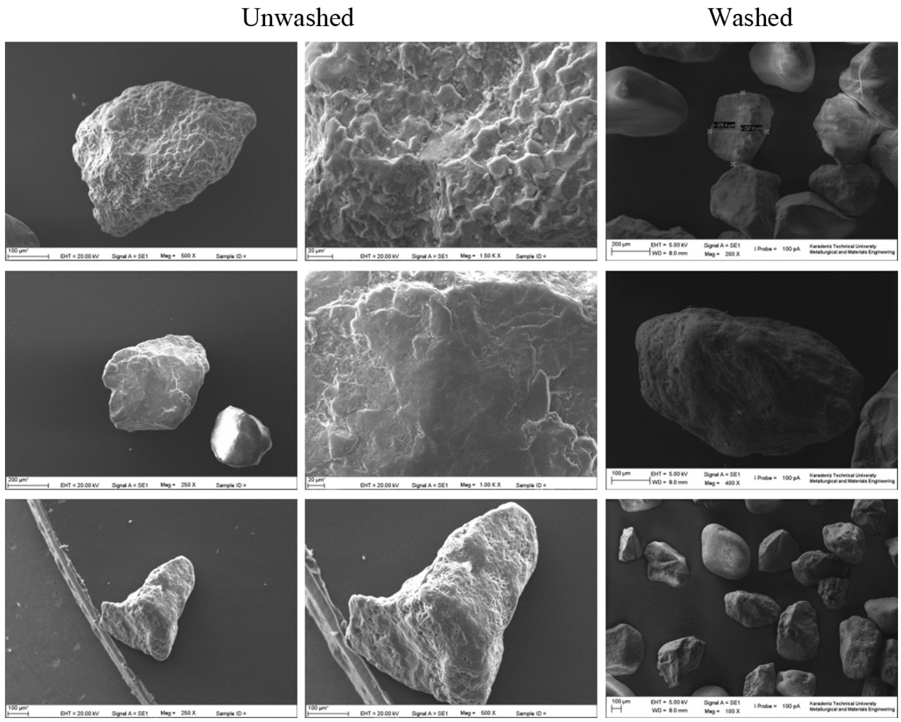
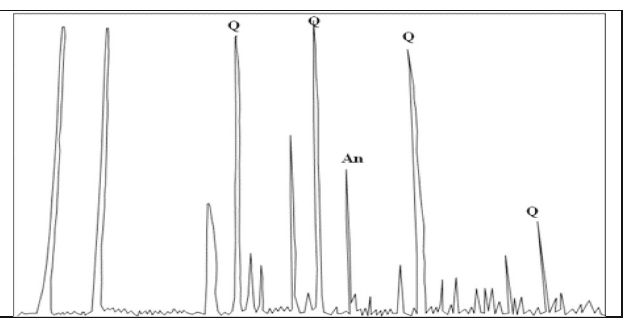


Fig. 7 SEM images of Type 5 sand sample

Table 3 X-ray results of unwashed and washed Type 9 sand sample (*Q* quartz, *An* anorthite)

Type 9 (Unwashed)		
Percentage	**Mineral**	**Formula**
45	Quartz	SiO_2
55	Anorthite	$CaAl_2Si_2O_8$
Type 9 (Washed)		
Percentage	**Mineral**	**Formula**
80	Quartz	SiO_2
20	Anorthite	$CaAl_2Si_2O_8$



Trabzon sand is composed of dark-colored granules, and Çine sand is composed of light-colored granules. While the Sinop and Zonguldak sands have images similar to each other, the Sinop sand has larger grains than the Zonguldak sand (Fig. 12).

The granulometry curves of the samples used in the study were determined by washing screen analysis. The curves for the sands are given in Fig. 13, and the grain distributions are shown in Table 6.

While Type 1 and Type 9 show similar grain distribution, Type 13 and Type 5 show some differences. The sands consist of medium and thick granules. C_r and C_u values of the sands were calculated. Specific gravity values were determined to be near the standard in Types 5, 9, and 13, while Type 1 showed differences due to mineral content. It was determined that the Type 13 sand has the highest value of maximum void ratio and the lowest minimum void ratio at the same time and therefore the largest

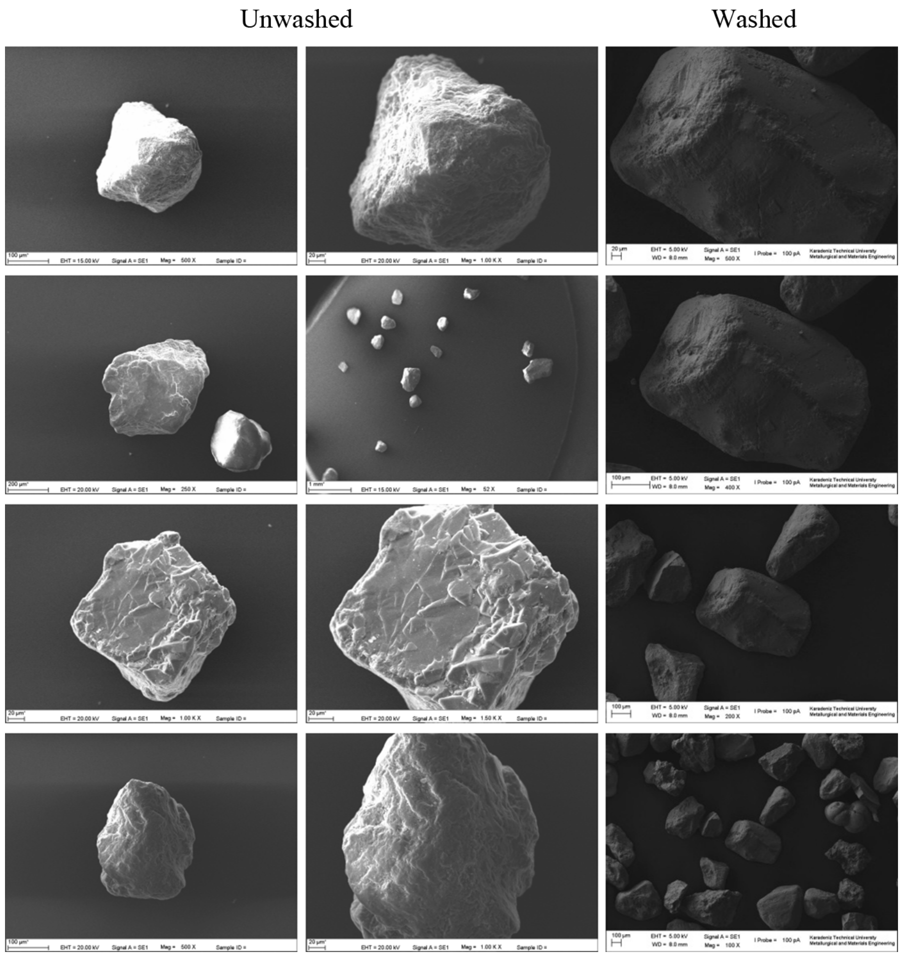
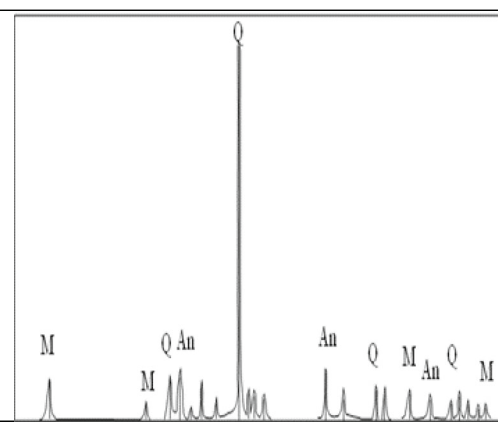


Fig. 8 SEM images of Type 9 sand sample

Table 4 X-ray results of unwashed and washed Çine sand sample (*Q* quartz, *An* anorthite, *M* muscovite)

Type 13 (Unwashed)		
Percentage	**Mineral**	**Formula**
71	Quartz	SiO_2
6	Anorthite	$CaAl_2Si_2O_8$
12	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$
9	Anorthoclase	$(Na,K)(Si_3Al)O_8$
Type 13 (Washed)		
Percentage	**Mineral**	**Formula**
48	Quartz	SiO_2
31	Anorthite	$CaAl_2Si_2O_8$
20	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$



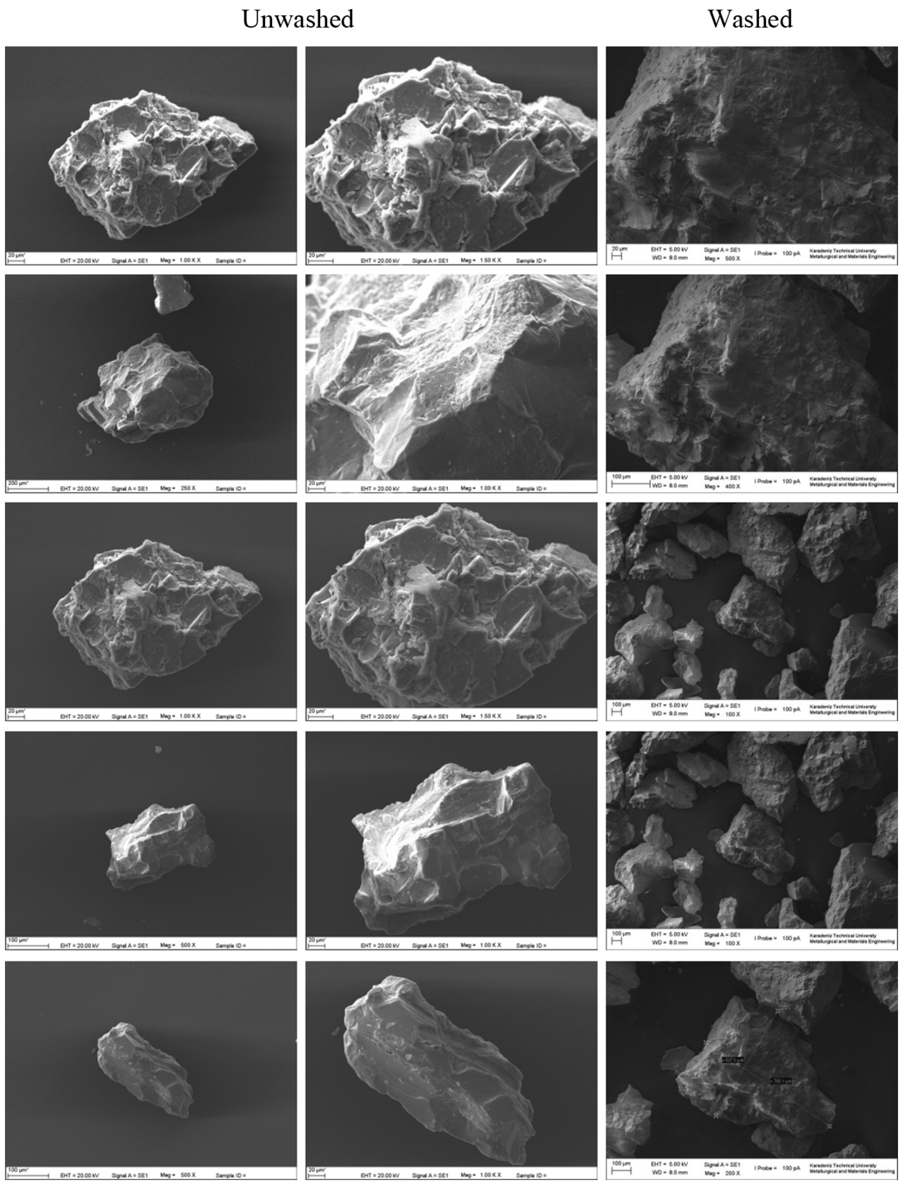


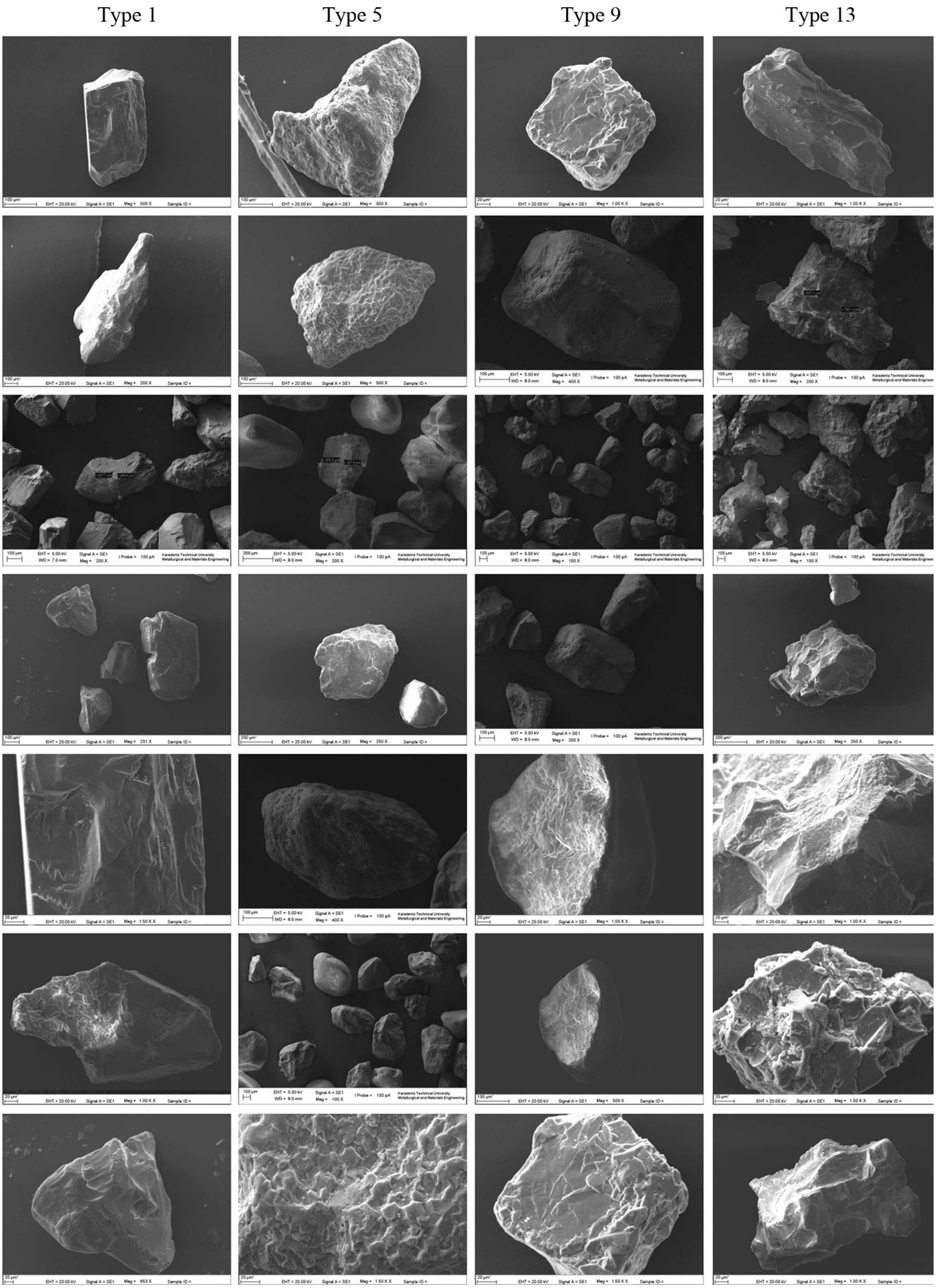
Fig. 9 SEM images of Çine sand sample

difference between the maximum and minimum void ratios.

5 Conclusions and Discussion

Sand samples taken from the Sinop, Trabzon, and Zonguldak coastal areas and from the Menderes River (Çine [Aydın]) district were used in this study. Sampling points of the sand samples were selected at a riverbed in the Aegean region and at three locations along the seashore in the eastern, central, and western regions of the Black Sea coast. Nearby rocks and basin formations were taken into account in the selection of the sample locations. Type 1 was located at a volcanic-sediment sequence. Type 5 and Type 9 were located at sedimentary basins, and Type 13 sand was situated along a metamorphic area.

The preliminary conditions of the sand and the thin sections prepared with epoxy were examined with


Type 1
Type 5
Type 9
Type 13

◀**Fig. 10** SEM images of the sands used in the study

optical and epi-illumination microscopes. Google Earth images and geological maps and images of the area were used. XRD, SEM, and microscope images of the sands were obtained. In the study, clean sand was prepared by using a 200-mesh sieve. Clay particles adhering to the sand particles were removed by means of a washed sieve analysis. It was determined that "SP" is poorly graded for the four sand samples.

Type 9 and Type 5 sands were compared because of their similar sedimentary mineral content. Type 1 sand of magmatic origin, Type 13 sand of metamorphic origin, and Type 5 and Type 9 sands of sedimentary origin were also compared with each other. In addition, Type 13 sand from the Menderes River, which is different from the samples taken from the other three (seaside) areas, was compared with the other sand types. Finally, the sands taken from different parts of the same region were evaluated among themselves.

Type 1 sand was taken from Akçakale Beach, Kabaköy Formation. The formation consists of sandstone-sandy limestone-tuff intervals, andesite lava, basalt lava, and pyroclastics. Type 5 sand, from the beach known as Sarıkum in the city center, was taken from the Sarıkum Formation. The formation consists of fine-grained sandstone, loam stone, conglomerate, and limestone. Type 9 sand was taken from the Yılanlı formation in the İnkumu district. The formation consists of limestone, dolomitic limestone, dolomite, and cherty limestone alternations. Type 13 sand was taken from the Menderes Massif located near the Menderes River. The Menderes Massif consists of gneisses of granitic origin, white-to-gray colored hard quartz schists, and weathered metamorphic rocks.

Sands are composed of granules of different sizes and shapes. They are also different according to their provenance environment and the rock types of their origins. In this study, we attempted to determine the effects of formation environment and mineralogical properties on sand behavior.

There were not many rounded grains found in any of the four sand types used in the study. This shows that they do not wear too much and that they are generated close to the rocks nearby.

Of the four sand types, Type 1 has the squarest corners. The mineral content of this type is more resistant when compared to the other sand types. Type 13 sand also has rounded particles due to the effects of migration and abrasion, as it was taken from the

Table 5 XRD results of washed Type 1, Type 5, Type 9, and Type 13 sands

	Type 1	Type 5	Type 9	Type 13
Quartz		X	X	X
Anorthite		X	X	X
Muscovite				X
Anorthoclase	X			
Augite	X			
Hedenbergite	X			
Diopside	X			
Fayalite	X			

Augite: $Ca(Mg,Fe)Si_2O_6$, Hedenbergite: $CaFe^{+2}Si_2O_6$, Anorthite: $CaAl_2Si_2O_8$, Diopside: $Ca(Mg,Al)(Si,Al)_2O_6$, Fayalite: $Fe^{+2}SiO_4$, Quartz: SiO_2, Muscovite: $KAl_2Si_3AlO_{10}(OH)_2$, Anorthoclase: $(Na, K)(Si_3Al)O_8$

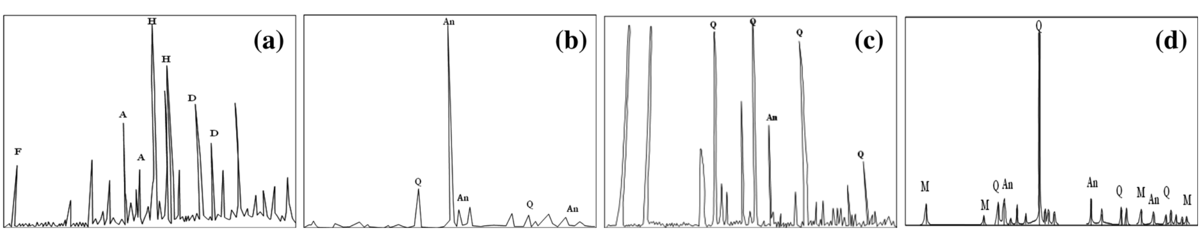


Fig. 11 XRD results of the sand samples used in the study: **a** Type 1, **b** Type 5, **c** Type 9, **d** Type 13 (*Q* quartz, *An* anorthite, *A* anorthoclase, *F* fayalite, *H* hedenbergite, *D* diopside, *M* muscovite)

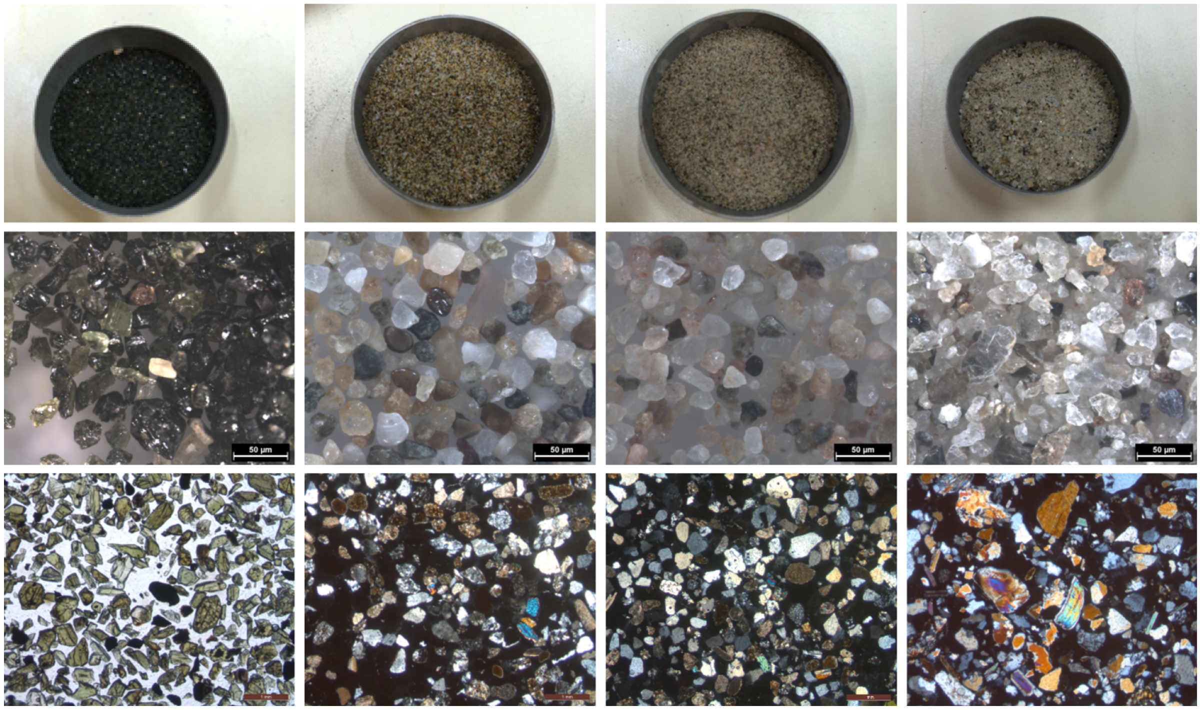


Fig. 12 Micro and macro photos of the sand samples

riverside instead of the seaside as the other three sands. Considering the mineralogical properties, Type 5, Type 9, and Type 13 sands, which display similar contents, are compared with each other. It was determined that, because of the river origin, Type 13 sand is composed of rounded granules, while both marine- and alluvial-derived Type 5 sands have granules that are composed of semi-round and semi-square granules. Type 9, which is sea sand, is composed of semi-square grains. Sands with similar mineralogical structures and with granular forms that have been influenced by their marine or alluvial origins were examined and described. Grain shape differences were observed between Type 1 sand, with highly angular grains, taken from the marine environment, and Type 9 sand, which is also marine.

When the grain distributions are examined, Type 1 and Type 5 sands, which are derived from marine environments, are very close to each other, while Type 5 and Type 13 sands show different distributions. That is due to the excessive erosion and transport of river sand. The grain size in the sand taken from the sea is larger than that of the sand taken from the river.

In general, the specific gravity values expected from sand are from 2.60 to 2.75 (Genç 2011). The specific gravities of the sands used in this study vary between 2.74 and 3.44. Type 5, Type 9, and Type 13 sands have specific gravity values of 2.74 and 2.75. Type 1 sand has a specific gravity of 3.44 due to its high content of augite.

The void ratio in the examined sand is generally between 0.5 and 0.9. In general, the void ratio in sand is predicted to be no less than 0.3 or more than 1.2 (Genç 2011). The minimum void ratios of sand used in the study are between 0.550 and 0.600, and the maximum void ratios are between 0.850 and 0.931. Thus the 0.550–0.931 values obtained from our dataset are compatible with standards. The largest void ration

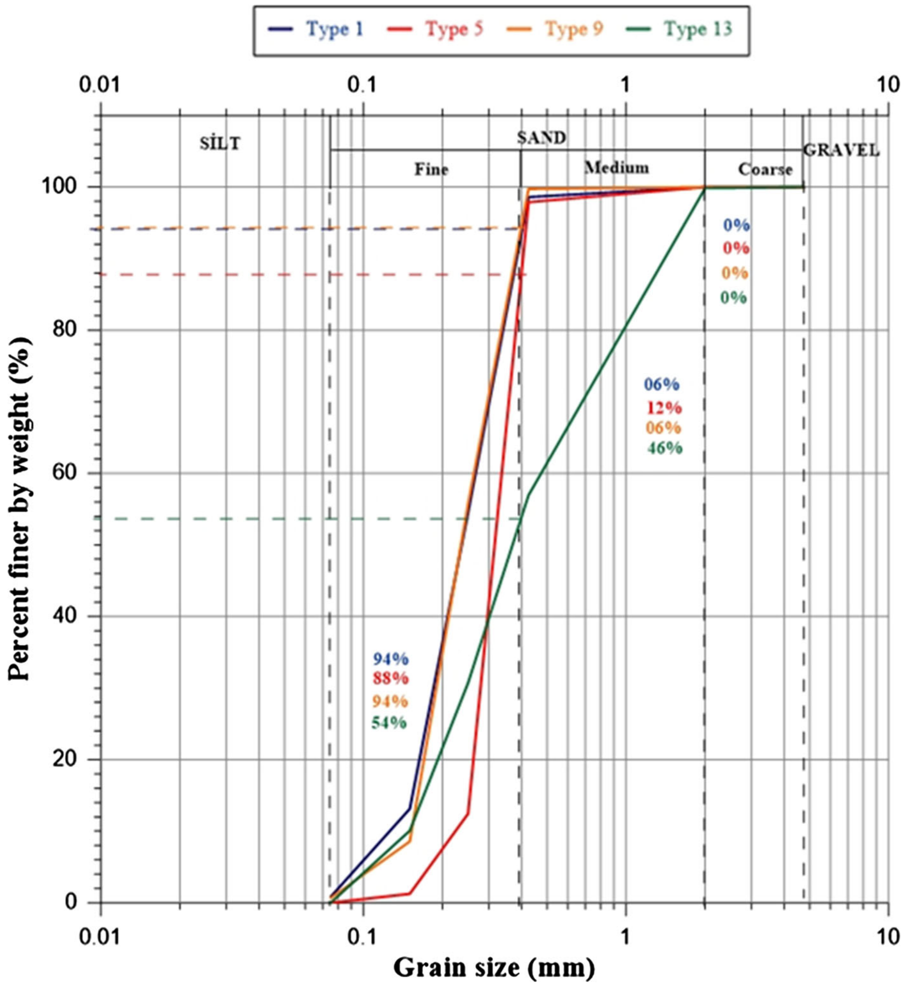


Fig. 13 Granulometry curves of Types 1, 5, 9, 13 sands

value was found in Type 13 (river sand). The differences for the maximum and minimum values are Type 1: 0.250, Type 5: 0.300, Type 9: 0.254, and Type 1: 0.335.

All four sand types were found to be poorly graded. Mica-containing sand is called micaceous sand, and even a small amount of mica can alter ground behavior. Type 13 and Type 5 sands contain mica. While the mica was removed from the Type 5 sand by washing, only a proportional change was detected in the Type 13 sand.

Of the four types of sand, the Type 1 sand is composed of the darkest granules, and the Type 13 sand is composed of the lightest-colored granules. Type 5 and Type 9 sands are similar to each other, whereas Type 5 sands have larger granules than Type 9 sands.

Sands taken from the same localities may have different mineralogical contents, while sands collected from different regions may exhibit similar mineralogical features. Thus, it has been determined that location is not a criterion for mineralogy.

Sand samples were subjected to a washing process in this study. As a result, while the anorthite was removed from Type 5 and Type 1 sands, Type 1 sand was enriched with fayalite and diopside. In Type 9, while there was no mineral eliminated by washing, an increase in the amount of quartz relative to anorthite was observed. In the Type 13 sand, while the anorthoclase was removed from the sample by

Table 6 Compilation of sieve analysis results of sands used in the experiment

	Type 1	Type 5	Type 9	Type 13
Gs	3.44	2.74	2.75	2.75
e_{max}	0.910	0.851	0.850	0.931
e_{min}	0.660	0.550	0.596	0.596
$e_{min} - e_{max}$	0.250	0.300	0.254	0.335
D_{10}	0.126	0.224	0.152	0.149
D_{30}	0.185	0.279	0.189	0.246
D_{50}	0.236	0.316	0.235	0.369
D_{60}	0.267	0.336	0.263	0.474
C_u	2.123	1.502	1.728	3.178
C_c	1.016	1.035	0.893	0.852
Fine	94%	88%	94%	56%
Medium	06%	12%	06%	46%

washing, there was an increase in the percentage of minerals other than quartz

In conclusion, it was determined that the sands used in the experiments have been affected by the geological characteristics of the areas from which they were taken, and that there are differences between marine and river sand. The test results are different according to the properties of the selected sands.

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