GEOTECHNICAL CHARACTERIZATION OF ZEOLITE-SAND AND BENTONITE-SAND MIXTURES

GEOTEHNIČNA KARAKTERIZACIJA MEŠANIC ZEOLITA IN PESKA TER BENTONITA IN PESKA

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Keywords

zeolite, bentonite, shear strength, correlation, neural networks, prediction

Abstract

This paper presents the characterization of pure bentonite- and zeolite-type clays and of various contents mixed with sand. The engineering properties of zeolites, bentonites and sand, which are commonly found in Malatya, Turkey, were evaluated in terms of their suitability for geotechnical applications. The crystallinity and structure of solid specimens of bentonite and zeolite were analysed with X-ray diffraction. Then both soils were mixed with sand in various proportions and the enhancement of the engineering properties was investigated. The properties of the mixtures, such as specific gravity, optimum water content, and dry unit weight mixtures, were initially determined. A set of direct shear tests was carried out to determine the shear-strength parameters of the specimens. As a result of extensive laboratory tests, linear correlations were observed between the water content and the consistency limits with the bentonite and zeolite contents in the sand mixtures. The highest for among each sample tested was achieved with the addition of 50 % bentonite and zeolite (i.e., BS50 and ZS50) as 44 and 38 kPa, respectively. A literature survey was carried out to reveal the test results of similar studies. In addition, using the test results from these literature studies and the current study, an NN-based prediction model was developed. The forecast models developed separately for cohesion and internal friction angle had high correlation coefficients: R^2 equal to 0.84 for cohesion and R^2 equal to 0.78 for the friction angle.

Ključne besede

zeolit, bentonit, strižna trdnost, korelacija, nevronske mreže, napovedovanje

Izvleček

V prispevku je predstavljena karakterizacija čistih bentonitnih in zeolitnih glin z različnimi vsebnostmi mešanic s peskom. Ocenjene so bile inženirske lastnosti zeolitov, bentonitov in peska, ki jih običajno najdemo v Malatyi v Turčiji, glede na njihovo primernost za uporabo v geotehniki. Z rentgensko difrakcijo sta bili analizirani kristaliničnost in struktura trdnih vzorcev bentonita in zeolita. Nato sta bili obe zemljini zmešani s peskom v različnih razmerjih in raziskano izboljšanje inženirskih lastnosti. Na začetku so bile določene lastnosti mešanic, kot so specifična gravitacija, optimalna vlažnost in suhe prostorninske teže mešanic. Za določitev parametrov strižne trdnosti preizkušancev je bil izveden niz direktnih strižnih preizkusov. Kot rezultat obsežnih laboratorijskih preizkusov so bile opažene linearne korelacije med vlažnostjo in mejami konsistence z vsebnostjo bentonita in zeolita v peščenih mešanicah. Najvišji kohezijski del strižne trdnosti med posameznimi preizkušanci je bil dosežen z dodatkom 50 % bentonita in zeolita (tj. BS50 in ZS50), in sicer 44 oziroma 38 kPa. Poleg tega je bil z uporabo rezultatov preizkusov študij iz literature in trenutne študije razvit napovedni model osnovan na nevronskih mrežah. Modela napovedi, razvita ločeno za kohezijo in kot notranjega trenja, imata visoke korelacijske koeficiente, in sicer: R^2 enak 0,84 za kohezijo in R^2 enak 0,78 za kot notranjega trenja.

1 INTRODUCTION

Soils that can be found freely in nature in different forms can provide remarkable improvements in terms of engineering and strength properties when combined with different types of soils or materials. Zeolites are natural and synthetic inorganic aluminosilicates that belong to a large family of open-framework materials consisting of aluminosilicate minerals. One of the most important features of zeolites, which contain a large number of channels and voids, is that they lose the water in these channels at high temperatures without destroying their structure. There are silicon, aluminum, and oxygen in their skeletal structures, and water molecules, alkaline and alkaline-earth cations allow ion exchange in their pores [1]. There are varieties of natural and synthetic zeolites such as clinoptilolite, chabazite, phillipsite and mordenite, which basically have similar molecular structures [2, 3]. Bentonites, on the other hand, are soft, porous and easily shaped, open rock, predominantly having a colloidal silica structure and consisting of clay minerals (mainly montmorillonite) with very small crystals formed by chemical weathering or the degradation of volcanic ash, tuff and lava rich in aluminum and magnesium. These two soil types, which stand out with their different structural and mechanical properties, are widely used in engineering applications and are still the subject of detailed experimental studies by researchers.

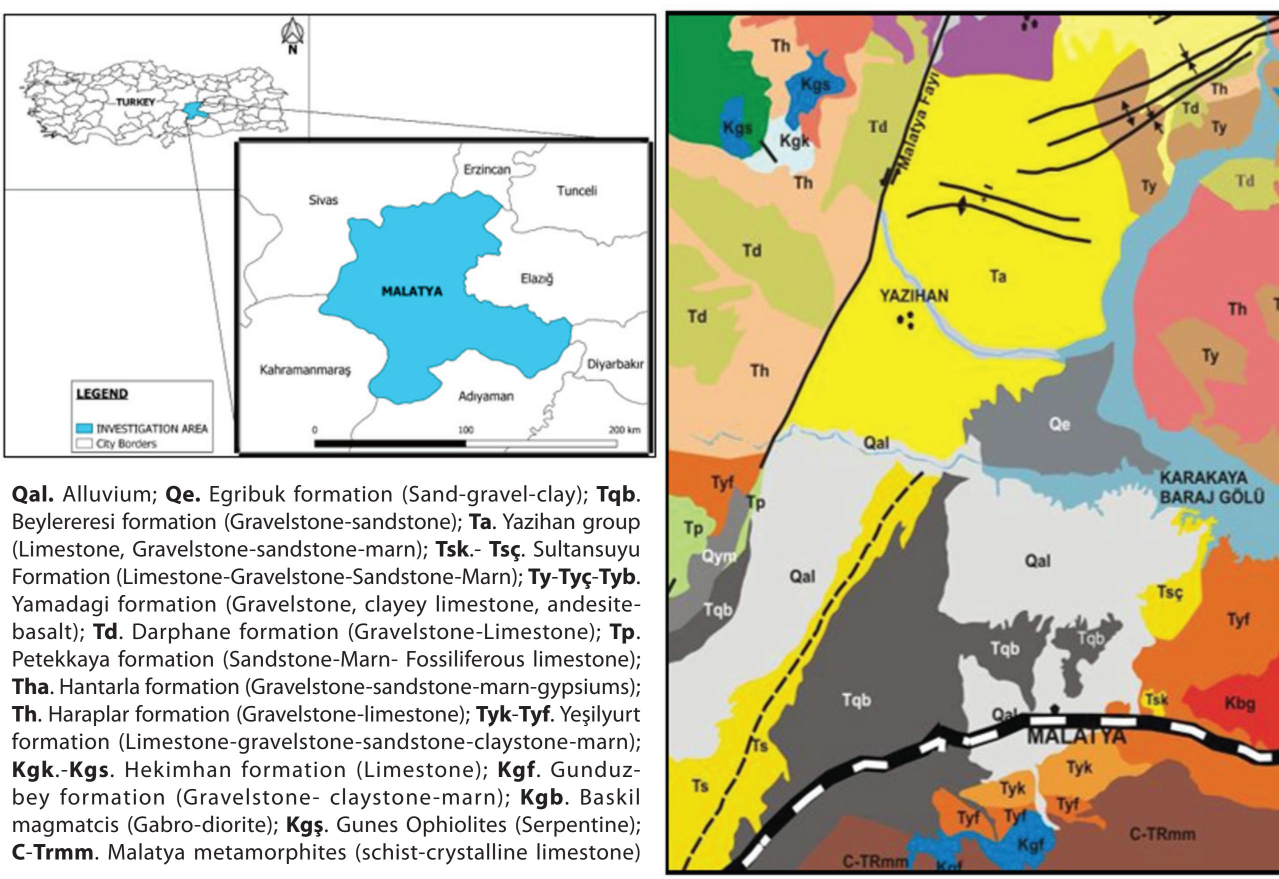
Zeolite, because of its abundance in nature and eco-friendliness, as well as its high potential to increase soil strength, can be a good alternative to a binding material. Due to its high cation-exchange capacity, zeolite can also be used as an adsorbent for the removal of pollutants in wastewater [4]. Besides, it is widely used as a soil-stabilization additive [5, 6, 7, 8, 9]. Yılmaz et al. [10] investigated the effects of zeolite on the mechanical properties of soil under the freeze-thaw effect. Mola-abasi and Shooshpasha [6] performed experiments and numerical modeling studies on the enhancement of the unconfined compressive strength of sand with the inclusion of zeolite. Yukselen and Aksoy [11] proposed zeolite-soil mixtures to be used as embankment- and landfill-liner material. Vogiatzis et al. [12] used Hellenic natural zeolite in mixtures with sand and portland cement. Natural zeolites used instead of sand in mortar mixes decreased the P-wave velocity of sand per unit weight. Mola-abasi et al. [13] investigated the effect of zeolite and cement on the strength of cemented sand specimens. Villalobos et al. [14] stated that zeolites improve the shear strength of the mixtures to which they are added, dependent on their grain size.

Bentonites, on the other hand, are defined as clays containing predominantly montmorillonite and have formed as a result of the chemical decomposition of volcanic ash, tuff, and lava rich in aluminum and magnesium. Its high swelling capacity is the most important feature that distinguishes bentonites from other clay minerals. Bentonite's properties, such as swelling with water, color, grain size, and moisture absorption ratio, mainly determine its usage areas. They are often used as an additive material and their physical properties are made use of rather than their chemical properties. Composed of high-swelling montmorillonite, bentonite has been used in various applications such as nuclear-waste dumps, drilling mud, and shear walls due to its water-holding capacity and permeability [15, 16]. To enhance the geotechnical properties of the host material, bentonites are jointly used with fly ash, graphite, basalt, or crushed rock as an additive [17, 18, 19]. The hydraulic conductivity of pure bentonite and bentonite-sand mixtures was investigated by considering the difference between the size of both materials [20]. Proia et al. [21] performed experiments with sand-bentonite mixtures of various contents. The inclusion of bentonite even at smaller amounts (i.e., ≤ 5 %) reduces the hydraulic conductivity and with the inclusion of higher amounts of bentonites, the mixture becomes more compressible. The hydraulic conductivity of sand-bentonite mixtures decreases by four orders of magnitude with the inclusion of 5 % bentonite [22]. Muntohar [23] stated that the existence of bentonite in the soil mixtures influences the swelling behavior, through a hyperbolic curve model. Alkaya and Esener [24], using various contents of cement and bentonite, revealed that the mixture with 10 % bentonite has the best performance in terms of hydraulic conductivity. Durukan et al. [25] investigated the suction behavior of zeolite-bentonite and sand-bentonite mixtures. In experimental studies where zeolite is used in different physical forms, it has been observed that as the grain size increases, the suction capacity increases, and zeolite-bentonite mixtures exhibit higher matric suction values than sand-bentonite mixtures.

The above-mentioned studies demonstrate that both bentonite and zeolite materials have been used in a wide range of applications and investigated in accordance with different purposes. In many of the studies, zeolite and bentonite were mixed with sand for different purposes and a summary of the literature survey is given in Table 1. In this study, experimental investigations will be carried out, particularly on zeolite and bentonites, which are two common soil types in the investigation area of the city of Malatya.In the first place, engineering properties (i.e., grain size, specific gravity, optimum water content, maximum dry unit weight, consistency limits and shear strength) were determined. The results obtained for both pure and mixed materials were examined to assess the materials' suitability for geotechnical applications. A literature survey was carried out and the results of similar tests were compiled. Using both literature and current test results, a prediction model was developed. The shear parameters of the specimens were estimated using the prediction model. The feasibility of NN-based prediction models in estimating the shear-strength parameters of multi-component composite materials such as the used soil pairs was demonstrated.

2 GENERAL GEOLOGY

The city of Malatya is located in eastern Turkey. It has an area of 12,313 km^2 (Figure 1). The Malatya plain was formed after the Alpine folding by the fractures and folds during the tectonic movements that emerged at the end of the third geological time and the beginning of the fourth period. It is one of the densest settlements in eastern Anatolia. The base rock unit in Malatya and its environs is metamorphites consisting of permo-carboniferous schists and crystallized limestones cropping out. In the south of Yeşilyurt and Gündüzbey, there is a conglomerate consisting of red-colored terrestrial conglomerate, sandstone, and mudstone from bottom to top. Inekpinari limestone consists of shallow marine carbonates, the Kapullu formation consists of conglomerate, sandstone, limestone, and shale alternation, and Haçova formation consisting of tuff and andesites exists at the top. On the other hand, in the surrounding Yeşilyurt and Gündüzbey areas, the Yeşilyurt group consists of Zorban pebblestone, red-colored conglomerate, and sandstones in the form of alluvials from bottom to top, and Yıldız limestone, which consists of reefal limestones. Overlying the Yıldız limestone, the upper Banazi formation with conglomerate, sandstone, and shale alternations emerge. This formation is also harmoniously overlain by Banaz limestones, the Malkuyu formation consisting of marls, and the Gedik formation consisting of reefal limestones. At the bottom of the Lower-Middle Miocene aged terrestrial formations outcropping in the near west, north, and east of Malatya, there is the Akyar formation, which consists of Lower



Qal. Alluvium; **Qe.** Egribuk formation (Sand-gravel-clay); **Tqb**. Beylereresi formation (Gravelstone-sandstone); **Ta**. Yazihan group (Limestone, Gravelstone-sandstone-marn); **Tsk**.- **Tsç**. Sultansuyu Formation (Limestone-Gravelstone-Sandstone-Marn); **Ty-Tyç-Tyb**. Yamadagi formation (Gravelstone, clayey limestone, andesite-basalt); **Td**. Darphane formation (Gravelstone-Limestone); **Tp**. Petekkaya formation (Sandstone-Marn- Fossiliferous limestone); **Tha**. Hantarla formation (Gravelstone-sandstone-marn-gypsiums); **Th**. Haraplar formation (Gravelstone-limestone); **Tyk**-**Tyf**. Yeşilyurt formation (Limestone-gravelstone-sandstone-claystone-marn); **Kgk**.-**Kgs**. Hekimhan formation (Limestone); **Kgf**. Gunduzbey formation (Gravelstone- claystone-marn); **Kgb**. Baskil magmatcis (Gabro-diorite); **Kgş**. Gunes Ophiolites (Serpentine); **C**-**Trmm**. Malatya metamorphites (schist-crystalline limestone)

Figure 1. Site location and the general geological map of Malatya [26].

Miocene aged reef limestone and marls. The Kuseyin formation, which consists of red conglomerate, sandstone, mudstone, and gypsum conformably overlies the Akyar formation. This Lower Miocene-aged succession is conformably overlain by the Middle Miocene-aged Kilayik, Parçikan, Şeyhler, Sultansuyu, and Beylereresi formations. The general geological map created by the local government officers is given in Figure 1.

The zeolites located in the vicinity of Hekimhan, a district of Malatya, are of marine origin and spread over an area of approximately 90 km^2. The Upper Cretaceous unit is separated into two different units: the lower zeolite and the upper zeolite unit. The lower zeolite unit consists of zeolite with mafic minerals and layers with massive zeolite minerals. Its thickness is at most 15 m and a lateral continuation of 5 km is observed. The upper zeolite unit consists of zeolite minerals with sandstone interlayers. Its thickness is at most 38 m and a lateral continuity of 24 km is observed. The total geological reserve of the lower and upper zeolite levels is 190 million tons [27]. In addition, it is predicted that there are bentonite reserves at the rate of 50 thousand tons/year in Malatya province Battalgazi, Arapgir, Taskiran and Karahüyük districts and localities. It is stated that when the research is expanded to include the surrounding provinces, important reserve areas suitable for the use of different industries can also be determined. The directorates of mineral research and exploration, affiliated with the central government, are actively operating in the region.

3 EXPERIMENTAL STUDY

3.1 Materials and Methods

In the experimental studies carried out within the scope of this paper, three different soils were used, i.e., sand, zeolite and bentonite. The selected sand type is widely used in Malatya, especially in the construction industry, and was obtained from the Hekimhan district of Malatya. Zeolite material is freely available in the district of Hekimhan in Malatya. Bentonite is also found freely in nature in the Battalgazi district of Malatya. Both of the materials were supplied in block form; they were grinded and were suitable for our experiments. The grain-size-distribution curves of sand, bentonite and zeolite are shown in Figure 2. According to the USCS (Unified Soil Classification System), sand is classified as SW. The bentonite and zeolite are categorized as MH and CH, respectively. Each of the tested materials and mixtures with varies proportions were demonstrated in Figures 3–5. A series of geotechnical laboratory tests were carried out to determine the engineering parameters of the sand, bentonite, and zeolite, as well as their mixtures with specified contents. In addition to clean specimens, bentonite and zeolite were mixed in five different contents with sand: 10 %, 20 %, 30 %, 40 %, and 50 %. The specimens were abbreviated as B, S, Z, BS10, ZS50, etc. The letters represent the initials of the components of the mixture. The numeral represents the percentage of the additive in the mixture. For instance, BS20 is the abbreviation for the mixture of sand with

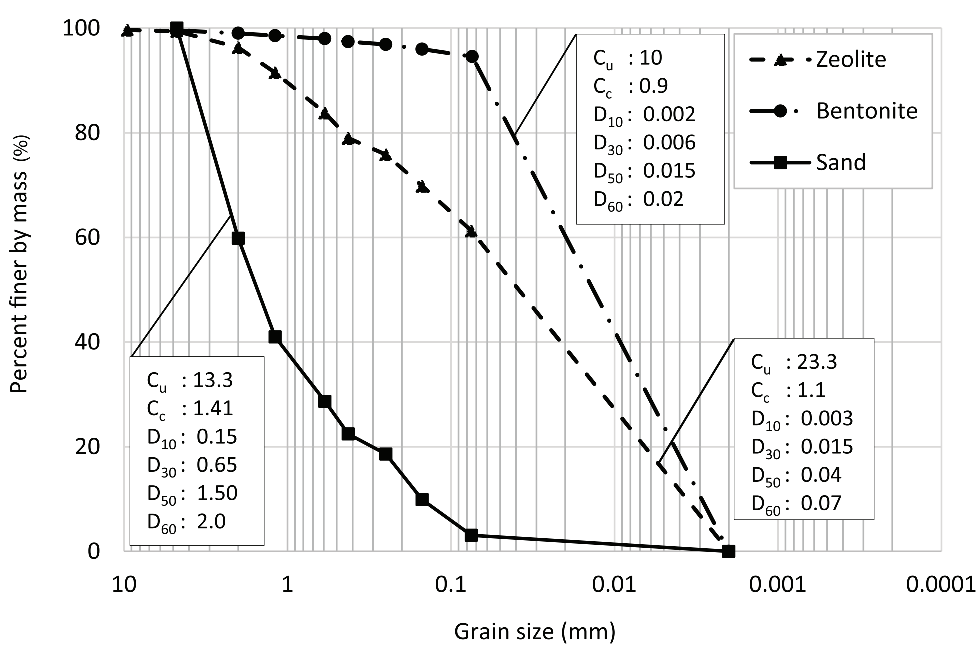


Figure 2. Grain size distribution of the soils.

Table 1. The summary of the recent studies on use of zeolite and bentonite.

Case	Soil*	Content (%)	PI (%)	w_{opt} (%)	γ (kN/m^3)	C (kPa)	φ (°)	Reference
1	B/S	10/90	13.7			3	28.7	[33]
	B/S	20/80	59.3			10	19.6	
	B/S	30/70	98.9			6	8.7	
	B/S	40/60	157.6			7	5.6	
	B/S	50/50	201.7			5	3.8	
	B/S	70/30	312.4			6	3.8	
2	B/S	10/90		18.6	16.1			[34]
	B/S	20/80		19	15.63			
3	Z/S	25/75		10.14	19.33			[35]
	Z/S	50/50		18.26	15.93			
	Z/S	75/25		27.03	13.89			
4	B/S	50/50		22.5	15.35			[36]
	B/S	60/40		19	15.96			
	B/S	70/30		16	16.3			
	B/S	80/20		15.1	16.77			
	B/S	90/10		14.5	16.39			
	B/S	50/50		22.5	15.54			
	B/S	60/40		20.5	15.64			
	B/S	70/30		18	16.23			
	B/S	80/20		18.4	16.68			
	B/S	90/10		17.2	16.08			
5	B/S	15/85	52	17	16.6			[37]
	B/S	25/75	70	15	17,2			
6	B/S	3/97		10	19.35	6.43	47	[22]
	B/S	5/95		10.5	19.1	21.47	37	
	B/S	7/93		11.2	18.68	24.11	35	
	B/S	9/91		12	18.56	24.9	33	
7	B/S	20/80		15.28	1727	16.4	24.9	[38]
8	B/S	15/85	115	15	17.3			[39]
	B/S	25/75	231	15.8	17.2			
	B/S	50/50	333	20	15.2			
9	B/S	70/30	59	27	15.1			[40]
	B/S	60/40	46	22	15.9			
	B/S	50/50	30	18	16.6			
10	B/S	5/95		19.4	15.79			[41]
	B/S	10/90		17.6	16.08			
	B/S	20/80		17	16.47			
	B/S	30/70		14.6	16.87			
	B/S	50/50		17.5	16.28			
11	Z/S	25/75		16.5	17.5	30.6	37.3	[42]
	Z/S	50/50		20	16.8	32.5	35.8	
	Z/S	75/25		22.5	15.7	31.2	31.7	
12	Z/S	5/95	3.85	9	20.08		31.23	[43]
	Z/S	10/90	3.848	10.2	19.5		31.48	
	Z/S	15/85	3.328	11.5	18.7		32.55	
	Z/S	20/80	3.08	12.3	18.3		33.34	
	Z/S	25/75	2.92	13	18		33.18	
	Z/S	30/70	3.84	13.8	17.93		33.27	
	Z/S	35/65	4.16	15.3	17.25		33.29	

* Z, B and S denote the zeolite, bentonite and sand, respectively.

20 % bentonite. Grain-size-distribution analyses, compaction tests, consistency limit tests, permeability tests, and direct shear tests were performed in accordance with ASTM D422-63, ASTM D698, ASTM D4318, ASTM D2434-94, and ASTM D3080-98, respectively [28, 29, 30, 31, 32]. The clean sand specimen used in the experiments was left to dry at room temperature in a laboratory environment. The dried specimens were sieved with # 4 (4.75 mm) and # 200 (0.075 mm) sieves, and the material remaining between the number # 4 and # 200 sieves were used in the experiments. Bentonite and zeolite specimens were taken from a depth of 1.5 to 2 m from the surface and left to dry at room temperature. The dried specimens were grinded in a ball mill and sieved through sieve # 200. In the experiments, materials finer than 0.075 mm were used. The materials were prepared by dry mixing the bentonite and zeolite with sand separately at the specified mixing ratios (i.e., 10 %, 20 %, 30 %, 40 %, and 50 %). While the samples for the consistency limit test were kept in a desiccator overnight, the samples soaked in the standard proctor test were subjected to the test by keeping them in sealed bags for at least 3 hours. The specimens that were moistured and compressed at an optimum water content were used in direct shear tests. Pure water was used for wetting specimens by spraying to form a homogeneous mixture.

Figure 3. Pure materials used in the experimental study.

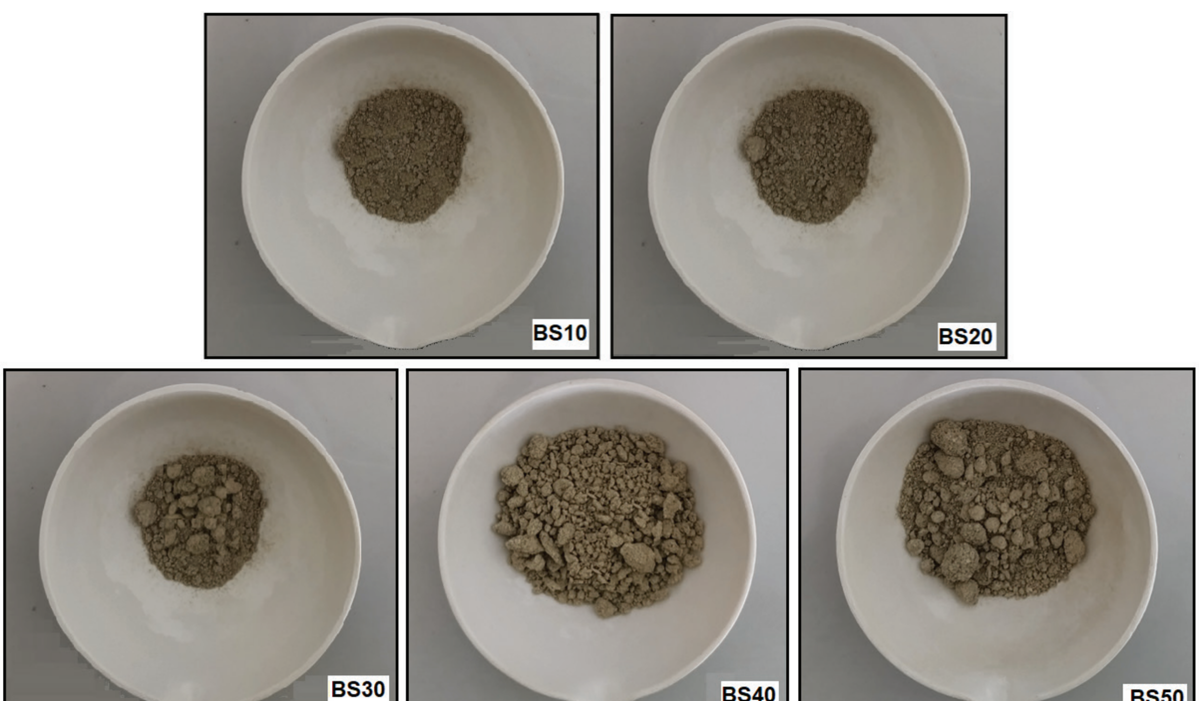


Figure 4. BS specimens with various bentonite contents.

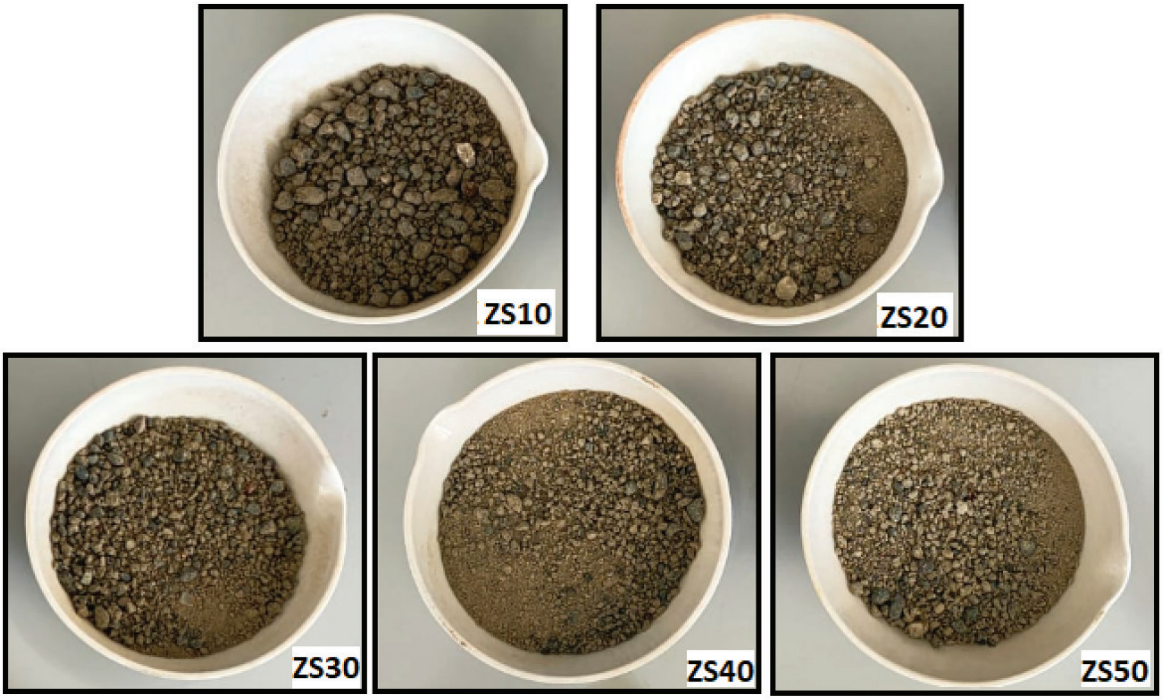


Figure 5. ZS specimens with various zeolite contents.

4 DISCUSSION AND RESULTS

4.1 Laboratory tests

Prior to the geotechnical laboratory tests, mineralogy and microscopic analyses of the zeolite were carried out. The identification of the zeolites using X-ray techniques is difficult because of the different cell dimensions and the differences in the relative intensities of the bands [11]. As can be seen in the XRD pattern in Figure 6, the zeolite has a high concentration of quartz and lower calcite and clinoptilolite content. controlled XRD analyzes were performed in Inönü University laboratories (IBTAM). The basis of the work was to detect different crystal structures or the parameters in crystalline materials based on the reflection (refraction) of the x-ray. The beam is reflected (i.e. or refracted) on the sample and the beam detected with the help of a detector is transferred to the graph with the 2θ value corresponding to the reflection intensity using software. To determine the mineralogical compositions of the raw materials used the materials were prepared by passing

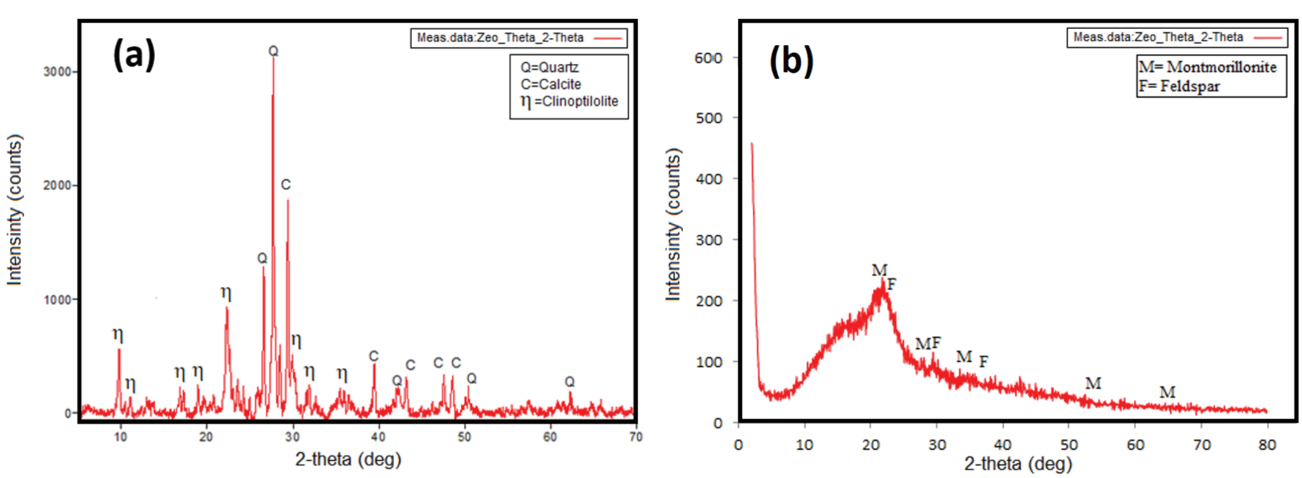


Figure 6. X-ray diffraction spectra of the (a) zeolite, (b) bentonite.

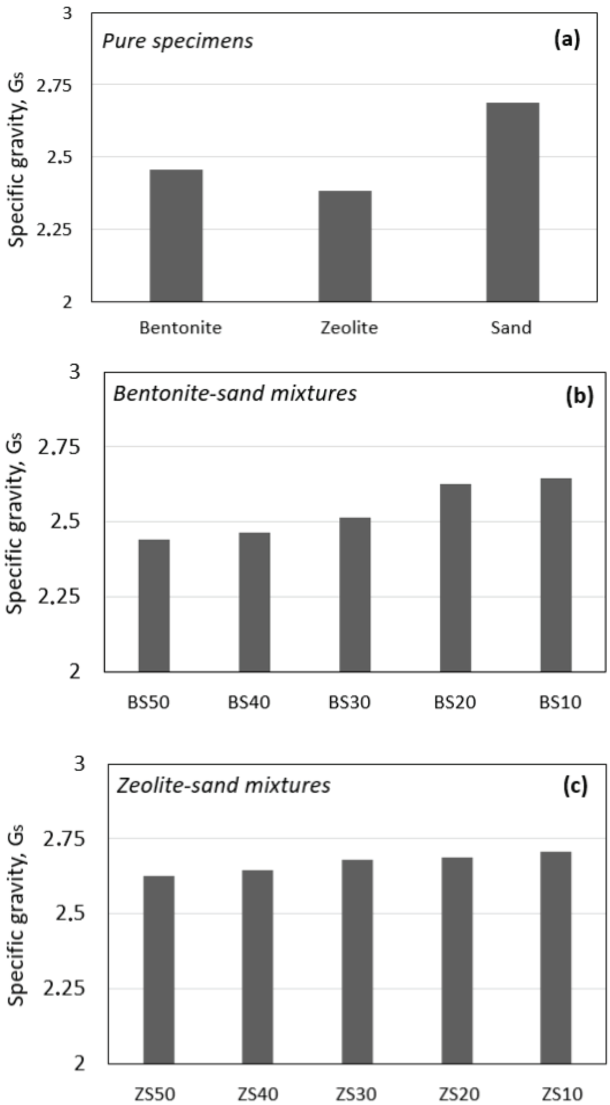


Figure 7. Specific gravity of pure specimens and mixtures.

through a 150-µm sieve. The X-rays were detected with a RigakuRadB-DMAX II computer-controlled X-ray diffractometer using Cu–Kα radiation. Measurements were scanned between $2\theta = 3°$ to 80° degrees and at a constant speed of 3°/min. The analyses were performed according to the ASTM D5758 standard [44]. The diffractogram of natural zeolite shows the intensity at a 2θ angle of 26° with a peak of 3100 counts corresponding to the presence of quartz (SiO_2), which is a very common and important mineral. The bentonite, on the other hand, includes montmorillonite at a 2θ angle of 22° with a peak of 235 counts. The second-most intense mineral was found to be feldspar in bentonite. The specific gravities of the sand, bentonite and zeolite were calculated as 2.69, 2.46 and 2.38, respectively. Accordingly, the increasing content of both bentonite and zeolite leads to a decrease in the specific gravity of the mixtures (Figure 7). As a host material, when the sand is mixed with bentonite or zeolite, a soil mass is formed in which sand particles make up the skeleton structure and additive particles occupy the voids in the matrix [41]. The size, distribution and compressibility of these voids are mainly dependent on the size, shape and proportions of sand particles in the mixture [36, 45]. Also, the mineralogy, content, compaction energy applied and moisture content are the influencing parameters for the mechanical characteristics of the compacted specimens [36, 41, 46, 47, 48, 49]. A set of modified proctor compaction tests was carried out and the optimum water content for the maximum compaction and unit weight was obtained for the specimens. As can be seen, the amount of water required to obtain the maximum unit weight is increasing with the increasing bentonite and zeolite content. The maximum unit weight of the BS10 specimen is 2.1 g/cm^3 for 12.3 % of water inclusion. The BS50 specimen including 50 % of bentonite in the mixture reaches the maximum unit weight as 1.67 g/cm^3 with 21 % of water content (Figure 8). In bentonite-sand mixtures, the values reached regarding the optimum water content are higher than that of the zeolite-sand mixtures (Figure 9). This is most likely because the included bentonite specimens have a relatively large surface area that causes a higher amount of water absorption than the included zeolite specimens. Since the bentonite particles are finer than the zeolite particles, the pores between the sand grains are reduced more easily in the BS specimens. Therefore, the optimum moisture content of the bentonite sand mixtures is higher than that of the zeolite-sand mixtures for the same additive content. The highest unit weight can be achieved with less water content for the ZS specimens. For example, the unit weight of the BS50 specimen is observed to be 14 % lower than that of ZS50 (i.e., 1.90 to 1.67 g/cm^3). The amount of water for the BS50 and ZS50 specimens is 21 % and 15 %, respectively. Even the compressibility of the clay-coarse-soil mixture is assumed to be dependent on the complex physicochemical interactions of the clay particles and the contribution of the mechanical properties of coarse soil (Bolt, 1956), a very clear pattern observed by the compaction curves [46].

Figure 10a shows the variation of the optimum water content needed to achieve the maximum unit weight for each content of bentonite and zeolite in the sand. The variations in the optimum water content due to bentonite and zeolite addition to the sand can be clearly observed. As the amount of inclusion increases, the optimum water content increases. Both the compaction curves of the BS and ZS specimens were following a definite pattern. As can be seen from the regression curves, the optimum water content for the maximum

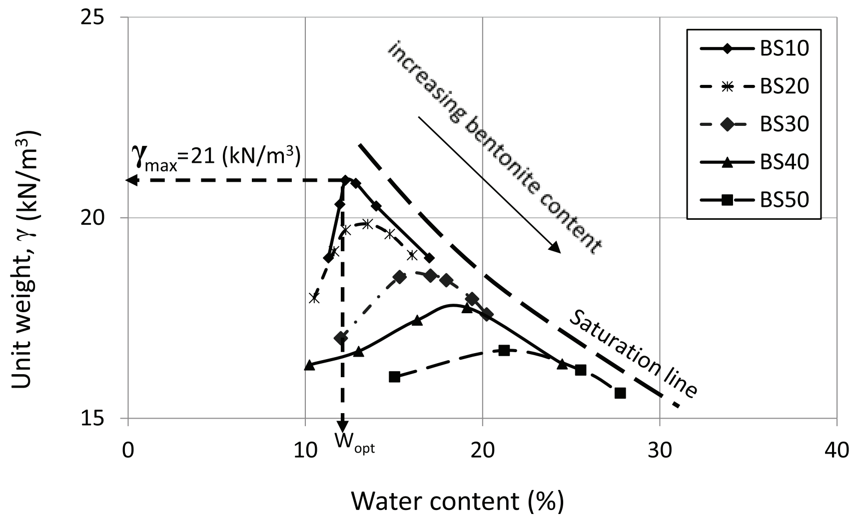


Figure 8. Compaction curves of the bentonite-sand mixtures.

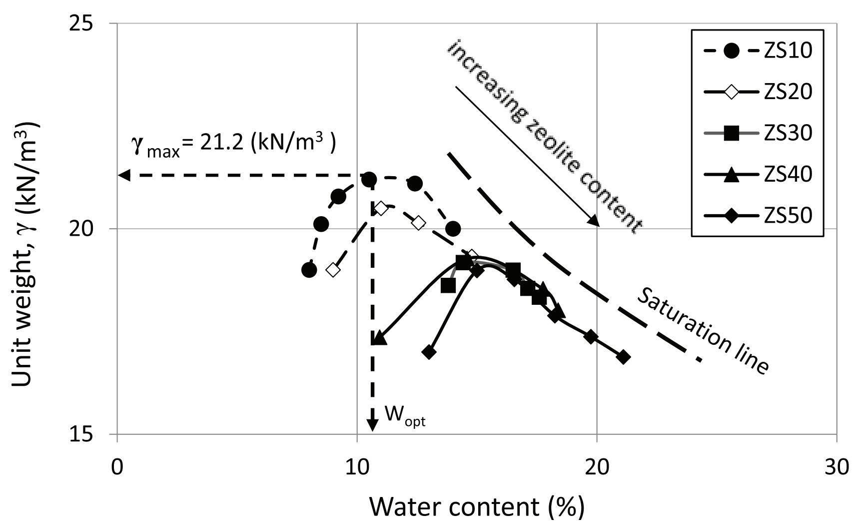


Figure 9. Compaction curves of the zeolite-sand mixtures.

compacted unit weight in correlation with bentonite/zeolite content in the mixtures. The amount of water required to bring the mixtures to the maximum unit weight is much less for the ZS specimens than for the BS specimens (Figure 10b). This is necessarily related to the difference between the gradational parameters and the compactional characteristics of both materials. It was observed that the water-holding capacity of bentonite is higher than zeolite for the same mixing ratios. In other words, the water-adsorption capacity of bentonite is higher than that of zeolite. The maximum unit weight of specimens decreases with the increasing water content. It should also be remembered that bentonite is used in engineering applications as a dispersive material. The high correlation coefficients between the content of both bentonite and zeolite in the mixture and the optimum water content clearly show how much the compaction behavior is suppressed by the additive content in the mixture. Depending on the types of soil used, linear relationships between the optimum water content, the maximum unit weight and the applied compaction energy were also developed with similar studies [24, 34, 50, 51, 52].

The plasticity characteristic of the mixtures depends on the content and type of mineral in the additive [53]. In some studies, it has been suggested that at low clay contents, the mixture exhibits predominantly granular properties, while higher ratios a gradual transition to mechanical behavior of the plastic clay occurs [21]. However, Bowles [54] stated that the addition of 2 % clay to sand is the initial value for transforming the

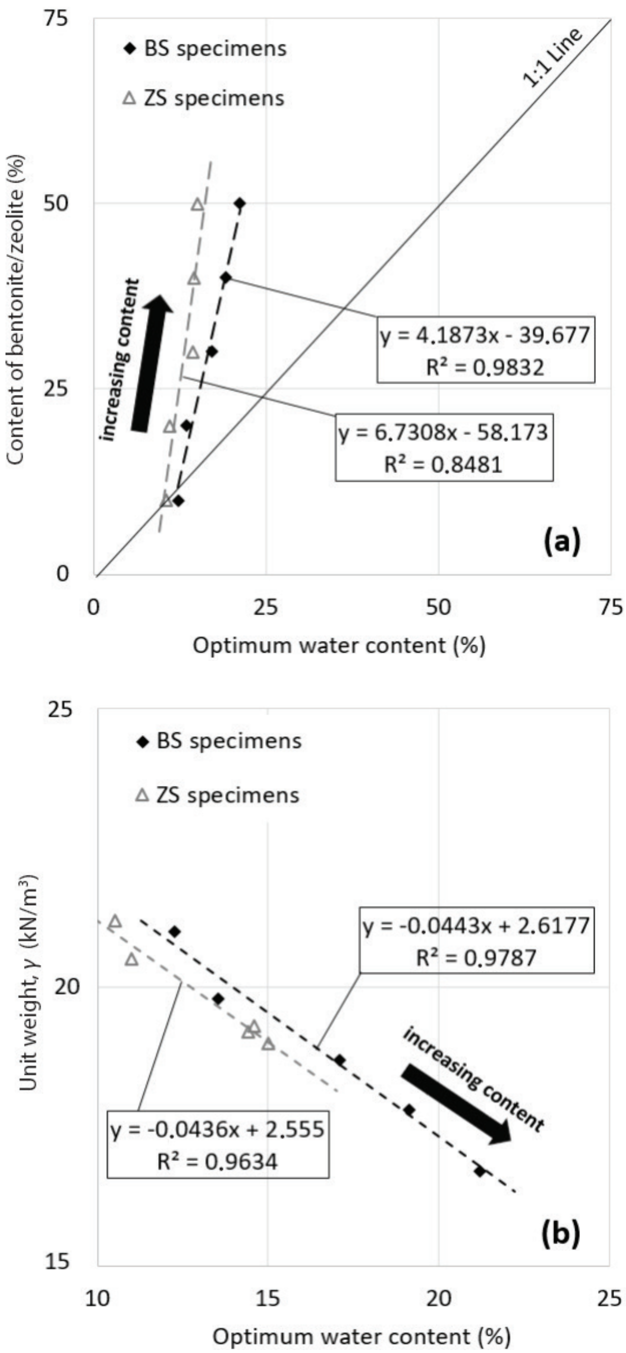
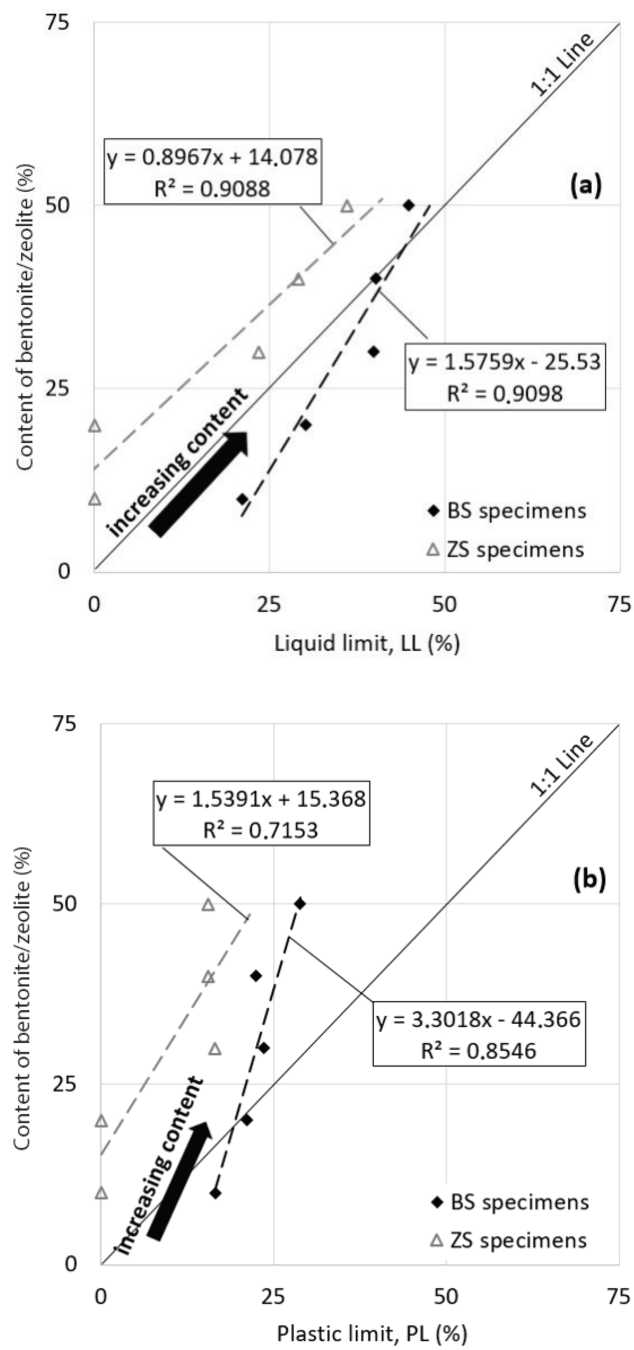


Figure 10. Variation of (a) additive content and (b) unit weight of specimens with optimum water content.

mixture from a sandy state to a clayey state. It is, therefore, the amount of zeolite and bentonite in the mixture was set at higher contents in this study. The variation of the consistency limits with additive content is presented in Figure 11. The consistency parameters of the mixtures increase with increasing both bentonite and zeolite content. The zeolite at a higher content of 20 % displayed an increase in the plasticity of the mixtures. The ineffectiveness of the zeolite addition at less than 6–10 % on the plasticity is attributed to chemical properties such as the sodium absorption ratio (SAR) and exchangeable sodium percentages (ESP) [55]. The bentonite, on the other hand, even with smaller contents, has led to an increase in plasticity. The montmorillonite included in the bentonite has a key role in its plastic behavior. As can be seen from the high correlation coefficient, the variation between the content and the liquid limit is almost linear



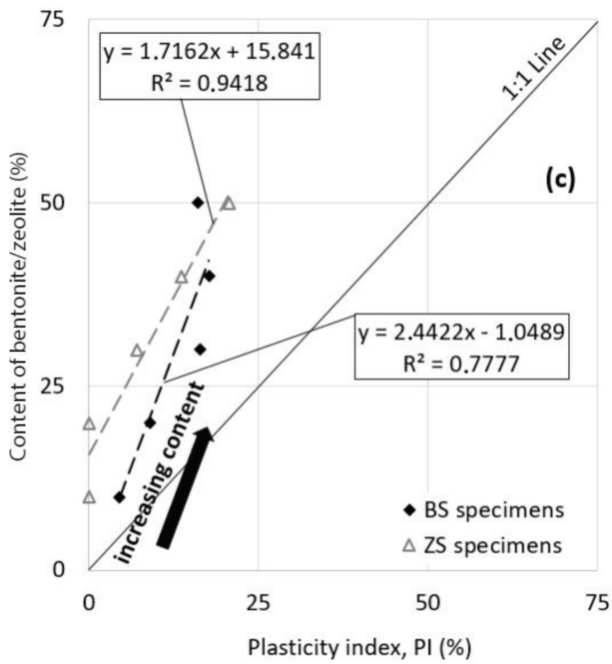


Figure 11. Variation of the consistency limits with additive content.

(Figure 11a). The regression lines show that the inclusion of additives has a lower effect on the plastic limit than on the liquid limit (Figure 11b). Bowles [54] also stated that the increasing bentonite inclusion into sand leads to a linear increase in the liquid limit, but has a limited effect on the plastic limit. It is clear that zeolite is more effective than bentonite on the plasticity index at mixing ratios greater than 20 % (Figure 11c). The plasticity characteristics of the sand-bentonite mixtures are dependent on the clay content and the clay-mineral type [56]. The granulometry and mechanical characteristics are also found to be factors influencing the plasticity [57]. It is assumed that the plasticity effect induced by the addition of zeolite and bentonite, even with the same content, is not at the same level. The Casagrande plasticity chart built with the consistency limits of the specimens is shown in Figure 12.

The specimens were obtained by artificially mixing soils with different physical and mechanical properties. Thus, the advantages of both materials can be combined by trying combinations with different contents [21]. It is important to examine the shear strength of the BS and ZS specimens formed by mixing at different ratios. The shear-strength parameters of the specimens are significant, especially for a stability analysis. In the case of their use as liners or backfill materials, the shear strength of the zeolites and bentonites was investigated for both the drained and undrained cases. In this study the cohesion and internal friction angle of the specimens were determined through undrained direct shear tests. The compacted BS and ZS specimens were sheared immediately after compaction. The normal stresses applied as 28, 56 and 111 kPa. A strain rate of 0.5 mm/min was used for all tests and the time required for shearing the specimens to failure was about 10 to 15 min. For each content of zeolite and bentonite, the test results demonstrated that increasing the applied normal stress leads to an increase in the shear stress. It was also observed that the measured maximum shear stress decreases with increasing additive content. The mixture with a 50 % inclusion of bentonite and zeolite (i.e., BS50 and ZS50) had the best performance as 92 and 87 kPa

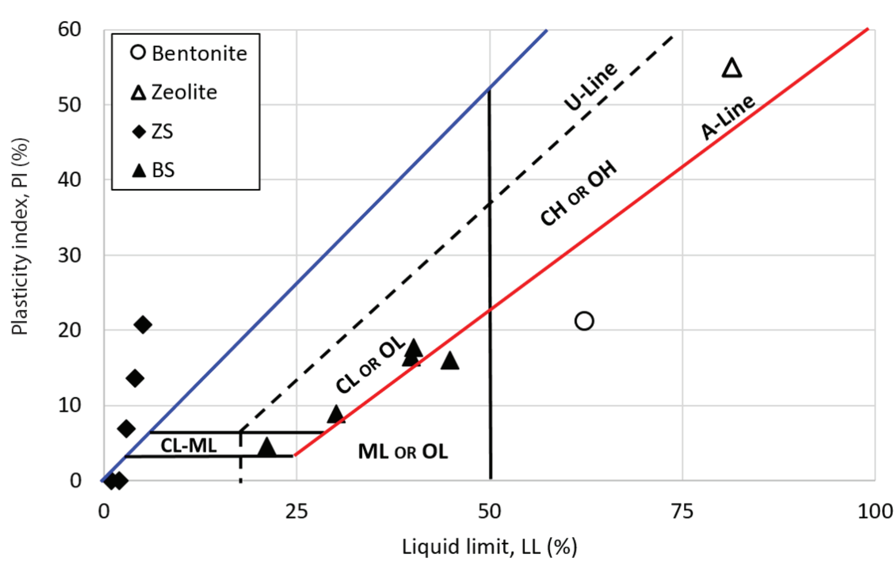


Figure 12. Casagrande plasticity chart of tested specimens.

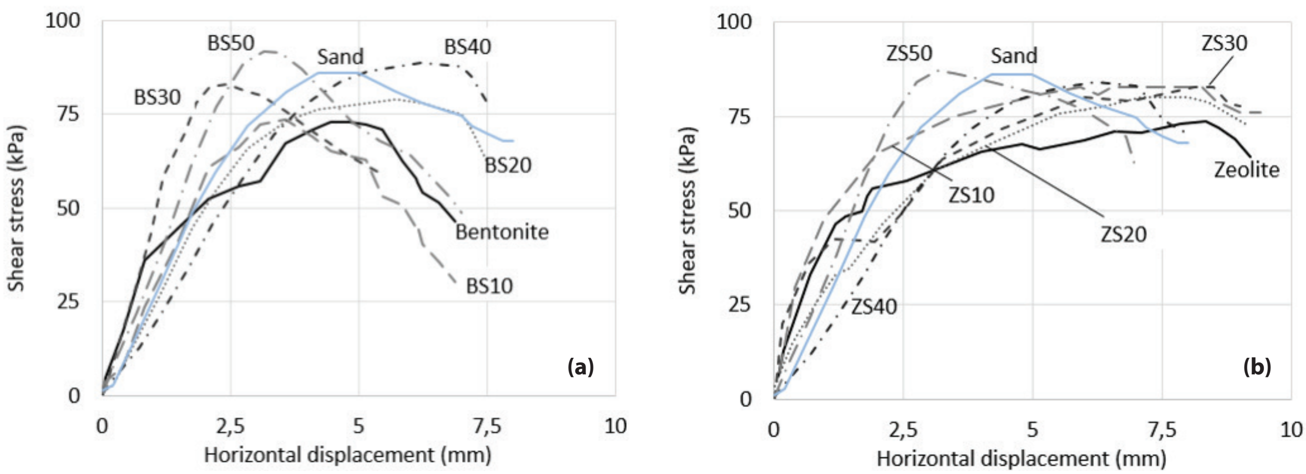


Figure 13. Direct shear test results of the specimens; (a) Bentonite and BS specimens, (b) Zeolite and ZS specimens.

under 111 kPa normal stress, respectively (Figure 13). The specimens having smaller contents of additives display a hardening behavior during shearing, which is more visible for the ZS specimens. The variation of the maximum shear stress with the normal stress is shown in Figure 14. Specimens containing both bentonite and zeolite under lower normal stresses show a higher shearing response than the clean sand. However, when the applied normal stress increases from 28 kPa to 111 kPa, the response of the clean sand and the mixtures to shearing becomes closer. Under higher normal stresses, only specimens with a greater content of bentonite and zeolite (i.e., BS40, BS50 and ZS50) have higher shear stresses than clean sand. This shows that the shear behavior of the mixtures is sensitive to the applied normal stress, so it makes sense to interpret the shear behavior in two parts. In contrast to some literature studies, the specimens appear to exhibit sand-like behavior at high bentonite and zeolite mixing ratios in terms of shear behavior.

The variation of the engineering properties of the specimens with multi-component soils is directly affected by the proportional distribution of the soil types in the mixture. As previously mentioned, one of the main motivations of this study is to combine different soil types and to take advantage of the better engineering properties of each of the components. Therefore, triple graphical representations of direct shear test results are given in Figure 15. While the shear stress was measured under 111 kPa normal stress with clean sand and pure bentonite was 86 and 73 kPa, respectively, this value increased to 92 kPa with the BS50 specimen. This situation occurred similarly to the ZS50 sample (i.e., 87 kPa) (Figure 15b). The shear strength of the specimens consists of two components: the cohesion and the internal friction angle. When bentonite and zeolite as cohesive materials were combined with sand, a decrease in the cohesion values was measured, as expected. Cohesion values of 67 and 69 kPa, measured for pure bentonite and pure zeolite, were decreased to 44 kPa and

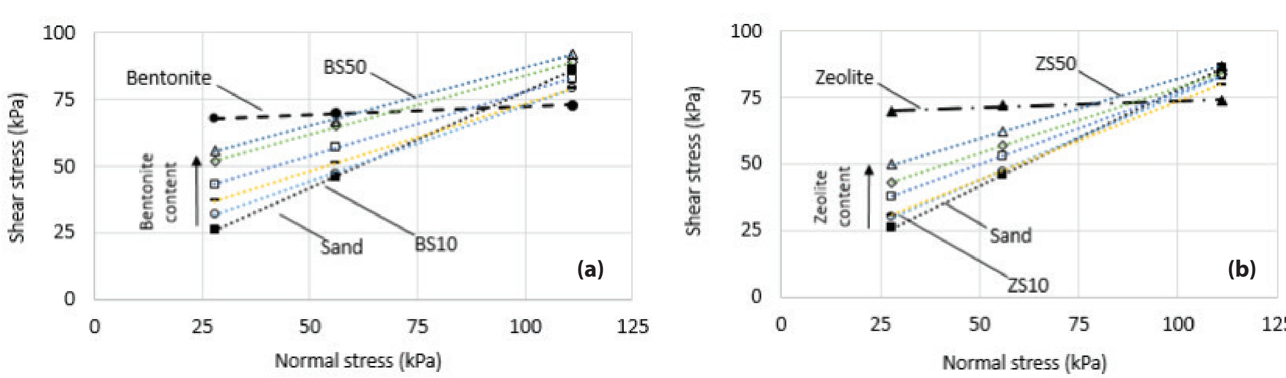


Figure 14. Shear resistance of the specimens tested under various normal stress;
(a) Bentonite and BS specimens, (b) Zeolite and ZS specimens.

38 kPa for the BS50 and ZS50 specimens, respectively (Figure 15c-d). However, the internal friction angles of the pure specimens, which were 3° and 2°, increased to 23° and 33°, respectively. When bentonite is mixed with sand, due to its very small particle size it occupies the pore space present between the individual sand grains which is also valid for zeolite [53]. The optimum amount of material replacement by zeolite or bentonite for the highest improvement in the shear-strength parameters was also investigated by different researchers [4, 58, 59, 60]. It is essential to determine the optimum content of the materials, which will meet the design target, with both strength values and other engineering properties. The basic engineering properties, compaction, consistency limits and direct shear test results of all specimens are collectively given in Table 3.

5 PREDICTION MODEL

Soft-computing methods, which are used in the analysis of multivariate and multi-parameter numerical problems that are difficult to interpret with analytical models, are widely used in almost every field. These methods have

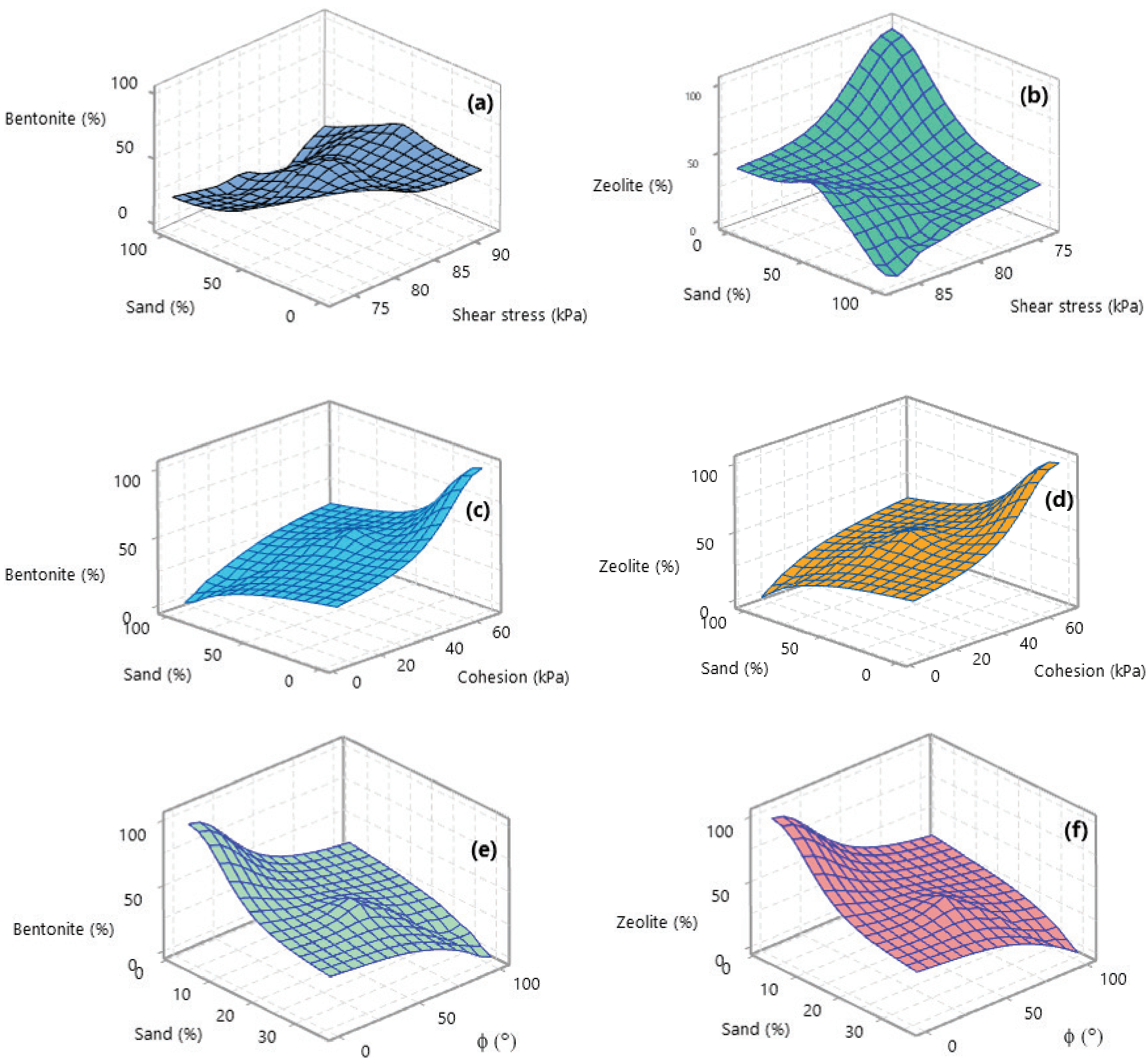


Figure 15. Variation of direct shear test results (a) bentonite, (b) zeolite content

Table 2. Summary of the geotechnical experiment results.

Specimen	G_s	LL (%)	PL (%)	PI (%)	w_{opt} (kPa)	ρ_{dmax} (g/cm^3)	C (kPa)	φ (°)	USCS
S	2.69	NP	NP	NP	-	1.34	6	36	SW
Z	2.38	81.5	26.5	55.0	20.4	1.49	69	2	CH
B	2.46	62.3	41.0	21.3	32	1.22	67	3	MH
BS10	2.65	21.1	16.5	4.5	12.3	2.10	16	30	ML
BS20	2.63	30.1	21.2	8.9	13.5	1.98	24	26	CL
BS30	2.51	39.9	23.6	16.3	17.1	1.87	30	25	CL
BS40	2.46	40.2	22.5	17.7	19.1	1.78	39	24	CL
BS50	2.44	44.9	28.8	16.1	21.2	1.67	44	23	ML
ZS10	2.69	NP	NP	NP	10.5	2.12	12	33	NP
ZS20	2.69	NP	NP	NP	11	2.05	15	30	NP
ZS30	2.68	23.5	16.5	7.0	14.4	1.92	23	28	CL
ZS40	2.65	29.1	15.5	13.6	14.6	1.93	29	26	CL
ZS50	2.63	36.1	15.5	20.6	15.0	1.90	38	24	*CL*

also been widely used by researchers in geotechnical engineering [61, 62, 63, 64, 65, 66]. Also, a comprehensive literature survey was carried out on the use of neural networks in geotechnics [67]. Prediction models were developed with the experimental results obtained from the literature review and this study. These models consist of an input layer with 6 parameters, a hidden layer and an output layer with target parameters. The input parameters are the soil types and their ratios in the mixture, the plasticity index, the optimum water content and the unit weight. The target parameters are set as the shear-strength parameters: the cohesion and the internal friction angle. The flowchart of the developed model is presented in Figure 16. Two sets of predictions were made separately with the prediction model developed for both the cohesion and the internal friction angle. As a result of a trial-and-error process, 10 neurons were identified in the hidden layer. A feed-forward error back propagation model is developed using the Levenberg Marquardt algorithm. The architecture of the model is given in Figure 17.

Laboratory test results are displayed as target values on the x-axis, and numerical analysis results are displayed on the y-axis. A performance evaluation of the model was made using MSE and square of correlation coefficient (R^2). The linear output indicates the success of the predictive model. In fact, the prediction models work separately on each data set randomly divided for training, validation and testing, and the correlation coefficients and MSE are calculated individually for each stage. However, the overall performance is represented by combining each of the three cases in one graph. The regression curves of the predictions for both target parameters, i.e., cohesion and frictional angle, were presented separately in Figure 18. Correlation coefficients for the measured and estimated cohesion and friction angle were obtained as 0.84 and 0.78, respectively. These success performances, which were developed with a limited number of data sets, showed a reasonable estimation of success. Although it was obtained from differ-

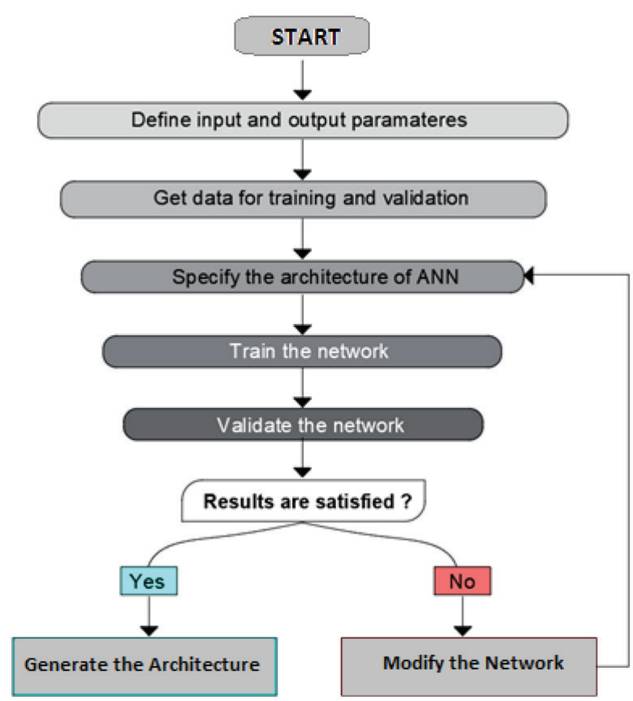


Figure 16. Flowchart of the neural network model.

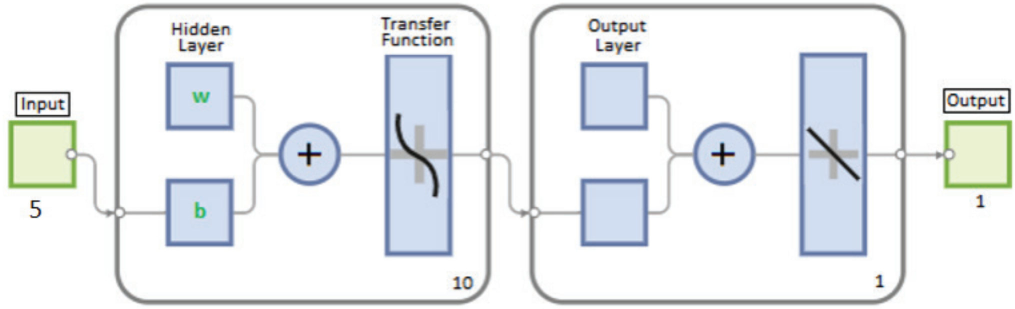


Figure 17. Architecture of the prediction model.

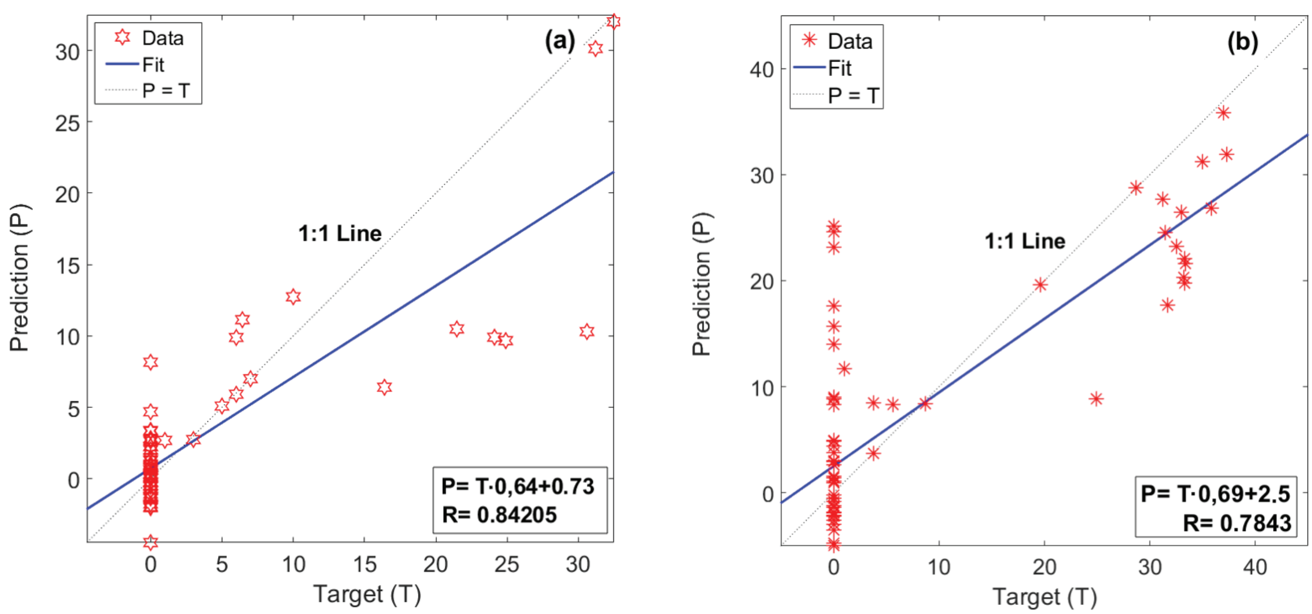


Figure 18. Scatter plots of the predicted versus target values of (a) cohesion and (b) frictional angle.

ent studies and consisted for a limited number of data, an acceptable success performance was obtained with the studied dataset. It is convenient in that it shows that the strength parameters can be estimated practically by soft-computing methods using the principle engineering properties. The statistical data of the predictions were summarised in Table 3.

Table 3. Statistical data of the predicted parameters.

	Cohesion		Angle of friction	
	MSE	R	MSE	R
Training phase	10.8881	0.9050	77.4662	0.8303
Validation phase	48.7666	0.7643	33.7122	0.8802
Test phase	45.0875	0.7929	18.0818	0.2991

6 CONCLUSION

This study was carried out to determine the geotechnical properties of pure zeolite and bentonite and their mixtures with sand, which are two common local soil types in the investigated area. In this context, the geotechnical properties and mineralogical properties of the materials were determined. In order to examine the improvements in the shear-strength parameters, direct shear tests were carried out on the combination of locally supplied sand with different contents. A NN-based model has been developed for the prediction of the shear-strength parameters of mixtures with existing geotechnical properties, with both results of literature studies and the current study. The main results are drawn in this study as follows:

- A significant increase was observed in the shear--strength parameters of the sand specimens with a mixture of zeolite and bentonite. The shear-strength parameters of the mixtures increase proportionally with increasing zeolite and bentonite content.
- The improvement in the shear-strength parameters with the addition of zeolite and bentonite is much more pronounced under low normal stresses. As the applied normal stress increases, the shear strength of both mixtures and the pure sand draw closer to each other.
- The maximum cohesion and friction angle measured for the BS50 and BS10 specimens were 44 kPa and 30°, respectively. Those parameters were measured by ZS50 and ZS10 specimens as 38 kPa and 24°, which indicates a remarkable difference in favor of the BS specimens in terms of the shear-strength parameters.
- Among the tested specimens it was observed that the BS40, BS50 and ZS50 specimens exhibited the highest strength values. These specimens significantly increased the plasticity properties of the clean sand in mixtures.
- With the compiled database, an acceptable accuracy was obtained regarding the estimation of the cohesion and the friction angle. The correlation coefficient R^2 = 0.84 was obtained for cohesion and R^2 = 0.78 was obtained for the internal friction angle, which shows the efficiency of the prediction models developed for multi-component soil specimens.

REFERENCES

[1] Breck, D.W. (1974). Zeolite Molecular Sieves, Structure, Chemistry and Use, John Wiley & Sons, New York.

[2] Ören, A. H., & Özdamar, T. (2013). Hydraulic conductivity of compacted zeolites. Waste Manag. Res. 31(6):634-40. DOI: 10.1177/0734242X13479434.

[3] Dyer, A. (1988). An introduction to zeolite molecular sieves. Chichester; New York: J. Wiley.

[4] Norouznejad, G., Shooshpasha, I., Mirhosseini, S. M., Afzalirad, M., & Afzalirad, M. (2021). Influence of Zeolite on the Compaction Characteristics and Shear Strength Parameters of Cemented Sand. Sains Malaysiana, 50(11), 3181–3191. https://doi.org/10.17576/jsm-2021-5011-03

[5] Savas, H. (2016). Consolidation and swell characteristics of dispersive soils stabilized with lime and natural zeolite. Sci Eng Compos Mater 26:589–598. https:// doi. org/ 10. 1515/ secm- 2014- 0202.

[6] Mola-Abasi, H., & Shooshpasha, I. (2017). Polynomial models controlling strength of zeolite-cement-sand mixtures. Scientia Iranica, 24(2), 526–536.

[7] Eyo, E. U., Ng'ambi, S., & Abbey, S. J. (2020). Performance of clay stabilized by cementitious materials and inclusion of zeolite/alkaline metals-based additive. Transportation Geotechnics, 23(February), 100330. https://doi.org/10.1016/j.trgeo.2020.100330

[8] Shahriarkian, M., Kabiri, S., & Bayat, M. (2021). Utilization of zeolite to improve the behavior of cement-stabilized soil. Int J Geosynth Ground Eng 7(2). https:// doi. org/ 10. 1007/ s40891- 021-00284-9

[9] Chenarboni, H.A., Lajevardi, S. H., MolaAbasi, H., & Zeighami, E. (2021). The effect of zeolite and cement stabilization on the mechanical behavior of expansive soils. Constr Build Mater 272:121630. https:// doi. org/ 10. 1016/j. conbuildmat. 2020. 121630

[10] Yılmaz, F., Sadoğlu, E., & Kamiloğlu, H. A. (2022). Evaluation of the effect of waste zeolite on the strength and micro-macrostructure of a high plasticity clayey soil stabilized with lime-waste zeolite mixtures subjected to freezing–thawing cycles. Arabian Journal of Geosciences, 15(6). https://doi.org/10.1007/s12517-022-09767-z

[11] Yukselen-Aksoy, Y. (2010). Characterization of two natural zeolites for geotechnical and geoenvironmental applications. Applied Clay Science, 50(1), 130–136. https://doi.org/10.1016/j.clay.2010.07.015

[12] Vogiatzis, D., Kantiranis, N., Filippidis, A., Tzamos, E., & Sikalidis, C. (2012). Hellenic natural zeolite as a replacement of sand in mortar: Mineralogy monitoring and evaluation of its influence on mechanical properties. Geosciences (Switzerland), 2(4), 298–307.

[13] Mola-Abasi, H., Kordtabar, B., & Kordnaeij, A. (2016). Parameters controlling strength of zeolite–cement–sand mixture. International Journal of Geotechnical Engineering, 11(1), 72–79. https://doi.org/10.1080/19386362.2016.1186412

[14] Villalobos, F. A., Leiva, E. A., Jerez, Ó., & Poblete, M. E. (2018). Experimental study of the fine particles effect on the shear strength of tuff zeolites. Revista de La Construccion, 17(1), 23–37. https://doi.org/10.7764/RDLC.17.1.23

[15] Murray, H. H. (2006). Bentonite Applications. Developments in Clay Science, 2(C), 111–130.

[16] Sun, Y., Fan, W., Zheng, H., Zhang, Y., Li, F., & Chen, W., (2015) Evaluation of Dewatering Performance and Fractal Characteristics of Alum Sludge, PLoS ONE, Vol. 10(6),1-16.

[17] Komine, H., & Ogata, N. (1999). Experimental study on swelling characteristics of sand-bentonite mixture for nuclear waste disposal. Soils Found. 39 (2): 83–97. Komine, H. 2004. "Simplified evaluation on hydraulic conductivities of sand–bentonite mixture backfill." Appl. Clay Sci. 26 (1–4): 13–19. https://doi.org/10.1016/j.clay.2003.09.006.

[18] Jobmann, M., & Buntebarth, G. (2009). Influence of graphite and quartz addition on the thermo-physical properties of bentonite for sealing heat-generating radioactive waste. Applied Clay Science, 44(3–4), 206–210. https://doi.org/10.1016/j.clay.2009.01.016

[19] Chen, T., Sedighi, M., Jivkov, A. P., & Seetharam, S. C. (2021). A model for hydraulic conductivity of compacted bentonite - Inclusion of microstructure effects under confined wetting. Geotechnique, 71(12), 1071–1084. https://doi.org/10.1680/jgeot.19.P.088

[20] Sivapullaiah, P. V., Sridharan, A., & Stalin, V. K. (2000). Hydraulic conductivity of bentonite-sand mixtures. Canadian Geotechnical Journal, 37(2), 406–413. https://doi.org/10.1139/t99-120

[21] Proia, R., Croce, P., & Modoni, G. (2016). Experimental Investigation of Compacted Sand-bentonite Mixtures. Procedia Engineering, 158, 51–56.

[22] Chalermyanont, T., & S. Arrykul. (2005). Compacted sand-bentonite mixtures for hydraulic containment liners. Songklanakarin J. Sci. Technol. 27 (2): 313–323.

[23] Muntohar, A.S. (1999). Swelling and compressibility characteristics of compacted sand-bentonite mixtures. Geotechnical Engineering, 30(1), 1–12.

[24] Alkaya, D., & Bariş Esener, A. (2011). Usability of sand-bentonite-cement mixture in the construction of unpermeable layer. Scientific Research and Essays, 6(21), 4492–4503. https://doi.org/10.5897/sre10.1189

[25] Durukan, S., Pulat, H. F., & Yukselen-Aksoy, Y. (2014). Suction characteristics of compacted zeolite-bentonite and sand-bentonite mixtures. Waste Management and Research, 32(2), 149–156. https://doi.org/10.1177/0734242X13518958

[26] ÇŞB, (2011). Malatya Province Environment Status Report. Ministry of Environment and Urbanization, Malatya.

[27] Dussan, A., Calderón, J. A., & Quiroz, H.P. (2020). Zeolites derived from natural minerals: Solid and volcanic ash., pp. 148-149. DOI:10.1016/j.mattod.2020.03.006

[28] ASTM D422-63, 2003. Standard Test Method for Particle-Size Analysis of Soils, In Annual Book of ASTM Standards, Volume 04.08, Philadelphia, PA, pp. 93-99.

[29] ASTM D-698, "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort," American Society for Testing and Materials, USA

[30] ASTM D4318-17e1. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils; ASTM International: West Conshohocken, PA, USA, 2017.

[31] ASTM D 2434-94. Standard test method for permeability of granular soils (constant head). Annual Book of ASTM Standards, American Society For Testing and Materials, West Conshohocken, PA (2000).

[32] ASTM D 3080-98, 2003. Standard Test Method for Direct Shear of Soils Under Consolidated Drained Conditions, In: Annual Book of ASTM Standards, Volume 04.08, Philadelphia, PA, pp. 417-422.

[33] Tiwari, B., & Marui, H. (2003). Estimation of residual shear strength for bentonite-kaolin-Toyoura sand mixture. Journal of the Japan Landslide Society, 40(2), 124–133. https://doi.org/10.3313/jls.40.124

[34] Ören, A. H., Kaya, A., & Kayalar, A. Ş. (2011). Hydraulic conductivity of zeolite-bentonite mixtures in comparison with sand-bentonite mixtures. Canadian Geotechnical Journal, 48(9), 1343–1353. https://doi.org/10.1139/t11-042

[35] Shang, H. (2015). Geotechnical laboratory characterization of sand- zeolite mixtures, MSc. Thesis, University of Louisville.

[36] Vadlamudi, S., & Mishra, A. K. (2018). Consolidation characteristics of sand–bentonite mixtures and the influence of sand particle size. Journal of Hazardous, Toxic, and Radioactive Waste, 22(4), 06018001.

[37] Ghadr, S., & Assadi-Langroudi, A. (2018). Structure-based hydro-mechanical properties of sand-bentonite composites. Engineering Geology, 235, 53-63. doi.org/10.1016/j.enggeo.2018.02.002

[38] Mukherjee, K., & Mishra, A. K. (2019). Hydraulic and mechanical characteristics of compacted sand–bentonite: Tyre chips mix for its landfill application. Environment, Development and Sustainability, 21(3), 1411-1428.

[39] Chen, Y., & Meehan, C. L. (2011). Undrained strength characteristics of compacted bentonite/sand mixtures. In Geo-Frontiers 2011: Advances in Geotechnical Engineering (pp. 2699-2708).

[40] Fattah, M. Y., Salim, N. M., & Irshayyid, E. J. (2022). Influence of soil suction on swelling pressure of bentonite-sand mixtures. European Journal of Environmental and Civil Engineering, 26(7), 2554-2568. DOI: 10.1080/19648189.2017.1320236

[41] Komine, H. (2004). Simplified evaluation on

hydraulic conductivities of sand–bentonite mixture backfill. Applied clay science, 26(1-4), 13-19.

[42] Kwan, P.S., Shahrokhi, R., Park, J., Kim,H., (2019). Zeolite mixtures as adsorptive fill material with sustainable bearing capacity. Waste Management and Environment IX, WIT Transactions on Ecology and the Environment, 231, 91-100.

[43] Aftabi, S., Fathi, S., & Aminfar, M. H. (2020). The Effect of Zeolite on Sandy-Silt Soil Mechanical Properties. International Journal of Geotechnical and Geological Engineering, 14(10), 269-278.

[44] ASTM D5758-01 Test Method for Determination of Relative Crystallinity of Zeolite ZSM-5 by X-Ray Diffraction

[45] Elsbury, B. R., D. E. Daniel, G. A. Sraders, & D. C. Anderson. (1990). Lessons learned from compacted clay liner." J. Geotech. Eng. 116 (11): 1641–1660. https://doi.org/10.1061/(ASCE)0733-9410(1990)(1641)

[46] Bolt, G. H. (1956). Physico-chemical analysis of the compressibility of pure clays." Géotechnique 6 (2): 86–93. https://doi.org/10.1680/geot.1956.6.2.86.

[47] Sridharan, A., & G. V. Rao. (1973). Mechanisms controlling volume change of saturated clays and the role of the effective stress concept. Geotechnique 23 (3): 359–382.

[48] Mitchell, J. K., & Soga, K. (2005). Fundamentals of soil behavior. 3rd ed. Hoboken, NJ: Wiley.

[49] Dutta, J., & A. K. Mishra. (2016). Consolidation behaviour of bentonites in the presence of salt solutions. Appl. Clay Sci. 120: 61–69. https://doi.org/10.1016/j.clay.2015.12.001.

[50] Boutwell, G. (1961). Effects of variation of fill construction on the material properties and the subsequent fill performance, Independent study Rep., School of Civ. Engrg., Georgia Institute of Technology, Atlanta, Georgia, USA.

[51] Blotez, L., Benson, C. & Boutwell, G. (1998). Estimating Optimum Water Content and Maximum Dry Unit Weight for Compacted Clays, J Geotech. Engrg., ACSE, 124(9), 907- 912.

[52] Jesmani, M., Manesh, A. N., & Hoseini, S. M. R. (2008). Optimum water content and maximum dry unit weight of clayey gravels at different compactive efforts. Electronic Journal of Geotechnical Engineering, 13 L(June).

[53] Srikanth, V., & Mishra, A. K. (2016). A Laboratory Study on the Geotechnical Characteristics of Sand–Bentonite Mixtures and the Role of Particle Size of Sand. International Journal of Geosynthetics and Ground Engineering, 2(1), 1–10. https://doi.org/10.1007/s40891-015-0043-1

[54] Bowles, J.E. (1998). Engineering Properties of Soil and Their Measurement, Mcgraw-Hill Book Company, Singapore.

[55] Turkoz, M., & Vural, P. (2013). The effects of cement and natural zeolite additives on problematic clay soils. Science and Engineering of Composite Materials, 20(4), 395–405.

[56] Sivapullaiah, P.V., & Sridharan, A. (1985). Liquid limit of soil mixtures. Geotech Test J 8(3):111–116.

[57] Harianto, T. (2022). Performance of Subbase Layer with Geogrid Reinforcement and Zeolite-Waterglass Stabilization. Civil Engineering Journal (Iran), 8(2), 251–262. https://doi.org/10.28991/CEJ-2022-08-02-05

[58] Sinha, A. N. (1998). Shear Strength of Bentonite-Kaolinite Mix in GCLs. pp, 889–896.

[59] Xiang, Gs., Ye, Wm. & Jalal, F.E. (2021). Shear strength of bentonite–sand mixture saturated with saline solution. Environ Earth Sci 80, 770.

[60] Cabalar, A. F., & Demir, S. (2022). Geotechnical properties of a bentonite treated with waste glass grains. Arabian Journal of Geosciences, 15(9). https://doi.org/10.1007/s12517-022-10169-4

[61] Goh, A. T. C. (1994). Nonlinear modelling in geotechnical engineering using neural networks. Australian Civil Engineering Transactions, CE36(4), 293-297.

[62] Goh, A. T. C. (1995). Empirical design in geotechnics using neural networks. Geotechnique, 45(4), 709-714.

[63] Cabalar, A. F., Cevik, A., & Gokceoglu, C. (2012). Some applications of adaptive neuro-fuzzy inference system (ANFIS) in geotechnical engineering. Comput Geotech 40:14–33

[64] Yıldız, Ö., & Berilgen, M. M. (2020). Artificial Neural Network Model to Predict Anchored-Pile-Wall Displacements on Istanbul Greywackes, Teknik Dergi, 31 (4), 10147-10166. https://doi.org/10.18400/tekderg.492280

[65] Yıldız, Ö. (2021). Correlation Between Spt and Pmt Results For Sandy And Clayey Soils. Eskişehir Technical University Journal of Science and Technology A - Applied Sciences and Engineering, 22 (2) , 175-188. https://doi.org/10.18038/estubtda.896491

[66] Cabalar, A. F., Karabas, B., Mahmutluoglu, B., & Yıldız, Ö. (2021). An IDW-based GIS application for assesment of geptechnical characterization in Erzincan Turkey. Arab J Geosci 14:2129. https://doi. org/ 10. 1007/s12517- 021- 08481-6

[67] Shahin, M.A., Jaksa, M.B., & Maier, H.R. (2001). Artificial Neural Network applications in geotechnical engineering. Australian Geomechanics Journal 36(1): 49–62