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# Stabilization of Zeolite and Bentonite with Sewage Sludge Ash

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**Abstract**

In this study, it is aimed to evaluate the wastewater sludge supplied locally at 100 tons/day in the investigation area. In this context, the geotechnical properties of bentonite, zeolite-type clays and sands, which are common in the investigation area, were determined by mixing with sewage sludge ash (SSA) in specified ratios. Grain size distribution and specific gravity of pure materials and mixtures were determined. Direct shear tests, permeability tests, consistency limits tests, modified proctor tests and PH determination tests were performed with the mixtures. Soils were mixed with 0.5, 7.5, 10 and 12.5 percent SSA in order to determine the physical, chemical and mechanical properties. Mixtures of sand with 40% bentonite (i.e., BS40) and sand with 40% zeolite (i.e., ZS40) were used as host materials for SSA inclusion. As a result of extensive laboratory studies, it was observed that the engineering properties of the specimens changed significantly as a result of the 7.5% and 12.5% mixture of SSA. BS40/SSA7.5 and ZS40/SSA12.5 samples from the mixtures reached 83 kPa and 80 kPa maximum shear strength under 200 kPa normal pressure. The maximum unit weight of specimens was achieved by BS40/S5 and ZS40/S5 specimens as 1.72 and 1.82 g/cm$^3$, respectively. With the addition of SSA, the hydraulic permeability of the mixtures decreased to an order of 10E$^{-8}$ (cm/s) for BS40/SSA12.5 and ZS40/12.5 specimens. Experimental studies have provided significant engineering and environmental benefit in the evaluation of sewage sludge ash, which is inevitable in residential areas.

**Keywords**

sewage sludge ash, zeolite, bentonite, shear strength, plasticity, permeability

## 1 Introduction

As a result of increasing population, rising living standards, technological developments, industrialization, and urbanization, consumption habits change and natural resource consumption reaches high levels accordingly. Therefore, the evaluation, recovery, and reuse of all kinds of waste become vital. There are examples of the technical and practical applications of waste reuse in different areas of civil engineering. Among these applications, geotechnical engineering applications are undoubtedly the most important burden. Waste tires, stone dust, industrial waste, fly ash, construction rubble, etc. The environmental and engineering contributions of these studies and suggestions regarding their use are indisputable [1–4]. It is an undoubted fact that in addition to these wastes, which constitute an important total among consumption wastes, municipal wastes also correspond to a significant amount. Sewage sludge represents the insoluble residue produced during municipal treatment and subsequent stabilization procedures of the dewatering [5]. Since it contains heavy metals, bacteria, viruses, and dangerous chemicals in its content that have the potential to cause environmental pollution, it has become a very crucial necessity to find new disposal methods for the efficient and beneficial use and evaluation of sewage sludge for sustainable environmental management. Long-term strategies need to be determined for the disposal of sewage sludge.

Residuals arising from the treatment stages of domestic and industrial wastewater are muddy and originate from the sedimentation tank and filter backwashing of the treatment plant. These residues, which can be called treatment sludge, should be disposed of in a way that is economically viable and does not harm the environment, which occurs in large volumes. Today, the use of sewage sludge has been examined by researchers, and it is still a research topic that is being studied. Studies carried out on the subject have revealed that sewage sludge can be used in various application areas in civil engineering as well as used as an adsorbent in the removal of various pollutants from wastewater. Balkaya [6] made a comprehensive study on the general properties of water treatment sludge and its use

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in geotechnical engineering. These materials, if examined from a geotechnical point of view, it was observed that they are mechanically stable materials with high shear strength and low permeability. This makes them suitable for various geotechnical and geo-environmental applications. Water treatment sludge is a convenient alternative for geotechnical applications where impermeability is required, such as daily and final cover layer in regular solid waste storage, especially due to its low permeability values. In addition, they can be used as backfill material in road filling and various geotechnical applications [6]. The use of water treatment sludge in geotechnical and geo-environmental applications has been examined in literature studies [7] and its potential use as geo-material has been revealed. In addition, water treatment sludges were used as lightweight aggregate [8], road fill and backfill material [9].

Although some of the researchers who conduct tests on the consistency limits of SSA define the material as non-plastic [10], there are researchers who reach different results [11]. The permeability of SSA is another parameter investigated due to its contents that may leak and affect permeability. The coefficient of permeability of SSA was measured to be between $1 \times 10^{-4}$ to $4 \times 10^{-4}$ (cm/s) [10]. SSA with lime as another admixture is suggested as a stabilizer for soft subgrade soils due to these admixture pairs improving basic soil properties such as compaction, shear strength, bearing capacity, etc. due to the pozzolanic reaction between sludge ash and lime. Regardless of the content and the treatment period, the PH of the soil stabilized with SSA has not considerably changed [11]. However, the unconfined shear strength of the clayey soil specimens improved by SSA was observed to be higher than that of pure specimens after 28 days of curing periods [12]. The sludge ash in burned form with a content of 7.5% in the soil increased both the cohesion and the angle of internal friction of the soil. It was also mentioned that the contribution of shear strength parameters due to the inclusion of sludge ash into high plastic soils (CH) is higher than low plastic soils (CL) [13]. Zabielska-Adamska [14] suggested the use of sewage sludge in an isolated environment from groundwater and rainwater due to the possibility of the leaching of heavy metals from the SSA mass. Aline et al. [15] investigated the influence of water treatment sludge on the geotechnical behavior of lateritic soils. The mixtures presented higher effective friction angles and lower cohesion than pure specimens. Sewage sludge ash was used with lime to stabilize soft cohesive soils [16]. It was indicated that the shear strength parameters of the soft cohesive subgrade subsoils were significantly improved with the use of hydrated lime. In contrast to Kadhim et al. [12], it is stated by Norouzian et al. [16] that the curing time does not seem to have any significant effect on the compressive strength of the specimens treated with SSA. Due to its hydraulic conduction properties, Chen et al. [17] indicated that deeply dewatered sludge can be used as an alternative material for the barrier layer of landfill covers. It was also indicated that the low permeability will favor the control of rainfall infiltration and phreatic line within the cover. In many studies, the fact that short-term performance criteria are met is considered sufficient for the developed method, technique, or the suitability of the composite material produced, but the long-term observation and examination often leave this aspect of the research incomplete. Chen et al. [17] indicated that the experimental evidence shows that the pore-fluid chemical change and organic decomposition in the sludge did not result in a significant deterioration in the long-term permeability and shear strength, further studies, especially field studies, are required on the long-term performance of the landfill cover made of the dewatered sludge.

Zeolites are widely found in many parts of the world, such as the western United States, Italy, and central and western Turkey, in different forms and engineering properties. According to the General Directorate of Mineral Research and Exploration, Turkey has around 344 million tons of zeolite reserves. 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. There is a significant number of studies on wastewater and water treatment sludge from bentonite and bentonite-based materials [18]. On the other hand, the usability of zeolite in water treatment is being investigated by researchers [19]. Cieślik et al. [20] conducted a comprehensive literature review of sewage sludge management methods and applications. In addition to all the advantages, it provides in terms of engineering, management methods, waste stabilization, and safe recycling strategies and legislations, programs, and developmental strategies of the countries were given.

There are many studies in the literature on the use of various wastes as construction materials. Arulrajah et al. [21] developed a geopolymer binder with Calcium Carbide Residue (CCR) which is a waste product of acetylene gas. Fly ash and slag precursors were also used in the stabilization of construction-demolition materials for comparison with CCR in the study. Moharejani et al. [22]

compiled a detailed literature review on the use of waste glass in the construction industry. Cabalar et al. [23] performed an extensive series of geotechnical laboratory tests with CNC (i.e., computer numerical control) milling spirals and soil mixtures. The results of CBR, UCS, consolidation, and permeability tests of mixtures revealed CNC spirals as an alternative soil reinforcement material. The use of waste rubber tires for various engineering purposes has been investigated in detail [24–26]. The compressibility and shear strength of the synthetic municipal solid wastes in fresh and aged forms were tested for compositions of different regions in the world [27]. Arulrajah et al. [28–29] investigated the geotechnical and geoenvironmental properties of recycled concrete (RC) and glass (RG), crushed bricks (CB) waste rock (WR), and reclaimed asphalt pavement (RAP). From a geotechnical engineering perspective, it has been suggested to mix CB with different waste materials in order to increase its durability and performance. The RCA and WR were observed to have satisfactorily high geotechnical properties to be used as a subbase material. The CB and RAP are found as less durable than RCA, CB, and WR. All mixtures have PH values above 7 which is an indicator of alkaline by nature.

Bentonites and zeolites are the soil types that are at the forefront of geotechnical engineering applications because of their widespread availability and the advantages they provide in terms of engineering applications. SSAs, on the other hand, are convenient wastes to be used to meet different engineering needs due to the environmental problems they create as a result of their accumulation. Literature studies include instances of the use of SSA for different purposes in geotechnical engineering. The benefits it provides in terms of environmental and cost economy and the effective solutions it brings to engineering problems highlight the use of SSA as a plausible option. In this study, it was aimed to investigate the geotechnical properties of the local soils in the investigation area of SSA products of a facility with an annual production of 100 tons/day. In this context, the optimum combination of bentonite-sand and zeolite-sand mixtures which are commonly found in the investigation area was accepted as the host materials. The physical, chemical and engineering properties of the samples obtained by mixing SSA with the host material in varying proportions were investigated. According to the results obtained, evaluations were made regarding the use of their mixtures in different geotechnical engineering applications. This research is a remarkable study in terms of evaluating a type of waste with a very high accumulation amount in residential places. The fact that SSA is tested both as an evaluable product in engineering applications and the environmental benefit it will provide gives the work a unique feature.

## 2 Materials and methods

Sewage sludge ash (SSA) used in this study was obtained from the Malatya Metropolitan Municipality Water and Sewerage Administration wastewater treatment plant (i.e., MASKI WTP) (Fig. 1). This facility consists of coarse screens, fine screens, aerated sand and oil traps, a selector tank, an anaerobic pool, aeration pools, blower unit, final sedimentation pools, recycle sludge pumping station, mechanical sludge densification and dewatering units, wastewater distribution, collection and discharge units, sludge collecting structures, foam collecting structures, transformer, generator and operation buildings (Fig. 2) [30]. This facility produces an average of 100 tons of sludge per day as a long-ventilated activated sludge process that can remove nitrogen, phosphorus and carbon at an advanced level without causing environmental pollution from the domestic wastewater of Battalgazi and Yeşilyurt settlements in Malatya. SSA is supplied from the treatment plant initially with a high water content, then it is dried and dehydrated. Pure bentonite, zeolite, and sand materials used in this study are shown in Fig. 3. As a result of a series of geotechnical laboratory tests, mixtures of sand with 40% bentonite (i.e., BS40) and sand with 40 % zeolite (i.e., ZS40) were determined as host materials for SSA mixtures. BS40 represents a sand specimen containing 40% bentonite and ZS40 represents a sand specimen containing 40% zeolite. The specimens containing 5, 7.5, 10, and 12.5% SSA of both bentonite and zeolite are presented in Fig. 4. The specimens were abbreviated as BS40/

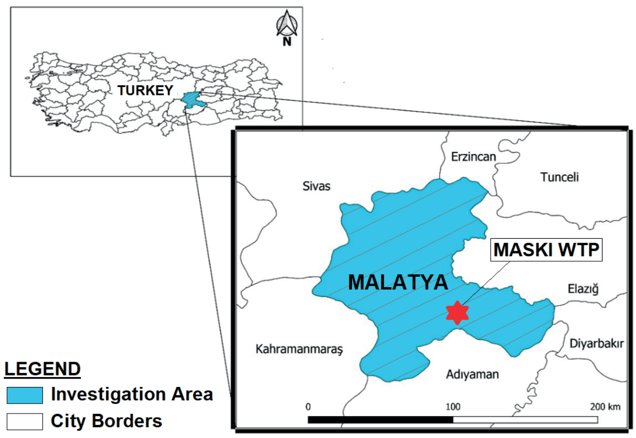



**Fig. 1** The location map of the Malatya city and MASKI WTP

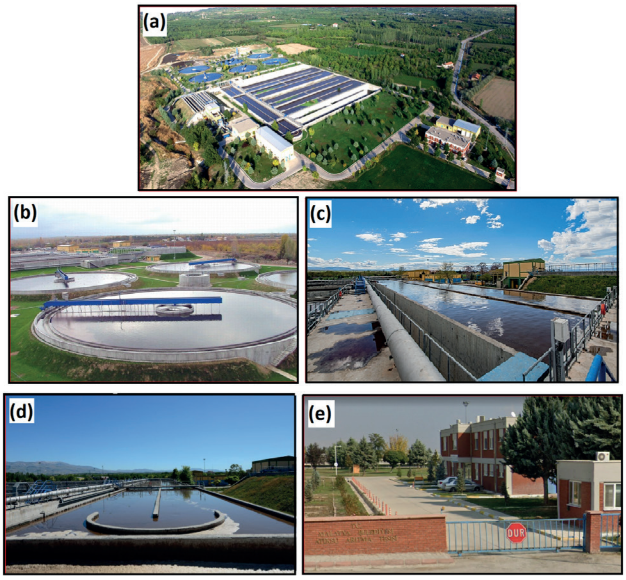



**Fig. 2** MASKI waste water treatment plant (MASKI WTP) and its units [30]


**Fig. 3** View of the sand, bentonite and zeolite materials

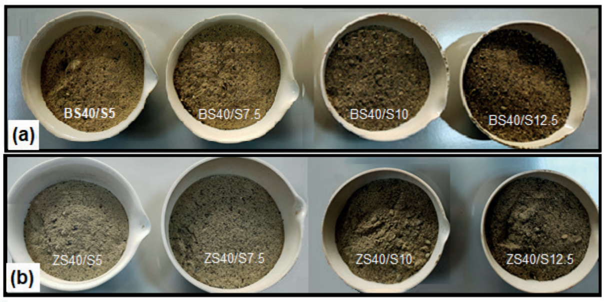



**Fig. 4** Materials used in the experiments; (a) bentonite and (b) zeolite mixtures with varied contents of SSA

SSA5, ZS40/SSA7.5, 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, BS40/SSA5 is the abbreviation for the mixture of sand with 40% bentonite and 5% of SSA. The selected sand type is widely used in Malatya, especially in the construction industry, and was obtained from the Hekimhan district of Malatya. Zeolite is freely available in the district of Hekimhan in Malatya city. Bentonite is also found freely in nature in the Battalgazi district of Malatya.

The sewage sludge used in the studies is liquid or semi-solid, odorous, contains up to 12% solids, and contains water in the amount of up to 95%. Since only a limited part of its content is solid, it also occupies significant volumes. It gives odor because it contains high amounts of organic matter, nutrients, and pathogenic microorganisms. The sewage sludge formed in wastewater treatment plants is roughly 50% to 70% carbon, 6.5% to 7.3% hydrogen, 21% to 24% oxygen, 15% to 1.88% nitrogen, 1% to 1.5% phosphor and 0% to 2.4% sulfur before stabilization processes. The specific gravity and PH of the SSA are obtained as 1.40 and 8.50, respectively. Images of both natural and dried forms of SSA are presented in Fig. 5. The grain size distribution of the zeolite, bentonite, and sand materials is demonstrated in Fig. 6.

## 3 Experimental study

The experiments carried out in this study can be explained in two categories; the determination of physical properties and of mechanical properties. Initially, the natural water content and specific gravity of the specimens were determined. The Atterberg limit tests were performed to evaluate the liquid limit (LL), plastic limit (PL), and plasticity index (PI) for each specimen in accordance with ASTM test specifications. Specimens with a weight of 100 grams were prepared to test the liquid limit. The number

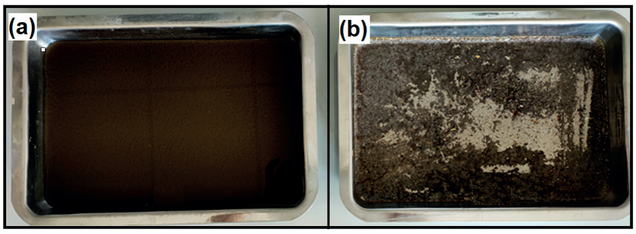



**Fig. 5** View of the SSA in; (a) natural and (b) dried form

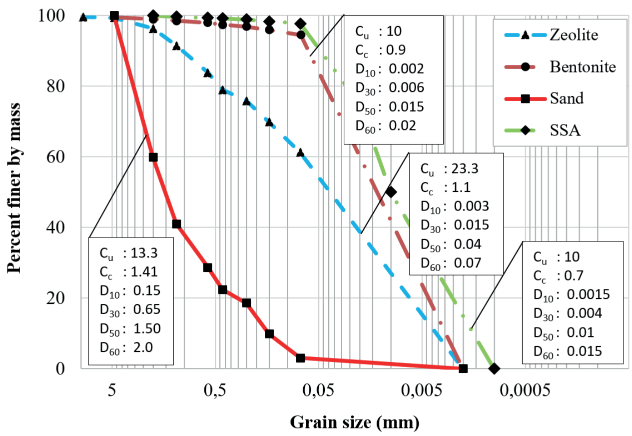



**Fig. 6** The grain size distribution of the materials

of blows corresponding to the grove closed at a distance of 12 mm was recorded and the water content of the specimen was calculated. When the tests were repeated with different water contents, the water content corresponding to 25 drops was accepted as the liquid limit value of the sample. The same mixed soil-admixture that was prepared for the liquid limit finding had been taken and placed on a flat plate and then rolled by hand fingers to make a thread of about 3 mm in diameter. The water content at which the soil threads crack at 3 mm in diameter is accepted as the plastic limit. The plasticity index is when the soil still has plastic behavior between non-plastic and viscous fluid states and is calculated by taking the difference between the liquid limit and the plastic limit.

The modified proctor test was performed for each specimen in accordance with ASTM standards. The sample was first mixed and the weight of the specimen with the compaction mold and base plate was weighed. Then, water was slowly added to the dry mixture at an interval of 3% by dry weight, carefully mixed until it became uniform, and placed in the compression mold in equal layers. Each layer was compacted by dropping it from a height of 45 cm with 25 blows with a specially designed 4.6 kg proctor hammer. After the compression was complete, the collar was carefully removed from the mold, and the elongated layer was cut with a spatula. The weight of the mold, which still had soil in it, was then recorded. The water contents of the samples taken from the top, middle, and bottom parts of the compacted soil were measured. The water content of the soil sample where the maximum compaction was measured was recorded as the optimum water content. Unit weight and water content curves were generated for each sample. The shear strength of mixtures of BS40 and ZS40 with SSA at varied contents was determined by direct shear tests. The tests were carried out with a fully automatic, non-staged servo motor with a shearing speed of between 1 mm/min which can reach a total load capacity of 5 kN. Specimens with 6 × 6 cm in dimensions and 2 cm in height, prepared at optimum water content, were sheared at a constant speed. The shear strength of the specimens prepared at optimum water content was determined under normal stresses of 50 kPa, 100 kPa, and 200 kPa. Tests were performed in accordance with the ASTM standards and shear strength parameters were determined. In addition, pH tests were carried out to determine the chemical properties of the samples. The tests were taken at 900 rpm for 10 to 15 minutes using a 4 g specimen in 190 g distilled water. It was determined that the pH values of each specimen were above 7 and in basic character. The results obtained from the tests performed are presented in Table 1. Grain size distribution analysis, compaction test, consistency limit tests, permeability tests, and direct shear tests were performed in accordance with ASTM D422-63 [31], ASTM D1557 [32], ASTM D2434-94 [33], and ASTM D3080-98 [34], ASTM D4318 [35], respectively.

**Table 1** The summary of the test results

| Specimen | $w_{opt}$ (%) | $\gamma_{d\max}$ (gr/cm$^3$) | $G_s$ | pH |
|---|---|---|---|---|
| Bentonit | 32 | 1.42 | 2.46 | 8.06 |
| Zeolit | 20.4 | 1.67 | 2.38 | 7.89 |
| BS40/S5 | 19.4 | 1.72 | 2.54 | 9.56 |
| BS40/S7.5 | 19.9 | 1.63 | 2.49 | 7.24 |
| BS40/S10 | 23.5 | 1.55 | 2.50 | 7.29 |
| BS40/S12.5 | 24 | 1.50 | 2.40 | 7.30 |
| ZS40/S5 | 15.5 | 1.82 | 2.56 | 7.34 |
| ZS40/S7.5 | 18 | 1.67 | 2.52 | 7.80 |
| ZS40/S10 | 19.4 | 1.62 | 2.50 | 7.86 |
| ZS40/S12.5 | 21.6 | 1.61 | 2,49 | 7.33 |

## 4 Results and discussions

The stress-strain behavior of pure bentonite and zeolite (i.e., B100 and Z100) was measured with a constant shearing speed under 50, 100, and 200 kPa normal stresses are shown in Fig. 7. The ultimate shear strength reached by both specimens are very close to each other. Pure bentonite reaches ultimate shear strength at 87 kPa and bentonite as 83 kPa. There is a clear difference in the shear behavior of specimens. Bentonite specimens reach their peaks and later decrease whereas the zeolite specimens tend to occupy the residual shear strength state longer. In order to examine the effect it will have on the shear strength properties, direct shear tests were carried out by mixing pure bentonite and zeolite specimens with sand in varying proportions (Fig. 8). Obtaining composites with different materials enables to combine of the advantages of each material with different physical and mechanical properties [36]. It is therefore important to examine the shear strength of the BS and ZS specimens formed by mixing at different contents. In fact, zeolite and bentonite with varied contents in soil were examined to achieve the highest shear performance level. For each content of sand in zeolite and bentonite, test results have demonstrated that increasing applied normal stress leads to an increase in shear stress. It was also observed that the measured maximum shear stress decreases with increasing additive content. The specimens with 50% of bentonite and zeolite

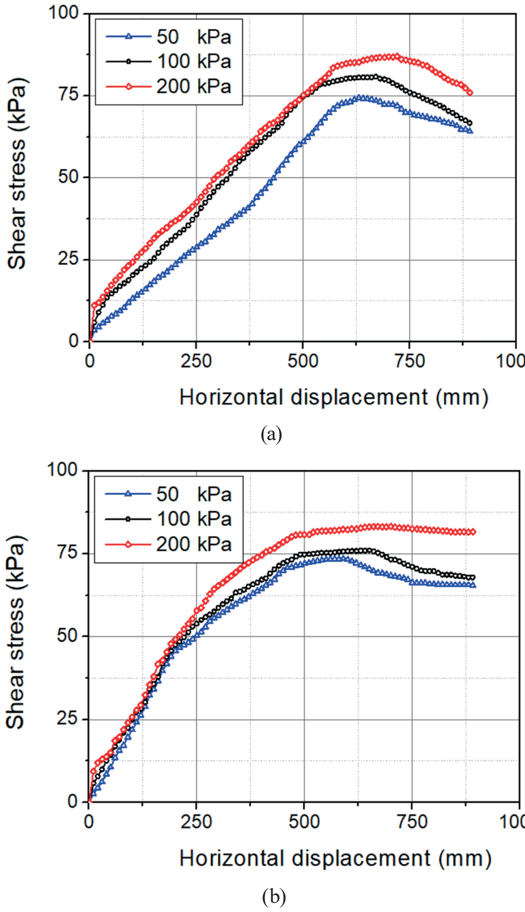



**Fig. 7** Direct shear test results of (a) B100 and (b) Z100 specimens

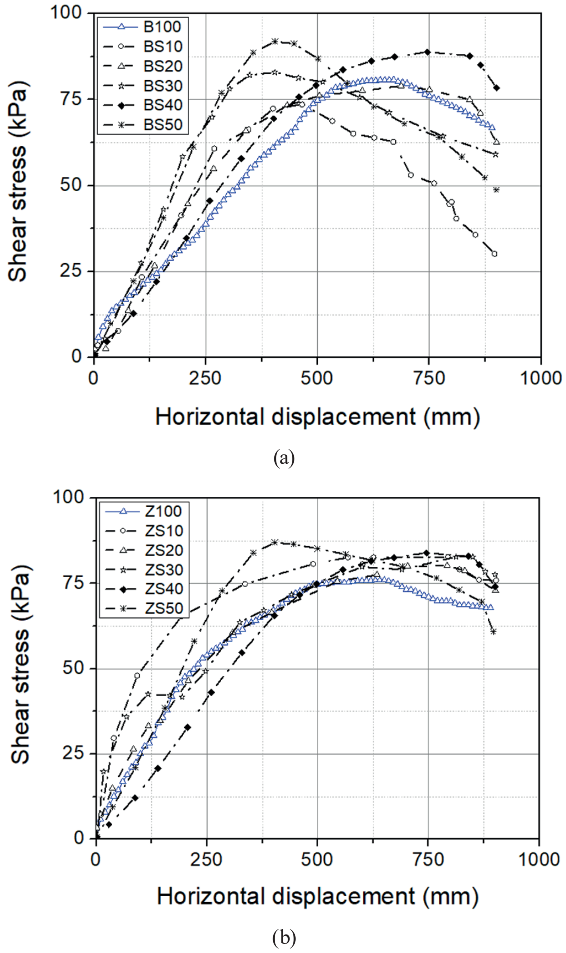



**Fig. 8** Direct shear test results of (a) bentonite and (b) zeolite with sand mixtures under 100 kPa normal stress

with sand (i.e., BS50 and ZS50) displayed the highest performances as 92 and 87 kPa, respectively. Due to the small particle size, bentonite occupies pore spaces between the grains resulting in higher strength [37] which is also valid for zeolite. Since the maximum shear strength is achieved at larger strain levels, in terms of the shear behaviors they displayed, BS40 and ZS40 mixtures are accepted as more convenient specimens from an engineering perspective. Therefore, those specimens are adopted as host specimens for SSA inclusion and will experimentally be examined in the subsequent stages of the study with the addition of SSA in varying proportions.

The shear strength parameters of the specimens are significant, especially for stability analysis. In the case of their usage as liners or backfill materials, the shear strength of bentonites was investigated by researchers both for drained and undrained cases. Yukselen-Aksoy [38] obtained high shear strength values under the slow loading rate of direct shear tests of two zeolite specimens taken from Türkiye. Regardless of the relative density, the ultimate shear stress of the pure bentonite specimens tested varies within similar ranges with literature studies [38]. Stone et al. [39] reported that the frictional angle for sewage sludge tends to increase slightly with the degree of degradation of organic mass. In addition to the organic content of the sludge, it was also reported that the duration of the treatment is also determinative on the shear strength of the sludge. Jagaba et al. [40] explained the increase of soil strength with the inclusion of sewage sludge ash with the cementing property of the ash, and the ability to alter the absorbed water films. The shear behavior of the mixtures of BS40 containing different dosages of SSA is shown in Fig. 9. In contrast to the literature studies, under the same normal stress, regardless of the content of additive, the BS40 specimen showed higher shear strength than the samples containing SSA. The main factors affecting the undrained shear strength are the cohesion of the soil particles and the internal friction angle, which are directly related to the soil water content. It is assumed that the water content ensuring the mixtures at maximum compaction state, the organic content of the SSA material, and the material gradations have an effect on this result.

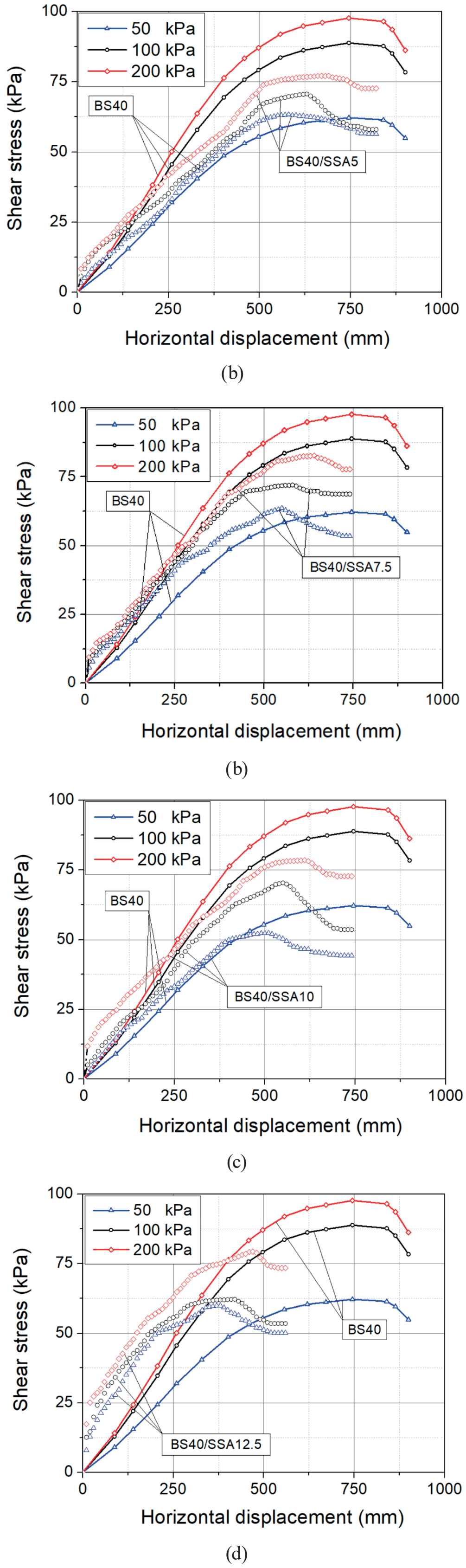



**Fig. 9** Direct shear test results of the BS40 and BS40/SSA mixtures with varied contents of SSA; (a) 5% SSA, (b) 7.5% SSA, (c) 10% SSA, (d) 12.5%SSA

Shear strength also plays an important role in the stability of slopes and in assessing the risk of progressive failure [40]. These parameters can also be used to evaluate the slope stability for landfill cover [41] and are determinative in the geotechnical assessment of a design. In general, it was observed that the shear strength of the zeolite decreased with the addition of sludge at varying contents (Fig. 10). The introduction of SSA displayed an enhancement in the shear strength of the zeolite only at 50 kPa normal stress. Higher normal stress mostly gives higher shear stress in the mixtures, because the bond developing between the sludge and soil particles is enhanced. However, under higher normal stresses, specimens containing SSA do not exhibit better shear strength than pure ZS40 specimens. The presence of SSA appears to provide slightly better improvement in the mixture at dosages higher than 10% (i.e., ZS40/SSA12.5). The ultimate shear strength of each SSA including specimens is lower than untreated specimens. Additionally, specimens with higher sludge contents mostly reached their failure state at lower shear strains (Fig. 10(c)–(d)). The corresponding strains of untreated specimens were generally more than those of treated ones. Although there was no improvement in ultimate shear strength with the addition of SSA, it was observed that specimens containing lower dosages of SSA imparted a more ductile behavior. The ductility can also be considered by the failure strain.

The relationship between the shear stress and the corresponding normal stress was plotted in Fig. 11. Under each normal stress, three data points were obtained by the parallel tests with an acceptable difference and the average was plotted as a single point. The interception and the inclination angle of the Mohr-Coulomb line are defined as cohesion and the internal friction angle. The pure BS40 sample achieved higher shear strengths under each normal stress than the mixtures containing SSA. Under lower normal stresses, the addition of SSA appears to improve the shear stress of ZS40 by up to 5%. However, it is obvious that SSA does not contribute to the shear strength of the specimen under higher normal stresses. Similar results were observed in studies by previous researchers. The lower shear strength of SSA soil mixtures is attributed to the dissimilar grain size distribution [14] and the non-cohesive property of the sludge ash in the mixtures [13]. As observed from the stress-horizontal displacement relationships, the addition of SSA contributes to ultimate strength at contents higher than 10%, but it is not effective at lower percentages.

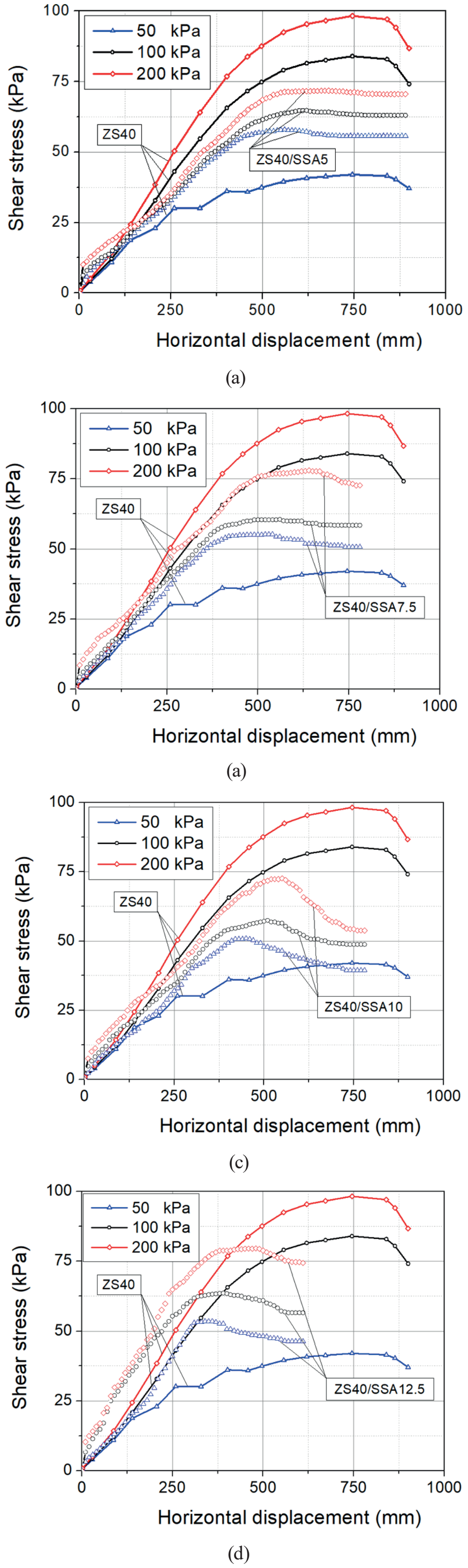



**Fig. 10** Direct shear test results of ZS40 and ZS40/SSA mixtures with varied contents of SSA; (a) 5% SSA, (b) 7.5% SSA, (c) 10% SSA, (d) 12.5%SSA

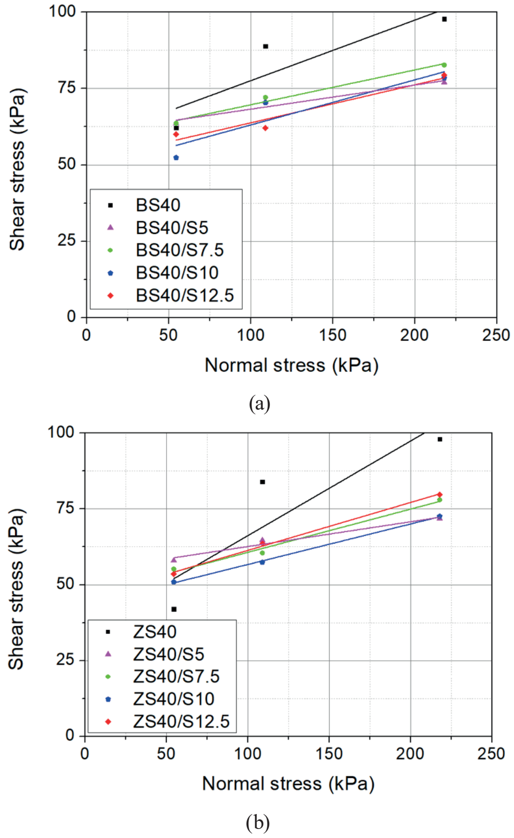
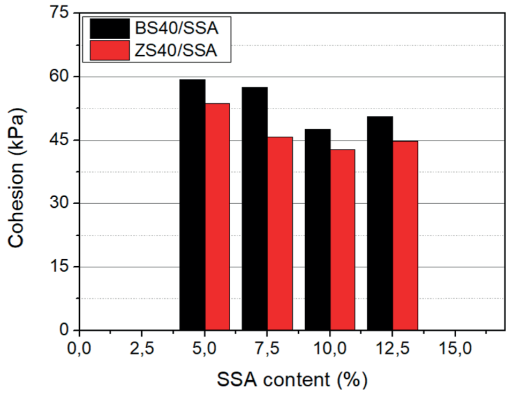
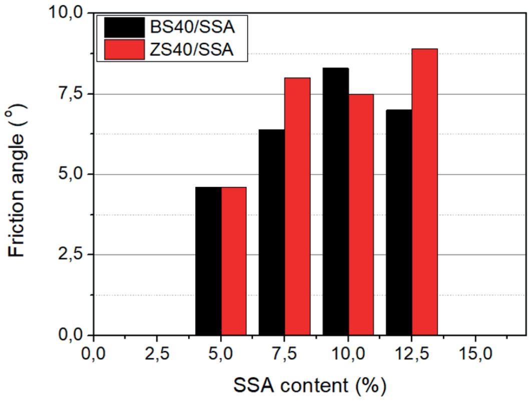



**Fig. 11** The variation of the shear stress of the tested specimens with normal stress; (a) BS40-Sand, (b) ZS40-Sand mixtures

In general, the cohesion, *c*, and shear strength of the stabilized soil improved with increasing cement additions [41]. Lin et al. [42] used SSA with hydrated lime and fly ash to improve the engineering properties of cohesive soils. Kadhim et al. [12] indicated that the inclusion of SSA with clayey soil improved unconfined shear strength with a 28-day curing time. Kadhim et al. [12] explained the increasing shear strength of SSA including specimens with the pozzolanic reactions of SSA. However, as in other studies, it was underlined that curing time is an important factor in the strength enhancement induced by SSA inclusion. Conversely, it was observed that cohesion decreased with sludge content up to 10%, while a slight increase occurred with 12.5% sludge content (Fig. 12(a)). The reduction of the cohesion is attributed to the non-cohesive property of the sludge ash in the mixtures. At higher contents of SSA, the increase of the cohesion is attributed to the accumulation of minerals such as Cao, MgO, and K2O that form cementation bonds with the minerals of the clay resulting in a higher cohesion [13]. The presence of cementing agents can provide significant cohesive strength. Stone et al. [39] pointed out that the increase in frictional angle in sludge including specimens is due to the

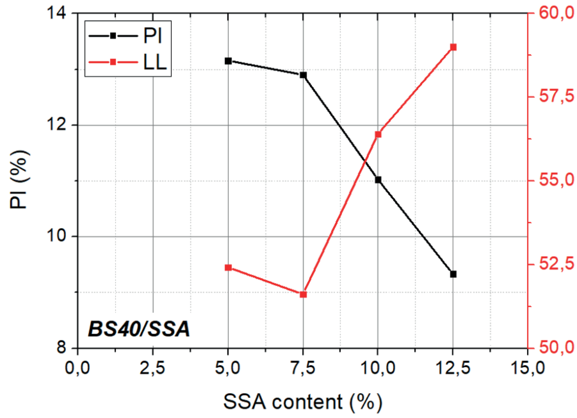



(a)

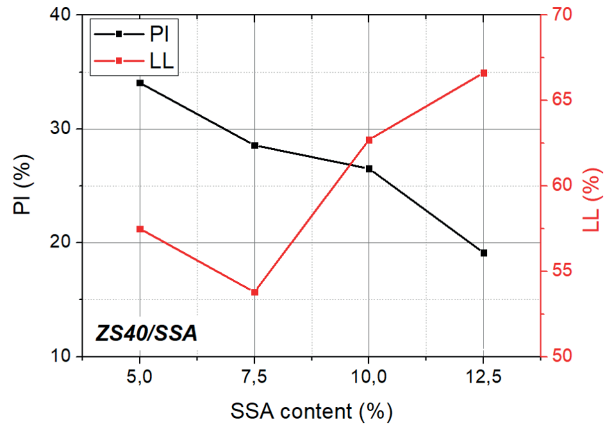



(b)

**Fig. 12** The variation of (a) cohesion and (b) friction angle with SSA content in the mixtures




(a)




(b)

**Fig. 13** The variation of the consistency limits with SSA content in the mixtures; (a) BS40/SSA, (b) ZS40/SSA specimens

degree of degradation of organic mass included in sewage. The increase is probably explained by the contribution of sludge to the enhancement of bonding forces among soil particles in the mixtures as a result of the analysis of microstructure [41]. The interactions between the grains with sewage inclusion result in additional friction in the mixtures [42]. It is visible that the increase in frictional angle is not proportional to the SSA content in the mixture. However, the results indicate that the internal friction angle of the untreated soil, regardless of the content, is significantly enhanced with the inclusion of SSA which can be deemed as the most striking outcome in the consideration of sludge with fine-grained soils. It should also be remembered that parameters such as degradation, mineralogical properties, water content, and level of plasticity of the selected material pairs have an effect on the results

The value of the plastic limit is inversely proportional to the amount of SSA introduced to the mixtures (Fig. 13). The increasing sludge content in the mixtures leads to a decrease in the plasticity index (PI) [43] and an increase in the liquid limit (LL). With the addition of 7.5% SSA, a decrease in LL was observed in both ZS40 and BS40 specimens, contrary to the general trend. Organic matter in soil is often responsible for high plasticity, high shrinkage, high compressibility, and low permeability [44]. The sludge material contains largely organic clay-sized particles and is classified as an extremely high plasticity organic clay according to the British Soil Classification System [45]. Due to high liquid and plastic limits and colloidal activity sewage sludge was similar in some respects to those of highly moistened peat [46]. Additionally, the plasticity characteristic of sand the bentonite mixture depends upon the clay content and the type of clay mineral present in the bentonite [47] and in the zeolite. The specimens with each content of SSA were classified as high-plasticity organic clay (Fig. 14). The high plasticity of specimens is attributed to; (i) the exceptionally high affinity of the alum coagulant for water, (ii) the destabilization of the dispersed solids during the chemical coagulation process and (iii) the very high solid organic content [45]. The compaction curves of SSA including bentonite and zeolite specimens display a similar pattern. (Fig. 15). The lower contents of SSA in

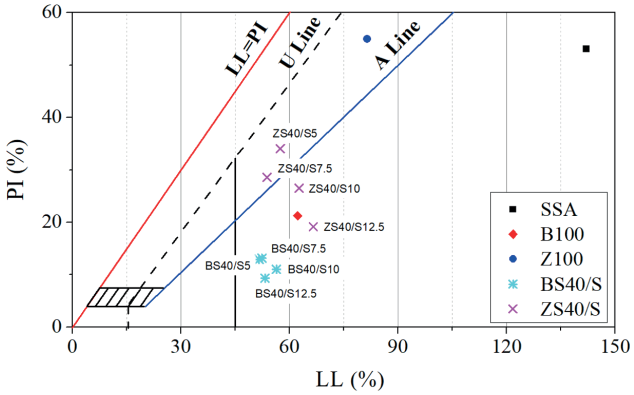
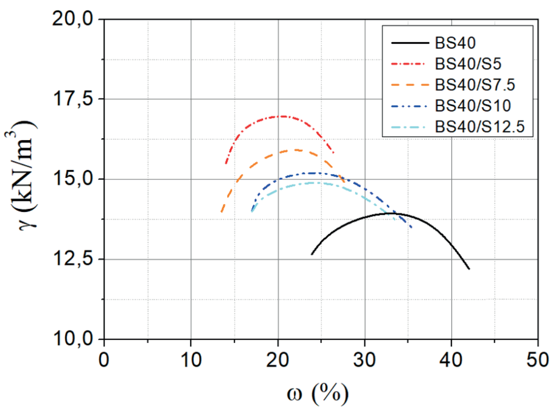
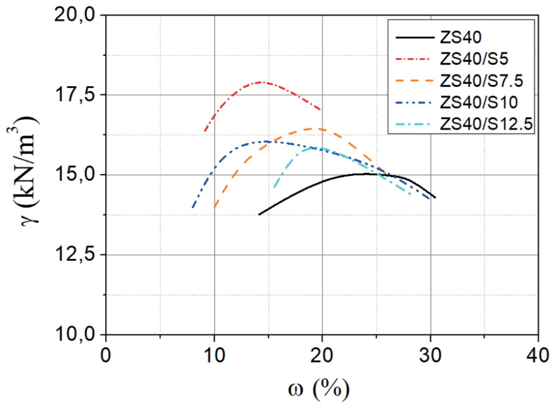



**Fig. 14** Consistency limits of the specimens plotted on the Casagrande plasticity chart




(a)

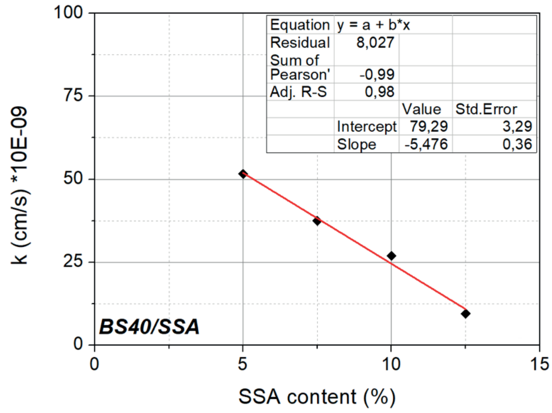



(b)

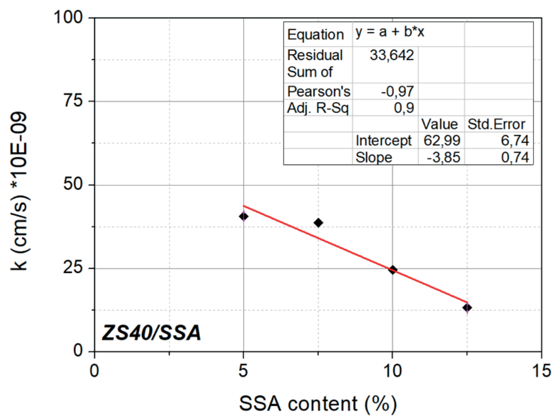
**Fig. 15** Compaction curves of (a) BS specimens and (b) ZS specimens

specimens lead to higher unit weight at optimum water content. (i.e., BS40/S5 and ZS40/S5). The optimum water content of specimens is increasing as the dosage of SSA introduced to the specimens increases.

When the hydraulic permeability of zeolite, sand, and bentonite and their separate mixtures are evaluated together, it shows that ZBM has much higher permeability [48]. Accordingly, during a desorption-subsequent sorption process of soil, it is assumed that permeability is a unique function of the water content of the soil. The permeability coefficients of BS40 and ZS40 measured at varying SSA contents indicate that the permeability of the samples decreased with increasing SSA (Fig. 16). It was observed that the permeability of BS40 was higher at lower SSA contents (i.e., 5% of SSA), while the permeability coefficients of BS40/SSA12.5 and ZS40/SSA12.5 specimens including 12.5% SSA were around $10^{-8}$ (cm/s). This indicates that with increasing SSA ratios, the void ratios of both specimens decrease gradually and get close to each other. In sand-bentonite mixtures, sand components increase their strength, and the bentonite component fills the gap between sand grains [47]. Zeolites, on the other hand, have the ability to absorb smaller molecules and suitable with it is hydraulic conductivity for the limitation of landfill liners [49]. Especially with the addition of 15% of SSA, both the permeability coefficient decreased, and a more convenient material composition was formed for the impermeable liner. The layers having a lower coefficient of permeability than $10^{-7}$ (cm/s) is suggested as barrier layer [50]. Provided that long-term application performance is also




(a)




(b)

**Fig. 16** The variation of the permeability coefficient with SSA content in the mixtures; (a) BS40/SSA, (b) ZS40/SSA specimens examined, Chen et al. [41] suggested deeply dewatered sludge for landfill cover material. The permeability coefficient of $10^{-5}$ (cm/s) is also considered appropriate if used together with the geomembrane [42], the hydraulic conductivity of solidified sludge with a $10^{-6}$ to $10^{-7}$ (cm/s) coefficient was found as too low to serve as a temporary cover layer, however, remolded sludge with an additive was found as appropriate with $10^{-4}$ (cm/s) coefficient of conductivity [39]. It should also be noted that sewage sludge should be used in an isolated environment from groundwater and rainwater due to the possibility of leaching of heavy metals likely to be present in the SSA mass [14].

## 5 Conclusions

In this study, experimental studies were carried out on the use of sewage sludge ash, a municipal waste, for geotechnical purposes. The sewage sludge ash used in the studies was obtained from the MASKI wastewater treatment plant, a locally operating government company. Sand, bentonite, and zeolite used in the studies are the soil types that can be found locally. In this context, optimum water content and unit volume weights of soil types were determined by proctor tests. The specific gravity and PH values of the samples were determined. Shear strength parameters of both pure samples and mixtures were determined by direct shear tests. Plasticity properties were determined by Atterberg consistency limit tests. The permeability of the samples was measured by falling-level permeameter tests. The main findings reached as a result of the experimental studies carried out are as follows:

- In bentonite-sand and zeolite-sand samples, BS40 and ZS40 samples containing 40% sand exhibited the best strength parameters. For this reason, BS40 and ZS40 were considered convenient as host materials for SSA mixtures.
- The determined SSA mixtures generally reached higher strength than the host material under normal stress of 50 kPa, and pure BS40 and ZS40 samples had higher shear strength than SSA mixtures under normal pressures of 100 and 200 kPa. BS40/SSA7.5 and ZS40/SSA12.5 samples from the mixtures reached 83 kPa and 80 kPa maximum shear strength under 200 kPa normal pressure. Accordingly, the maximum cohesion and friction angle of specimens were measured by BS40/S5 and ZS40/S12.5 as 59 kPa and 9°, respectively.
- With the increasing SSA contents of both BS40 and ZS40 samples, the plasticity index decreases and the liquid limit values increase. The maximum LL and PI were measured by ZS40/S12.5 and ZS40/S5 specimens as 67% and 34%, respectively. Except for the low SSA contents of ZS40, all SSA-containing BS40 and ZS40 mixtures are classified in the high plasticity soil group.
- With the addition of SSA, the hydraulic permeability of the mixtures decreases up to 3 times. The permeability coefficients of the BS40/SSA12.5 and ZS40/12.5 samples were measured as 9.5 × 10 $E^{-9}$ and 12.5 × 10 $E^{-9}$ (cm/s), respectively.
- Depending on its permeability and strength properties, deeply dewatered sludge can be used as an alternative material for the barrier layer of landfill covers. SSA is suggested to be used in an environment isolated from groundwater and rainwater due to the possibility of heavy metals leaching in its mass.

## Author contributions

Conceptualization: Ö. Yıldız and Ç. Ceylan; Methodology: Ö. Yıldız and Ç. Ceylan; Interpretations of results: Ö. Yıldız; Investigation: Ö. Yıldız; Writing -original draft: Ö. Yıldız; Writing-review and editing: Ö. Yıldız and B. Kövesdi.

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