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Waste utilization to enhance performance of road subbase fill

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Abstract

Purpose – The purpose of this study is to use waste materials in construction to create sustainable practices. This will contribute towards circular economy which has gained momentum in recent years throughout the world.

Design/methodology/approach – Waste materials cause enormous environmental problems that can have an adverse effect on the environment. Recycling of waste consists an important part of the circular economy. Therefore, researchers have been investigating the economic use of a variety of waste materials for reducing their environmental impact. One potential usage is in road subbase fill materials where wastes can be incorporated in large quantities. In this study, the engineering properties of road subbase fill materials (i.e. kaolinite) mixed with Granite Waste (GW), coal Fly Ash (FA) and lime are investigated. Kaolinite was replaced with 15% lime and FA, whereas the GW replacement varied from 10% to 20%. Testing included strength of the various soil compositions subjected to different curing times. Also the microstructural analyses and phase changes of samples were conducted using scanning electron microscopy and x-ray diffraction techniques, respectively. The results obtained indicate that GW can be incorporated in road base materials to improve its bearing capacity. The mixture consisting of 15% lime, 15% FA, 20% GW and 50% kaolinite resulted in maximum dry unit weight and optimum moisture content. Using GW exhibited a noticeable increase in the California Bearing Ratio of more than eight times at 1 day and 28 days curing regime compared with the control sample.

Findings – This study shows that GW and FA can be used for road subbase materials and can contribute toward a better and cleaner environment.

Originality/value – In this study, the engineering properties of road subbase fill materials (i.e. kaolinite) mixed with GW, coal FA and lime are investigated. This are value added in circular economy.

Keywords Fly ash, Circular economy, Lime, Engineering properties, Granite waste, Road subbase

Paper type Research paper

1. Introduction

In developed countries, the industrial waste, by-product materials and waste streams have a wide range of applications including construction. However, in the developing countries, the use of waste and low-cost technologies is much more critical. It is necessary to create sustainable infrastructures for low-cost technologies. The most important criterion for

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creating sustainable construction is the completion of a construction project at a low-cost (Assaf and Faour, 2018). Also sustainable construction requires an in-depth review of established practices and techniques to minimise the impact of construction activities on society, economy and environment. Regulatory bodies should establish guidelines to facilitate, encourage and enforce sustainable practices in their regulations. A safe and long-lasting conservation of virgin materials for construction can be achieved through the recycling and reuse industrial wastes (Micheal *et al.*, 2016). In addition, the utilization of waste would reduce the impact on the environment (Dahale *et al.*, 2012). Industrial wastes or recycling materials can be used in many construction applications including road surface coatings and subbase fillings (El-Assaly and Ellis, 2001).

The purpose of using waste materials is to create sustainable practices. In this study, an attempt was made to use waste materials, namely, fly ash (FA) and granite waste (GW) in the base and subbase of road construction. The usability of wastes in soil stabilization was investigated. This will lead to conservation of natural resources for future generations. Kaolinite clay was used as the original soil sample. FA, GW and lime were added to the soil sample. Various properties of the soil mixtures were tested which included; liquid limit, dry unit weight, swelling ratio and California bearing ratio (CBR). Also, the X-Ray Diffraction (XRD) and scanning electron microscopy (SEM) techniques were used to assess the microstructure of the various soil mixtures. The lime and FA are kept constant for all mixtures at 15% replacement of Kaolinite soil (by weight). However, GW replacement was Kaolinite between 10% and 15% (by weight) of the Kaolinite soil. Dry unit weight, CA bearing ratio and swelling of kaolinite clay samples containing varying amounts and types of waste were investigated.

This study is aimed to reuse the wastes in soil stabilization, thus reducing the amount of virgin materials used in construction and lowering the footprint of construction activities, thereby contributing toward the circular economy.

In the first part of our study, the introduction part is presented as general information about our study subject. In the last paragraph of the introduction, the aim and originality of the work we will do is mentioned. In the second part, the studies and results obtained by different researchers with similar subject content are given. In the third part, all the materials in the study were introduced and all the experimental processes were introduced. In the fourth chapter, the results obtained from all experimental studies are presented with tables and graphics. At the end of the fourth part, the topics that can be the continuation of this study are mentioned. Considering the materials used and the results obtained, it is mentioned that the study is practical and applicable. In the last part, the findings obtained from the study are included and the contribution of this paper to the literature is mentioned.

2. Background of theory

During road construction, the excavated materials are removed and substituted with new materials that satisfy the requirements for road construction including better load-bearing capacity. In recent years, many governments throughout the world have set targets to reduce the harmful gas emission into the atmosphere. This has resulted in a set of new environmental legislation that have made construction professionals consider different approaches when constructing roads. These methods include improving the properties of the locally excavated materials through stabilization and the use of waste materials or industrial by-products. Of these methods is stabilizing the existing materials with other additives to improve their performance. In addition, the increase in the number of vehicles on the roads has led to the need to build more and better road. This would require large amounts of materials and the associated impact on natural resources (Abukhettala, 2016). This can be alleviated through the use of waste materials from waste including; recycled concrete and brick, construction debris, reclaimed highway paving materials and secondary materials. This will also lead to a reduction in energy requirements and the associated cost, thus contributing toward sustainable development (Cetin *et al.*, 2010).

Khazaei and Moayedi (2017) examined the effect of quicklime as a hydraulic binder and bentonite on the stabilization of expansive soil. The results indicated that mixing soil with 8% lime and bentonite leads to an increase in unit dry weight. Beyond 8% the dry unit weight decreases. The trend in the unconfined compression tests is similar to those of the dry unit weight. Soil with 10%–12% lime addition yielded the maximum shear strength (Khazaei and Moayedi, 2017).

Firat *et al.* (2013) examined the effect of adding waste materials to existing excavated soil. The waste materials used were FA, marble dust and waste sand. The addition of waste materials was between 5% and 20% (by mass) of the existing soil. After mixing, the soil/waste mixtures were left to cure for 1 day, 7, 28, 56, 90 and 112 days before testing. The dry unit weight, unconfined compressive strength (q_u) and CBR were determined for all soil mixtures. Also, XRD analysis and SEM observation were conducted. The results showed that increasing the waste material content increase the q_u values. This trend is somewhat similar to those in a previous investigation (Firat *et al.*, 2017).

Marble dust and municipal solid waste incineration ash were used to stabilize the geotechnical properties of clayey soil. These materials could be used in the pavement subbase and their damage to the environment can be minimized. Singh *et al.* (2020) reported a decrease in dry density in the presence of municipal solid waste incineration ash while an increase was observed when marble dust was added to the soil.

In addition to being a waste, FA is a pozzolanic material and reacts with calcium hydroxide to form cementitious products. Researchers have studied different types of waste materials that are used to improve the bearing capacity of road subbase. Significant improvements were obtained by using industrial by-products which are normally disposed of and harming the environment (Firat and Cömert, 2011).

There is a substantial amount of wastes generated annually due to the extraction of natural resources. Since the start of the industrial revolution, there has been a steady increase in the use of coal such as coal power stations. This has led to the generation of huge quantities of ash. The current annual generation of coal ash is estimated at over 850 gigatonnes globally (Heidrich *et al.*, 2013) with FA constituting about 750 million tonnes (Yao *et al.*, 2015). Thus, the amount of FA generated by factories and power stations in the world is alarming and has a drastic and serious effect on the environment. The present global utilization of FA varied widely from 3% to 57% depending upon the country in which coal ash is generated. The remaining amounts of FA are normally destined to landfill, thus causing economic and environmental concern (Ahmurazzaman, 2010). In Turkey, 70 million tons of lignite coal is burnt annually resulting in the generation of 19 million tons of FA (Yao *et al.*, 2015; Pandey and Singh, 2009; Uyanik and Topeli, 2014). The production and consumption of FA from selected countries are shown in Figure 1. Also, there is a huge amount of GW from granite cutting. It is estimated that approximately 5.4 million metric tons of GW are generated annually (Siraj, 2016).

Clayey soil can have many problems in the construction of roads and runways. The use of mineral additives to this type of soil can alleviate these problems. Ural (2016) examined the performance of clay when adding lime, cement and FA or other waste materials. The XRD and SEM analyses of compacted samples were performed. It was found that an increase in lime and cement content led to a more refined pore structure and this refinement increased with the increase in the curing period (Ural, 2016).

Bhardwaj and Sharma (2020) tested natural soil at a depth of 1–1.5 meters from the ground surface with and without the addition of lime. It was concluded that the plasticity index decreases while there was an increase in unconfined compressive strength (UCS).

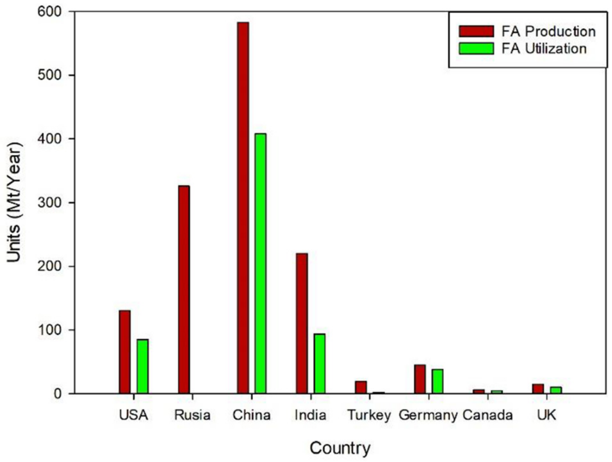


Figure 1.
Fly Ash production and utilization in some selected countries

Source: Yao *et al.* (2015), Pandey and Singh (2009), Uyanik and Topeli (2014)

Firat *et al.* (2020) conducted some tests on Kaolinite soil containing lime, coal FA and basic oxygen furnace slag Kaolinite at different curing times. It was found that maximum dry unit weight (γ_{dmax}) increases as the percentage of FA increases. Using FA and BOF slag increased the UCS (q_u). This was attributed to the pozzolanic reaction with lime (Firat *et al.*, 2020).

The effect of lime and cement on the compacted silty and clayey soil layers of the Mexican region was investigated. 10% lime was used in the mixtures. Lime had a better effect than cement by drying faster with lower energy. In the results of the undrained consolidation (UU) and drained consolidation (CU) test results, the lime additive accelerates the compaction of the soil layers of clayey and silty soils (Aquino *et al.*, 2020).

Engineering properties of fine and coarse-grained polyethylene wastes and their usability as fillers in engineering applications have been studied. Gunaydin *et al.* (2016) conducted various tests soil including compaction, shear box, uniaxial compressive strength and ultrasonic tests on silty soil incorporating polyethylene waste. The shear strength was 2,812 kPa and 2,840 kPa for the soil containing fine and coarse polyethylene waste respectively. Also it was concluded that the addition of waste did not change the internal friction angle of the soils. However, the cohesion value increased with the increase in polyethylene waste. They concluded that the maximum amount of polyethylene waste can be added to the soil is 45% (Gunaydin *et al.*, 2016).

3. Materials and method

In Section 3, the materials used in the study and the testing conducted are described.

3.1 Materials

3.1.1 Fly ash. The FA was obtained from Seyitömer (Kütahya) thermal power plant (Turkey). Chemical analysis of FA is given in Table 1. The amount of SiO_2, Al_2O_3 and Fe_2O_3 content is 84.34%, while its CaO content is 4.26%. Based on the ASTM C 618 classifications, the FA is classified as type F (ASTM C 618, 2005).

3.1.2 Granite waste. GW is a by-product of cutting granite is collected in an overbear pole (Figure 2a), then squeezed to extract water (Figure 2b) This process reduces the total waste volume and land space. Generally, GW is disposed of in open spaces or landfill sites. The chemical composition of and specific gravity of GW are given in Tables 1 and 3.

3.1.3 Kaolinite. Kaolinite is used for mixtures of natural soil. It was obtained from a private company. The characteristics values of Kaolinite are given in Tables 1 and 3.

3.1.4 Lime. Lime is used to produce quicklime (CaO) through the calcination of limestone (calcium carbonate). The temperature is about 900–1,000°C for this process. The chemical equation for this reaction is;

$$\mathrm{CaCO_3} + \text{heat} \qquad \mathrm{CaO} + \mathrm{CO_2} \tag{1}$$

3.2 Experimental methods

In subsection 3.2, the experiments and the applied procedures are explained. The standards used for the experiments are included. Conducting experimental research to test theories or construct theoretical explanations requires careful attention to all details from setting up the laboratory, develop procedures and implementing the experiment. Experimental research is undertaken to trace cause and effect relationships between defined variables.

In the study, four soil mixtures containing different proportions of lime, FA or GW were prepared. The control mixture (M-1) had 100% kaolinite clay. In the other three mixtures (M-2, M-3, M-4), the kaolinite clay was replaced with 15% lime and 15% FA. However, the variable material in the study is GW. There was a constant addition of 15% lime and 15% FA to all mixtures. However, there was a varied replacement of 10%, 15% and 20% GW, respectively. The samples were compacted and cured for 1, 7, 28 and 56 days. Some samples were also cured for 56 days. Testing

Table 1. Chemical compositions of materials

Type of properties	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	TiO_2 %	CaO %	MgO %	Na_2O %	K_2O %	MnO %	SO_3 %	Combustion Loss (C.L) %
Kaolinite	45.65	37.63	0.73	0.13	0.3	0.27	0.62	2.4	–	–	11.91
Fly Ash	54.49	20.58	9.27	–	4.26	4.48	0.65	2.01	–	0.52	3.01
GW	64.454	20.571	0.548	0.598	1.973	2.699	5.132	0.996	0.016	0.133	2.880
Lime	0.70	0.40	0.40	0.5	87	4.50	–	–	–	0.80	4

(a) (b)

Notes: (a) GW overbear poll; (b) GW is extracted from the water

Figure 2. Process of GW generation

included; plastic limit, liquid limit, specific gravity, swelling, strength (Compaction and CBR) and CBR. Table 2 shows the mixture proportions.

3.2.1 Specific gravity. Specific gravity is the ratio of the density of a substance to the density of a given reference material. Knowing the specific gravity will help to predict the physical properties of the samples. It is a property that can affect the mechanical properties of a material or a soil mixture.

The pycnometer used in the experiment is cleaned and dried. The completely dried pycnometer is weighed in its empty state. The sample is placed in the pycnometer and weighed again. The pycnometer containing the sample is filled with water and weighed. The completely emptied pycnometer is filled with water and weighed again. The specific gravity value of the sample is determined according to ASTM (ASTM D 854, 2014).

The dry density of a granular material is much influenced by the specific gravity. This will also affect the CBR and strength values. Therefore, the specific gravity of dry materials was determined according to ASTM (ASTM D 854, 2014). The specific gravity values of all samples are shown in Figure 3 and Table 3.

3.2.2 Soil classification (particle size distribution). Particle size distribution is important for understanding the physical and chemical properties of a material. Particle size

Table 2.
Details of mixtures

	Materials used			
Mixtures	GW* (%)	Lime (%)	FA** (%)	Clay***) (%)
M-1	–	–	–	100
M-2	10	15	15	60
M-3	15	15	15	55
M-4	20	15	15	50

Notes: *Granite waste; **Fly ash; ***Kaolinite clay

Figure 3.
Process of specific gravity

distribution can be an important physical property for a variety of manufactured products across many industries. The particle size distribution of a material can be important in understanding its physical and chemical properties. It affects the strength and load-bearing properties of granular materials including soil.

It is necessary to determine the particle distribution curves to determine the gravel, sand, silt and clay contents of the soil samples used. The hydrometer test was used to determine the particle size distribution curve of fine grained soils (below 200 μm). The ASTM standard was used to determine the particle size distribution curves of the materials (ASTM D 7928, 2017).

The hydrometer test is an experimental procedure used to find the particle size of the material. In the hydrometer test, first the organic wastes in the sample should be burned (using perhydrol). For the burned sample, dispersion (decomposition) process is applied using sodium hexametaphosphate. To determine the precipitation analysis, the time-dependent collapse of the sample is determined by taking readings from the 1,000 ml scaled sample at certain times. Samples with large diameters will collapse first, and samples with a small diameter will sink to the bottom in time. Hydrometer test period of each sample is 24 h. The particle size distribution of the sample can be drawn with the values obtained at the end of this period.

Figure 4 plots the particle size distribution of kaolinite clay and GW samples using the hydrometer tests. The uniformity (C_u) and curvature coefficients (C_c) are shape factors that can be obtained from the particle distribution curves. They are used to determine the distribution of well graded and poorly graded soils. The kaolinite clay and GW were classified as CH (high plasticity clay) soil type, respectively.

3.2.3 Plastic limit. The plastic limit test is the water content value at which the soil changes from a semi-solid consistency to a plastic consistency. This test is performed by hand rolling the soil sample on a glass surface with a palm until no further deformation is obtained as shown in Figure 5. Then the plastic limit was determined according to ASTM standard (ASTM D 4318, 2017).

3.2.4 Liquid limit. The liquid limit is defined as the water content at which the behavior of a clayey soil changes from the plastic state to the liquid state. It is used for fine grained soils. These soils tend to swell with water. When silt and clay interact with water, their shear strength can change. They are used to differentiate silt and clay and to measure the water absorption capacity of these samples.

The completely dry sample is taken into the mixing cup and a small amount of water is added. The sample is mixed homogeneously with a spatula. Water is added slowly until the sample becomes liquid and mixing is continued with a spatula. The sample is then in a cylindrical container in such a way that no air remains. The cylindrical container is placed in the test device and the amount of the conical tip penetrating the sample is measured using the one-point method (ASTM D 4318, 2017).

Table 3.
Physical properties of the materials

Geotechnical properties	Soil (Kaolinite)	Wastes		
		GW	Lime	FA
Liquid limit (%)	53.59	39.80	N/A	N/A
Plastic limit (%)	30.00	24.80	N/A	N/A
Plasticity index (%)	23.59	15.00	N/A	N/A
Specific gravity	2.57	2.49	2.41	1.83
Soil Classification USCS (TS 1500)	CH (high plasticity clay)	CL (low plasticity clay)	N/A	N/A
Silt/Clay/Sand (%)	4/96/0	9/77/14	N/A	N/A

Figure 4.
Hydrometer test analysis

Figure 5.
Plastic limit test phase of samples

Atterberg limit tests for the natural soil sample and other waste materials used in the study were performed using the ASTM D 4318 standard. The cone penetration method was used for the liquid limit value determination from the Atterberg limits. Liquid limit values of samples are shown in Table 3. The performance of the liquid limit test is shown in Figure 6. The cone penetrometer test method for Liquid Limit is based on the relationship between the moisture content and the penetration of a cone into a soil sample.

3.2.5 Compaction. Soil compaction is the process of removing the voids between soil grains by applying a stress to a soil. This test is necessary to know the engineering properties of the soil including the compressive strength. Other engineering properties include the dry unit weight and water content. The standard compaction method was used for optimum water content and dry unit weight values of the samples (ASTM D 698, 2012). In the compaction experiment, five tests were made for each mixture with five different water contents. A total of 20 compaction tests were carried out. Figure 7 shows the compaction test apparatus and sample.

All the dry materials were prepared and thoroughly mixed. Water was then added slowly into the dry mixture. Then, homogeneously mixed samples were placed in the compaction mold in three layers. Each layer, the sample was compressed 25 times using a 2.5 kg hammer. The top surface of the compressed sample was smoothed and the compressed sample weight was determined. Dry unit weight value was obtained from the

Figure 6.
Liquid limit test phase of samples

Figure 7.
Standard compaction test specimen and phase of samples

compressed sample weight and mold volume. A certain amount of the compressed sample was taken into a container dried and the water content was found. Finally, the compaction curve was drawn using the water content and dry unit weight values. This test conforms to ASTM standard (ASTM D 698, 2012).

3.2.6 California bearing ratio. CBR is a mechanical test for determining the strength of soils such as the subbase layers of roads. Based on the results of the test, the thickness of the subbase layer can then be determined.

The dry materials for each soil are mixed until a homogenous mixture is obtained. Then the optimum waste content obtained from the compaction test is added to the dry mixture. The penetration value is determined for the sample compressed in the standard compaction mold. The samples were placed in a pool and cured for 1, 7, 28 and 56 days to study the effect of curing time on soil properties. At each curing age, the required number of sample was removed and the CBR value was measured. While in the pool, the swelling of the samples compressed in the standard compaction mold was measured according to ASTM standard (ASTM D 1883, 2007).

The penetration values of prepared CBR test samples were determined in the device shown in Figure 8. The penetration test is performed by immersing a standard piston with a diameter of 50 mm into the compressed soil at a speed of 1.25 mm/min with a hydraulic force. The experiment continues until there is 2.5 mm penetration in the soil and the result obtained is divided by the CBR ratio of a standard crushed rock to obtain the CBR value of the soil.

CBR, swelling ratio and compaction were conducted at all curing times. However, XRD and SEM analyses were conducted at 7, 28 and 56 days of curing for samples with 20% waste (FA or GW) only.

4. Experimental results and recommendations

4.1 Test results

4.1.1 Soil classification. Liquid limit and plastic limit tests are performed to obtain Unified Soil Classification System (USCS) according to TS1500/2000 (TS 1500, 2000) and ASTM D4318 (ASTM D 4318, 2017).

Figure 8.
CBR test device and sample

The ratio of fine grains in GW was 9%, and the ratio of fine grains in Kaolinite was 4%. These ratios are shown in Figure 9.

Highway standard requires that minimum liquid limit values should be less than 60% according to ASTM D 4318 (ASTM D 4318, 2017). In this study, the liquid limit value of the kaolinite sample was found to be 53,587% and the liquid limit value of the GW was found to be 39,80%. These values meet the requirements of the Turkish Highway Standards (Highway Technical Specification, 2013).

The plastic limit is also found to be 30% and according to USCS, the soil is named as high plasticity clay (CH). Liquid limit results of Kaolinite and GW are given in Figure 10.

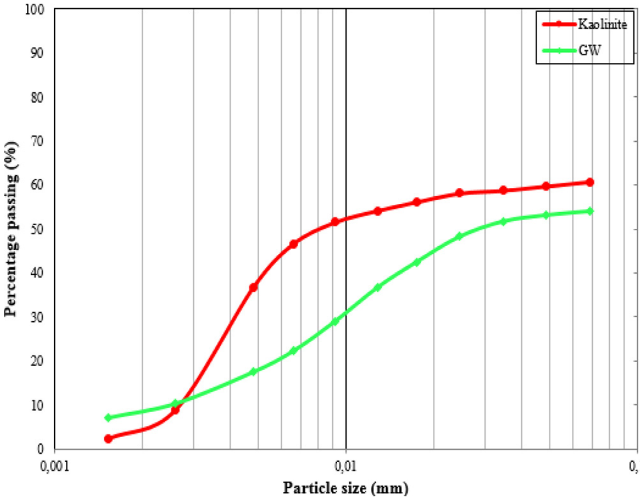


Figure 9. Particle size distribution of kaolinite and GW

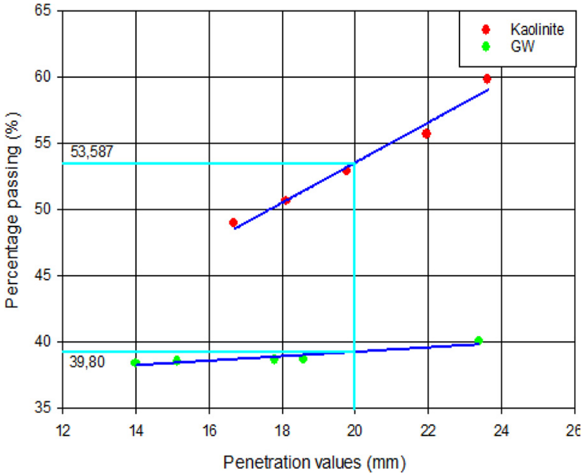


Figure 10. Liquid limit results of kaolinite and GW

Table 3 presents the classification and physical properties of dry materials used in this study.

4.1.2 Compaction Test. The Standard Proctor Compaction enables the determination of the optimum moisture content of the soil for achieving its maximum dry density (ASTM D 698, 2012). Figure 11 shows the variation of dry density with the changes in moisture content. The maximum value for the dry unit weight corresponds to the optimum moisture content.

In this research, FA and lime contents are kept constant for all compaction tests at 15% of the original kaolinite soil. The GW replaced 10%, 15% and 20% of kaolinite soil (by weight). Increasing the ratio of GW into the mixtures caused an increase in dry unit weight.

The composition of soil mixtures and optimum moisture content are given in Table 4. Samples are then prepared with optimum moisture content and the CBR test was conducted.

Maximum dry unit weight is obtained for the Kaolinite itself, which is 10.49 kN/m^3. Replacing 20% of the soil with GW (M-4) caused the maximum dry unit weight to increase as 12.38 kN/m^3. This value complies with regulations of the stabilization of road subbase fill materials (Highway Technical Specification, 2013).

The optimum water content and dry unit weight for all mixtures are presented in Table 4.

Singh *et al.* (2014) studied the effects of different waste materials on the soil. They concluded that the dry density of the soil increased when the waste materials were added to the soil. It was found to be consistent with the results obtained in our study.

4.1.3 California Bearing ratio. CBR test is performed to evaluate the bearing capacity of the soil and to assess its suitability to use for road substructures. In this investigation, a

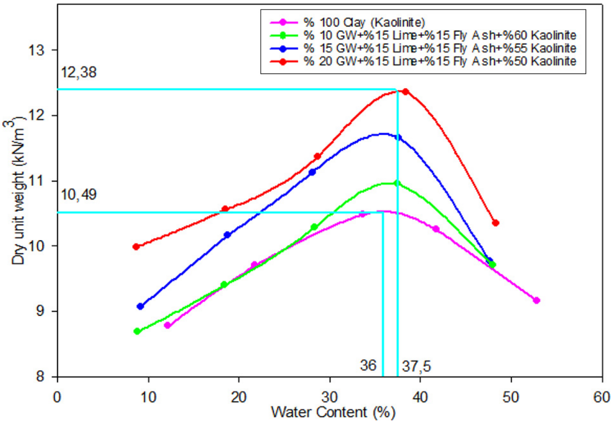


Figure 11.
Effects of GW addition on standard compaction test

Table 4.
Compaction test results

Mixtures	Optimum water content (%)	Dry unit weight (kN/m^3)
M-1	32.2	10.49
M-2	37.44	10.96
M-3	37.62	11.70
M-4	38.19	12.38

soaked CBR test was conducted for assessing the bearing capacity of the soil subjected to the worst conditions. Two samples were prepared for the CBR test; one was directly placed in the water whereas the other sample was cured for 28 days in air (stored in a way that there is no air intake and in a moisture-free environment). Figure 12 shows the soaked CBR values for soil mixtures containing varying amounts of wastes and cured for 1, 7, 14, 28 and 56 days.

CBR values of pure Kaolinite samples cured at different times are given in Table 6. The pure Kaolinite CBR value was 2.71% for 1 day of curing, whereas at 56 days curing the value increased to 4.06%. This is an increase of 49%. Using an increasing amount of GW led to a noticeable increase in CBR. The percentage increase in CBR with respect to the control (M-1) was 430%, 460% and 860% for soil mixtures containing 10%, 15% and 20% GW, respectively. The mixture containing 20% GW (M-4) had a CBR values of 1.73% and 16.76% at 1 day and 56 days of curing, respectively, for samples cured in air (stored in a way that there is no air intake and in a moisture-free environment). This is an increase of 860%. However, samples cured in water for four days for the same mixture (M-4) had values of 4.54% and 20.49%, respectively, at 56 days which is an increase of 350%. This result is consistent with the results in the study of Niyomukiza *et al.* in the literature (Niyomukiza *et al.*, 2019).

Table 5 shows the swelling percentage of the kaolinite material. The swelling potential of the kaolinite material obtained as a result of the swelling test was found to be high. It has been proven that kaolinite material has a high swelling potential according to the swelling potential classification chart (Seed *et al.*, 1962; Highway Technical Specification, 2013).

Each country has its own standards to assess the performance of the soil. Soaked CBR value cannot be less than 10% according to Turkish Standards Requirements (Highway Technical Specification, 2013). Also the swelling should not exceed 3%. According to this result, the CBR of soil mixture containing 20% GW (M-4) met this requirement beyond 14 days of curing (Table 5).

The swelling test apparatus is shown in Figure 13. The test gives the value of the swelling ratio of the samples. Table 5 presents the swelling values for M-4 mixture. Replacing kaolinite soil with 15% FA, 15% lime and 20% GW led to a substantial reduction in swelling. The values obtained are negligible (< 0.014%) for soil mixture M-4 compared with 11.1% for pure kaolinite soil (M-1).

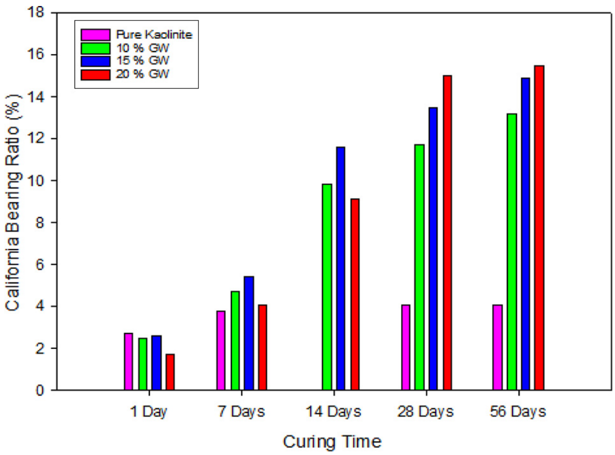


Figure 12.
CBR values of all soil mixtures at different curing times

According to Highways Technical Specification (Highway Technical Specification, 2013) swelling value should not exceed 3%. The swelling value is obtained by 20% GW (i.e. M-4) added mixtures which gave the highest compaction value compared to other mixtures. As can be seen in Table 5, the swelling values are not exceeded according to technical specifications.

Figure 12 shows the CBR values for Kaolinite soil containing 10%, 15% and 20% of GW for different curing times. There is a significant increase in CBR for soils as the period of curing increases. For example, the CBR was 2.48% at 1 day curing, whereas at 56 days of curing the CBR was 13.17%, which is an increase of 430% in Figure 12 compared with the 1 day curing. A similar increase occurred as curing time increases at 15% and 20% GW.

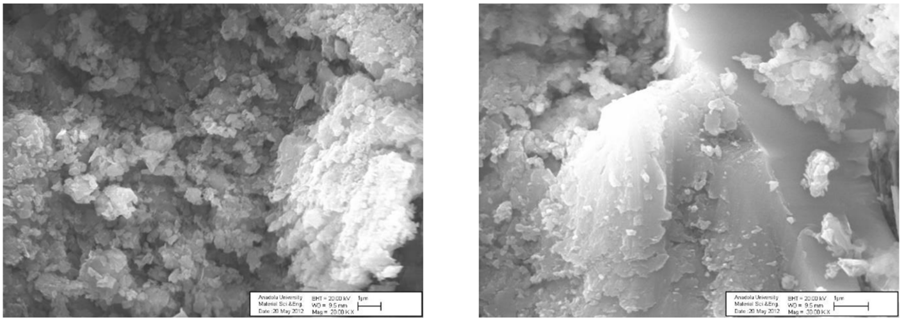
4.1.4 Microstructure analysis. XRD analysis was performed using Rigaku Rint-2200 diffractometer in a scanning range of 10°–90° (2θ) at a rate of 2° (2θ) min. -1CuKα radiation was used. The secondary images of gold–coated fracture surfaces by using a ZEISS Ultra plus field emission scanning electron microscopy (FE-SEM) after Au-Pd coating. These images were used to observe the microstructural properties of soil mixtures by observing the surface texture. Figures 14, 15 and 16 shows SEM analysis of soil mixture M-4 containing 20% GW, 15% lime and 15% FA at 14, 28 and 56 days of curing,

Table 5.
Results of CBR values containing 20% GW addition

					Curing time					
	1 day		7 days		14 days		28 days		56 days	
					Penetration values (mm)					
Types of tests	2.5	5	2.5	5	2.5	5	2.5	5	2.5	5
Soaked CBR(%)	1.45	1.73	3.54	4.04	9.03	9.15	12.13	15.02	12.45	16.76
Unsoaked CBR (%)	4.49	4.54	7.87	9.13	13.91	17.3	14.28	16.96	16.26	20.49
Pure kaolinite CBR (%)	2.22	2.71	3.6	3.8			4.0	4.06	4.0	4.06
CBR(mm) swelling	0.001 0.00079%		0.003 0.0024%		0.01 0.0079%		0.013 0.01%		0.014 0.011%	
Kaolinite swelling (%)	11.1									

Figure 13.
Soaked and swelling measurement of mixture

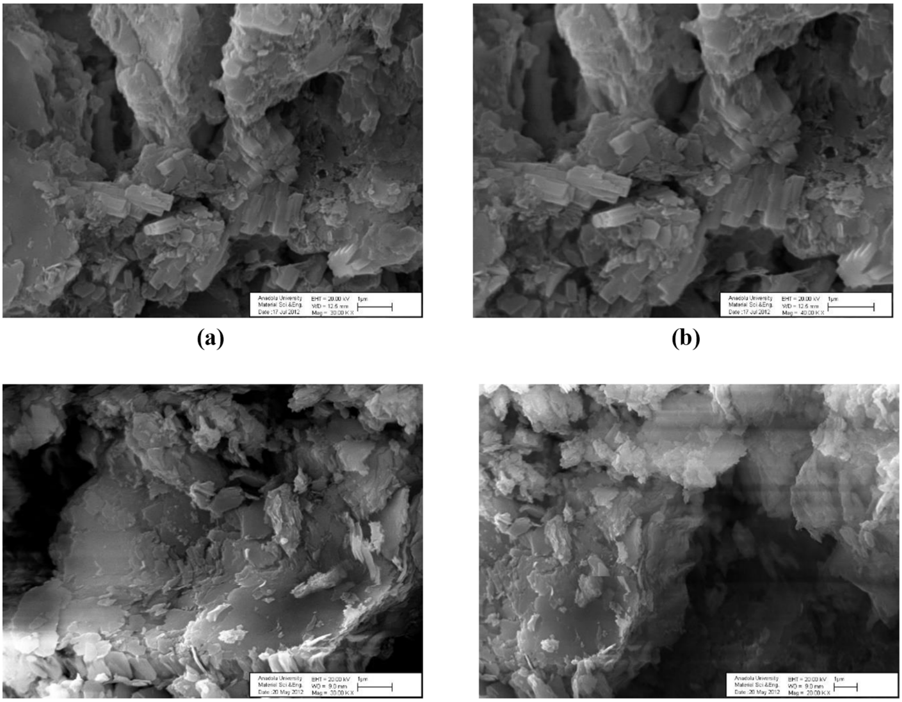
respectively. At 56 days of curing, (Figure 14), there seems to be a flocculated structure. As higher magnification (3,0000 X) the crystal structure of quartz and Kaolinite became clear. This situation can be explained by the decrease in interaction of lime and FA due to the increasing curing periods.



(a) **(b)**

Notes: (a) Point chosen for SEM image; (b) magnified SEM image of the selected point

Figure 14. SEM images with different magnifications for soil mixture M-4 (15% Lime, 15% FA and 20% GW) at 14 days of curing



(a) **(b)**

(c) **(d)**

Notes: (a) Point chosen for SEM image; (b) magnified SEM image of the selected point; (c) SEM images of different point; (d) magnified SEM image of the selected point

Figure 15. SEM images with different magnifications for soil mixture M-4 (15% Lime, 15% FA and 20% GW) at 28 days of curing

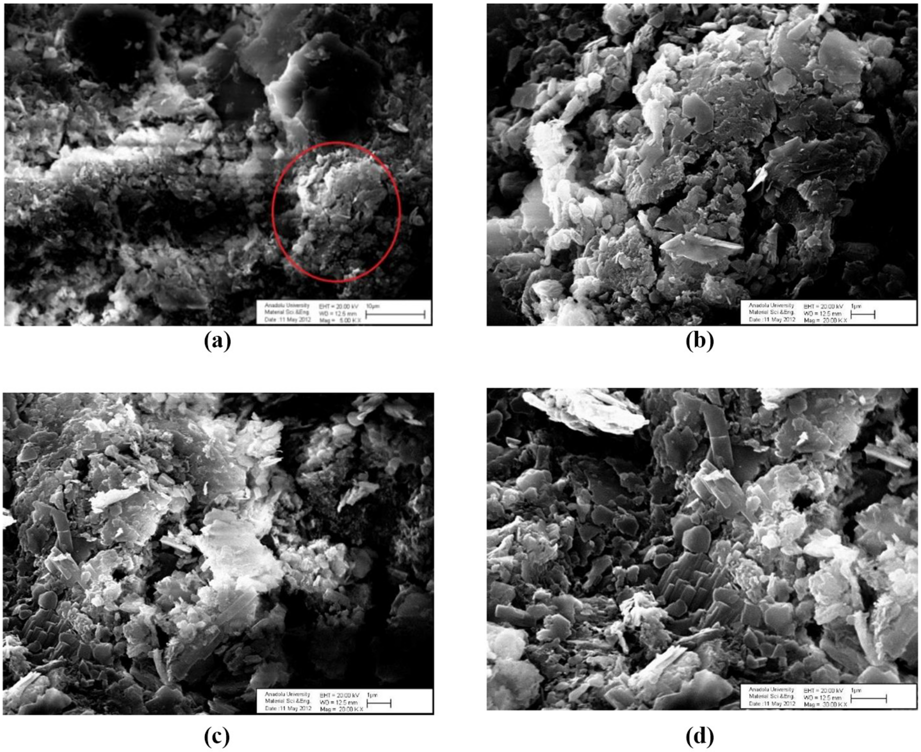


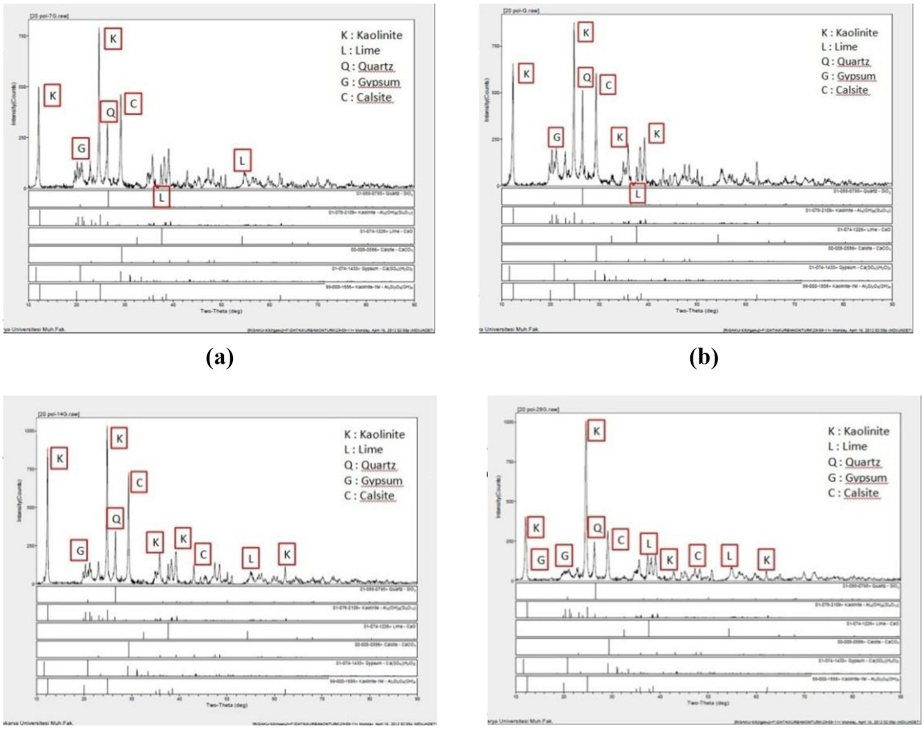
Figure 16.
SEM images with different magnifications for soil mixture M-4 (15% Lime, 15% FA and 20% GW) at 56 days of curing

Notes: (a) Point chosen for SEM image; (c) SEM images of different point; (b) magnified SEM image of the selected point; d) magnified SEM image of the selected point

Figure 17 shows that XRD analysis for soil mixture M-4 containing 15% lime, 15% FA and 20% GW + at 1 day, 7, 14 and 28 days of curing. The XRD diagrams show that the main mineralogical constituents of these samples are Kaolinite, lime, quartz, gypsum and calcite at all curing ages.

When comparing the XRD diagrams for samples cured at 1 day, 7, 14 and 28 days, it can be noticed that there is a remarkable increase of these compounds. This is attributed to the effect of adding GW, FA and lime. Because FA offers easy production of hydraulic compounds at the early ages. However, a decrease in intensity values of quartz, lime and calcite of main peaks was observed. Also, the main peak of Kaolinite is due to the increasing curing period that increased in intensity is also observed.

The study covers excellent reading for all international readers to have good insight for solid waste that improves the mechanical and strength properties of soil. It has been concluded that it can be used in stabilization processes of problematic soils and its application is practical. With the use of solid wastes, natural resources will be preserved and the circular economy will be profitable. Finally, with the use of waste in recycling, reductions in carbon footprint measurements will occur and environmental pollution will decrease.



(a)

(b)

(c)

(d)

Notes: (a) 1 day XRD analysis; (b) 7 days XRD analysis; (c) 14 days XRD analysis; (d) 28 days XRD analysis

Figure 17. XRD analysis of the mixture samples having content 20% MGW +15% lime +15% FA + 50% clay according to the curing time

5. Conclusion

In this study, mixtures of Kaolinite, FA, GW and lime are used to determine the CBR values. The CBR is one of the most widely used methods to determine the bearing capacity of the soil. Waste materials, GW and FA, in addition to lime are incorporated with the kaolinite clay soil. Generally, the use of the previously mentioned waste materials improved the properties of the soil. This would lead to reduction in pollution and economic benefit.

Maximum dry unit weight (γ_{dmax}) is increased by 20% when replacing the kaolinite soil with 20% GW, 15% FA and 15% lime. Therefore, these mixtures are used to carry out the CBR test procedures.

The CBR test specimens are tested in wet and dry conditions by considering different curing times as 7, 14, 28 and 56 days. The dry CBR values gave higher results than wet ones in terms of bearing capacity as the ratio of 25%–30%.

Increasing the amount of GW increases the surface area of the sample while the amount of Kaolinite is reduced and thus optimum water content of the mixture is increased.

The additives also reduced the Kaolinite swelling values. They also increased the CBR values by increasing the additives percentages used in mixtures.

This is conducted due to the presence of lime which has a pozzolanic effect as well as GW and FA additives. As curing time increased the mixtures became more hardened because of CaO (Calcium Oxide) presence.

When the curing time increases as a result of the CBR experiment the CBR value obtained also increases. After four-day swelling measurement was completed, the sample was taken out of the water pool and the CBR test was performed. A similar increase was observed as a result of the CBR test performed after the sample with increased curing time was taken out of the pool.

It is a preferred alternative method for soil stabilization thanks to the cost-effective, durable and light characteristics of waste materials. As a result of this work, natural resource reserves will be preserved and waste materials will be recycled. Solid wastes used in the study are some of the factors that cause environmental pollution. The use of these wastes in construction instead of virgin materials will reduce the environmental pollution and the carbon footprint. In addition, the easy accessibility and recycling of these wastes makes will reduce the manpower needed for the disposal of the waste and divert the efforts toward more sustainable option.

Also, the process of using waste materials in soil stabilization is a practical, easy and little time-consuming process.

Future research would include higher amounts and different combinations of these waste materials to partially replace the existing soil. This will contribute toward a cleaner environment, sustainability, thus assisting in the creation of circular economy.

This paper has proven that solid waste improves the mechanical and strength properties of soils. Therefore, these types of waste can be used in the stabilization processes of problematic soils and contribute toward sustainable development.

References

Abukhettal, M. (2016), "Use of recycled materials in road construction", *Proceedings of the 2nd International Conference on Civil, Structural and Transportation Engineering (ICCSTE'16), Paper No. 138*.

Aquino, A.A.V., Mujica, J.A.E., Sanchez, J.F.P., Leal, C.Z., Perez, A.P. and Dominguez, E.J.S. (2020), "Compressed earth block reinforced with coconut fibers and stabilized with aloe vera and lime", *Journal of Engineering, Design and Technology*, Vol. 19 No. 3, pp. 795-807.

Ahmurazzaman, M. (2010), "A review on the utilization of fly ash", *Progress in Energy and Combustion Science*, Vol. 36, pp. 327-363.

Assaf, S. and Faour, K. (2018), *Low-Cost Construction Using Waste Materials*, AUB Maroun Semaan Faculty of Engineering and Architecture IDEAS.

ASTM C 618 (2005), "Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete", *Annual Book of ASTM Standards*.

ASTM D 1883 (2007), "Standard test method for CBR (California bearing ratio) of Laboratory-Compacted soils", *Annual Book of ASTM Standards*.

ASTM D 4318 (2017), "Standard test methods for liquid limit, plastic limit, and plasticity index of soils", *Annual Book of ASTM Standards*.

ASTM D 698 (2012), "Standard test methods for laboratory compaction characteristics of soil using standard effort", *Annual Book of ASTM Standards*.

ASTM D 854 (2014), "Standard test methods for specific gravity of soil solids by water pycnometer", *Annual Book of ASTM Standards*.

ASTM D 7928 (2017), "Standard test method for Particle-Size distribution (gradation) of Fine-Grained soils using the sedimentation (hydrometer) analysis", *Annual Book of ASTM Standards*.

Bhardwaj, A. and Sharma, R.K. (2020), "Effect of industrial wastes and lime on strength characteristics of clayey soil", *Journal of Engineering, Design and Technology*, Vol. 18 No. 6, pp. 1749-1772.DOI, doi: 10.1108/JEDT-12-2019-0350.

Cetin, B., Aydilek, A.H. and Güney, Y. (2010), "Stabilization of recycled base materials with high carbon fly ash", *Resources, Conservation and Recycling*, Vol. 54 No. 11, pp. 878-892.

Dahale, P.P., Nagarnaik, P.B. and Gajbhiye, A.R. (2012), "Utilization of solid waste for soil stabilization: a review", *Electronic Journal of Geotechnical Engineering*, Vol. 17.

El-Assaly, A. and Ellis, R. (2001), "Evaluation of recycling waste materials and by-products in highway construction", *International Journal of Sustainable Development and World Ecology*, Vol. 8 No. 4, pp. 299-308.

Firat, S. and Cömert, A.T. (2011), "Curing time effects on CBR of stabilized kaoline with fly ash, lime and cement", *GMMFD*, Vol. 26, pp. 719-730.

Firat, S., Dikmen, S., Yilmaz, G. and Khatib, J.M. (2020), "Characteristics of engineered waste materials used for road subbase layers", *KSCE Journal of Civil Engineering*, Vol. 24 No. 9, pp. 1-14, doi: 10.1007/s12205-020-2242-0.

Firat, S., Khatib, J.M., Yilmaz, G. and Cömert, A.T. (2017), "Effect of curing time on selected properties of soil stabilized with fly ash, marble dust and waste sand for road Sub-base", *Waste Management and Research*, Vol. 35 No. 7, pp. 747-756.

Firat, S., Yilmaz, G., Vural, I., Khatib, J.M. and Kinuthia, J.M. (2013), "Reducing energy requirement using waste materials", *II. International Workshop on Earthquake and Sustainable Materials (IWESM), Sakarya University, Technology Faculty, Ed.: Prof. Dr. S. Firat*, *ISBN: 978-605-4735-07-05*, pp. 200-213.

Highway Technical Specification (2013), *Republic of Turkey Ministry of Public Works and Settlement. General Directorate of Highways*, Ankara (in Turkish).

Gunaydin, O., Dere, T., Soylemez, M. and Yaman, Z.D. (2016), "Soil improvement characteristics of polyethylene terephthalate wastes", *Environmental Engineering and Management Journal*, Vol. 18.

Heidrich, C., Feuerborn, H.J. and Weir, A. (2013), "Coal combustion products: a global perspective", *World of Coal Ash (WOCA) Conference, April 22-25, Lexington.*

Khazaei, J. and Moayedi, M. (2017), "Soft expansive soil improvement by eco-friendly waste and quick lime", *Arabian Journal for Science and Engineering*, Vol. 44 No. 10, doi: 10.1007/s13369-017-2590-3.

Micheal, T., Singh, S.K. and Kmar, A. (2016), "Expansive soil stabilization using industrial solid wastes a review", *International Journal of Advanced Technology in Engineering and Science*, Vol. 4 No. 9.

Niyomukiza, J.B., Wardani, S.P.R. and Setiadji, B.H. (2019), "The effect of curing time on the engineering properties of sawdust and lime stabilized expansive soils", *2nd International Symposium on Transportation Studies in Developing Countries (ISTSDC 2019), volume 193*.

Pandey, V.C. and Singh, N. (2009), "Impact of fly ash incorporation in soil systems", *Agriculture, Ecosystems and Environment*, Vol. 136 Nos 1/2, pp. 16-27.

Seed, H.B., Woodward, R.J. and Lundgren, R. (1962), "Prediction of swelling potential of compacted clays", *Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers*, Vol. 88 No. 3, pp. 53-87.

Singh, P., Boora, A. and Gupta, A.K. (2020), "Sub-grade characteristics of clayey soil incorporating municipal solid waste incineration ash and marble dust", *Journal of Engineering, Design and Technology*, doi: 10.1108/JEDT-08-2020-0347.

Singh, B., Kumar, A. and Sharma, R.K. (2014), "Effect of waste materials on strength characteristics of local clay", *International Journal of Civil Engineering Research*, Vol. 5 No. 1, pp. 61-68.

Siraj, M.A. (2016), “Granite is just fine”, available at: www.thehindu.com/features/homes-and-gardens/granite-is-just-fine/article8198102.ece (accessed 24 April 2021).

TS 1500 (2000), “Classification of soil for civil engineering purposes”, *TSI 2000, 25-57, Ankara (in Turkish)*.

Ural, N. (2016), “Effects of additives on the microstructure of clay”, *Road Materials and Pavement Design*, Vol. 17 No. 1, pp. 104-119.

Uyanik, S. and Topeli, M. (2014), *The Opportunities and Challenges of Fly Ash in Turkey*, Iskenderun energy production and trading corporation, Turkey.

Yao, Z.T., Ji, X.S., Sarker, P.K., Tang, J.H., Ge, L.Q., Xia, M.S. and Xi, Y.Q. (2015), “A comprehensive review on the applications of coal fly ash”, *Earth-Science Reviews*, Vol. 141, pp. 105-121.

Further reading

Ahmed, A.G.A. (2014), “Fly ash utilization in soil stabilization”, *International Conference on Civil, Biological and Environmental Engineering, (CBEE), May 27-28, Turkey*.

Firat, S., Yilmaz, G., Cömert, A.T. and Sümer, M. (2012), “Utilization of marble dust, fly ash and waste sand (Silt-Quartz) in road subbase filling materials”, *KSCE Journal of Civil Engineering*, Vol. 16 No. 7, pp. 1143-1151.

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