Strength Properties of Coffee Waste Based Geopolymers

Tugba Eskisar and Selim Altun

Abstract A considerable amount of coffee waste is disposed in the landfills annually. This study aims to investigate the possible use of coffee waste based geopolymers as a green construction material for landfills. Coffee is an organic and a biodegradable material. In order to use coffee waste as a construction material, the strength development of a coffee-based geopolymer was observed. Fly ash or rice husk ash were used as a precursor. These precursors were preferred because they are silica and alumina rich materials. Alkaline activator formed of sodium silicate and sodium hydroxide (Na_2SiO_3–NaOH) was used to trigger the geopolymerization process. Three variables were tested, the ratio of Na_2SiO_3–NaOH; effect of ash type, and curing time on the strength development of coffee-based geopolymers. By adding 30% of ash into coffee waste, a geopolymer was synthesized with an activator/ash ratio of 1.7 and Na_2SiO_3–NaOH ratio of 90–10%, which provided the highest (up to 1000 kPa) unconfined compressive strengths. This paper denotes that the coffee based-geopolymerization products will further develop the organic material into a nondegradable material, therefore suggesting geopolymers as an option to stabilize highly organic soils.

Keywords Geopolymer · Coffee waste · Unconfined compressive strength

1 Introduction

Recycling the waste products in the construction industry is a popular topic as it provides an alternative way of creating a sustainable environment and contributes to the economy. Environmentally friendly solutions could be achieved with recycled bio-materials. Coffee waste is an insoluble residue that remains after coffee beans are dehydrated, milled, and brewed. The coffee waste comes from two origins, those generated by the soluble coffee industry, which uses almost the half of the global

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coffee harvest each year, and those generated by cafes and the public, constituting the other half [1].

The International Coffee Organization (ICO) estimates that in the years 2018–19, global consumption of coffee is 165.18 million bags leading to a total of 9.9 billion kilograms of coffee in total, the majority of which have been consumed in the EU, the USA, and Japan [2]. The major problem is soluble the producers dump large amounts of coffee waste in landfills, a practice that might affect and harm the local ecology [3].

Coffee waste is a highly organic material, and therefore, when it is planned to be a part of a geotechnical study, it could be regarded as an organic soil and it should be investigated through the soil mechanics concepts. Average coffee waste has 86–89% of organic content; it has low shear strength and high compressibility [4].

Ground improvement methods or geopolymerization process could be different alternatives to treat coffee wastes and use them as fill materials in embankments. Geopolymers, an alternative binder based on fly ash that is activated by an alkaline activator, has a lower carbon footprint compared to cement [5]. According to IPCC data, ordinary Portland Cement is responsible for about 7% of the total CO_2 emissions in the world [6]. Therefore, utilizing geopolymers may be an ecological approach to the solution of the coffee waste problem. Alkaline metals react with alumina-rich and silica-rich materials and produce a three dimensional alumino-silicate complex with a strong bindery network of alumina and silica elements. The initial materials for making geopolymer stabilizer could be any alumina and silica-rich natural minerals such as kaolinite and other clays, and wastes such as fly ash and rice husk ash [7]. Arulrajah et al. [8] recently produced a geopolymer made of coffee waste and fly ash to develop a green engineering fill material.

This study can be divided into two parts: First, traditional improvement techniques were applied to the coffee waste and the success of these methods is discussed. Second, a coffee waste-based geopolymer is synthesized. The aim of this study is to evaluate the strength development in coffee waste with different ash types and a liquid alkaline activator to determine the optimum amount to produce a coffee-based geopolymer to be used in as a fill material in embankments. 7–28–90 days of curing is applied to the specimens in a humidity controlled environment. The optimum liquid alkaline activator content and unconfined compressive strength (UCS) of the composite material are investigated. Test results are examined to see the capability of geopolymer as an alternative stabilizing agent for highly organic coffee waste. Test results contribute to a better understanding of geopolymer stabilization of highly organic waste material and soils.

2 Materials and Testing Methods

Coffee waste was collected from a branch of a USA-based coffee chain store located in Turkey. As the collected waste was moist, it was observed that molds grew within five days. The mold needs air and warmth to grow for this reason, the waste stored in sealed plastic containers in a cool place, until they were transferred to the laboratory. First, coffee waste was laid flat on a large surface and removed from any other waste like paper cups, coffee filter paper, paper napkins, etc., and air drying was held for a day. Then, the material was placed in a drying oven. Coffee brewing temperature of 90 °C was applied as the oven temperature as higher would burn the organic material. This stage was completed in four days. Grain size distribution analysis was performed on the dry material (see Fig. 1). The particle size distribution of dried coffee waste shows that 85% of the waste was in sand size, and the rest of the material was in silt size. In this way, the grain size distribution of the waste is similar to silty sand, but this material is considered as a highly organic one. Class F fly ash (FAF) and class C fly ash (FAC) were derived from coal plants, and rice husk ash (RHA) was derived from a local producer in Turkey.

Sukmak et al. [9] and Horpibulsuk et al. [10] achieved desired levels of strength when 30% of ash in dry weight was added to the silty clay specimens. The ash content of 30% was kept constant during this study, regardless of the ash type. An alkali activator liquid was used to trigger the geopolymerization process. The activator was composed of two chemicals, NaOH in bead form and Na_2SiO_3 solution, respectively. NaOH with 97% purity and three modules 40 baume Na_2SiO_3 were commercially purchased. WG is also known as water glass, therefore in the text it will be denoted as WG. Different percentages of WG-NaOH were used to see the effects of the chemical compounds forming the geopolymers. The molar concentration of NaOH was eight molars in water solution. Coffee waste and ash was dry mixed and the alkali activator liquid added to this mixture at different percentages relative to the dry weight of the coffee waste and ash. The optimum alkali activator liquid contents were determined for each activator/ash ratios. Standard Proctor testing was performed to achieve the optimum alkali activator contents. After the optimum activator amount was determined, conditions representing wet and dry sides of the optimum were also considered. Specimens with 10 cm height and 5 cm diameter were formed by applying compactive effort. The specimens were wrapped and sealed in stretch film layers to

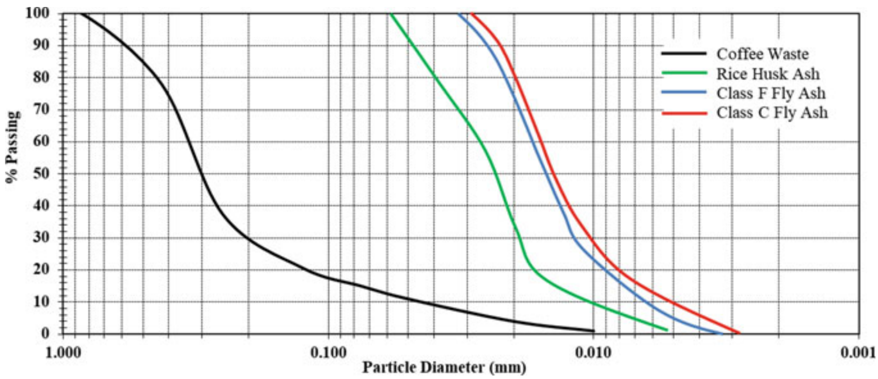

Fig. 1 Grain size distributions of the materials used in this study

avoid moisture content loss and they were cured for 7–28–90 days. Unconfined compressive tests were held on the specimens to observe stress-deformation patterns according to ASTM D2166 [11]. The load was applied so as to produce an axial strain at a rate of 1%/min. The rate of strain was chosen so that the time to failure did not exceed 15 min. The loading continued until the load values decreased with increasing strain, or until 15% strain was reached.

3 Results and Discussion

3.1 Cement Treated Specimens

Before applying the geopolymerization process, the effectiveness of a traditional improvement technique, cement treatment was evaluated. The coffee waste was considered as a weak soil and first its own compressive strength is determined with specimens constituted at the optimum water content of the medium. Similar to a sand specimen, the coffee waste has no cohesion, but it can stand alone in cylindrical form due to the interlocking of irregular porous particles and the suction occurring due to the presence of water between the particles. The coffee waste specimen at the optimum water content resulted in compressive strength of 18 kPa. The additive content is defined as the ratio of the mass of the dry additive to the mass of coffee waste; 3–10% of cement was added into the coffee waste. In a similar manner, some specimens were prepared with cement and FAF. FAF ratio was 10%.

The specimens were cured for 28 days and then subjected to unconfined compression tests (see Fig. 2). Adding 3 or 5% of cement contributed to a rise of the compressive strength. The specimens with 10% of cement had the highest strength of 83 kPa. However, the introduction of 10% fly ash to the mixture reduced the strength of the specimens. This result may be observed because of the insufficient amount of lime content in the composite material. A reduction in the rate of hydration caused lower compressive strength and a similar result was also observed by Saha [12]. As a result of these findings, it is possible to increase the strength of coffee waste with

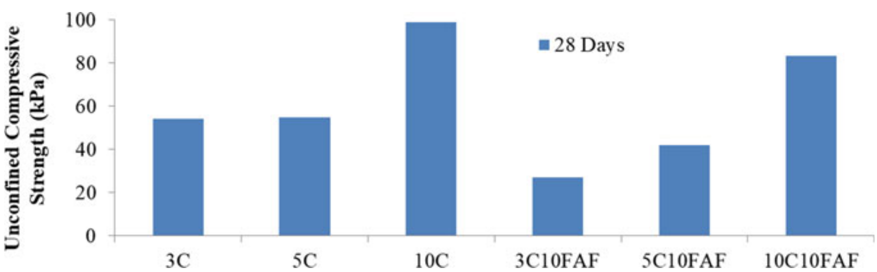

Fig. 2 Unconfined compressive strength of specimens prepared with cement (C), and cement and class F fly ash (FAF)

cement, but there is not enough material—additive interaction to have strength at a desired level. Coffee waste is lack of minerals that are readily available in soils and this condition blocks the development of chemical reactions within the medium. Therefore, an effective solution is necessary to reach high strength values.

3.2 Liquid Activator Content

The coffee waste—ash mixtures were treated with three different solutions of WG-NaOH. The percentages of WG-NaOH were 90–10%, 70–30%, and 50–50% by weight, respectively. The compaction curves of the specimens prepared with different WG-NaOH content converged at the same optimum liquid content. As an example, specimens prepared with 70%WG–30%NaOH had a maximum dry density of 8.72kN/m^3 and the corresponding optimum activator content was 51%.

Unconfined compressive testing was performed on seven day specimens to see the effect of liquid activator contents. Three different WG-NaOH contents, activator ratios (dry side, optimum, and wet side) were considered. The ashes are mixed at a ratio of 30% by dry weight into the coffee waste. FAC was the most effective precursor by means of compressive strength, hence, only the unconfined compressive strength (UCS) values of the specimens containing FAC are presented in Fig. 3a.

In Fig. 3a, it is shown that the maximum 7-day UCS is achieved at an activator/ash ratio of 1.7 for 90%WG–10%NaOH for specimens prepared with FAC. 950 kPa of strength was achieved in these specimens. It is seen that FAC caused an early strength development due to its high amount of calcium oxide casing cementing agents in the medium.

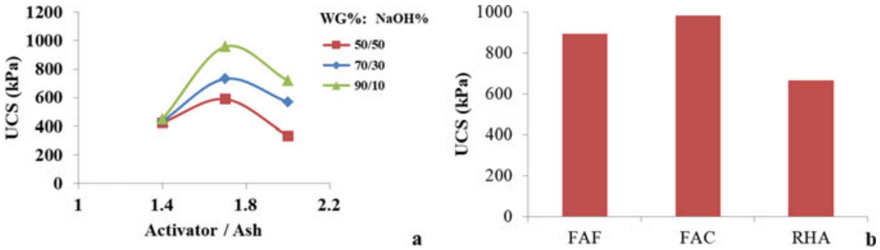

Fig. 3 **a** Unconfined compressive strength of specimens prepared with different activator ratios. Ash type is FAC. **b** Effect of ash type on the specimens prepared with 90%WG–10%NaOH activator content and activator/ash ratio of 1.7

Table 1 Change of UCS with curing time

Specimen	Activator/ash	UCS (kPa) 7 days	UCS (kPa) 28 days	UCS (kPa) 90 days
30%FAC (with 90%WG–10%NaOH)	1.4	448	644	1165
	1.7	957	982	1490
	2.0	720	842	1157

3.3 Precursor Type

The activator content was fixed to with 90%WG–10%NaOH. The optimum amount of activator/ash ratio was 1.7. 28-day specimens were tested to evaluate the effect of ash type (see Fig. 3b). Similar to the 7-day specimens, 28-day specimens containing 30% FAC had the highest UCS. The second highest UCS values were observed in the specimens prepared with 30% FAF. The UCSs were close to each other and this was attributed to the proximity of the grain size distribution of the fly ash materials.

However, RHA was composed of coarser particles in the shape of platelets, this condition may have caused larger voids than the fly ash containing specimens in the macro scale. Another concern is, RHA is a silica-rich component, the presence of NaOH may have leached high amount of SiO_2 and as there was not a high amount of CaO supplied to the medium, less CSH and CASH gels may have formed reducing the strength values. On the contrary, FAC is rich in CaO, and better bonding and geopolymerization was established in the specimens.

3.4 Curing Time

The strength development of the specimens in the long term is given in Table 1. It is evident that geopolymerization is a longer process compared to the well-known methods of stabilization. Kua [13] reported that geopolymerization could be completed from 60 to 90 days. In this study, it was seen that between 28 days and 90 days there is an apparent improvement in UCS values. Curing times longer than 90 days should be checked to see the threshold where the continuous strength development is satisfied.

4 Conclusions

The engineering properties of coffee waste-based geopolymers were evaluated to seek for the possible use of this material as a fill material. Also, geopolymer stabilization effectiveness in improving the mechanical behavior of highly organic waste material and soils was addressed. The strength developments were observed with unconfined compressive tests.

Coffee waste itself is an organic material and subject to biodegradation. However, in this study, it was stabilized with different types of precursors such as fly ash and rice husk ash, and with alkali activators. This process formed a strengthened medium, thus changing the degradation properties of the waste into a nondegradable state. The strength development was found to be highest in specimens treated with an activator/ash ratio of 1.7 for 90%WG-10%NaOH for specimens prepared with FAC. The strength improvement continued for 28–90 days, showing that geopolymerization is a longer process compared to the traditional stabilization methods.

Recycled coffee waste as well as fly ash/rice husk ash has potential to withdraw the major amount of waste from the landfills if a sustainable stabilization procedure is developed. This paper shows the preliminary research results that geopolymer stabilization is a feasible method for the stabilization of highly organic soils, which can decrease the carbon footprint for future infrastructure projects.

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