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Unconfined compressive strength and freeze-thaw resistance of sand modified with sludge ash and polypropylene fiber

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Abstract. In recent years, the amount of sludge ash (SA) has considerably increased due to rapid urbanization and population growth. In addition, its storage in landfills induces environmental pollution and health problems. Therefore, its disposal in an environmentally friendly way has become more important. The main goal of this study is to investigate the reusability of sludge ash as an additive with polypropylene fiber (PF) to stabilize marginal sand based on the compressive strength performances from UCS tests. For this purpose, a series of UCS tests was conducted. Throughout the experimental study, the used inclusion rates were 10, 15, 20 and 30% for sludge ash and 0, 0.5 and 1% for polypropylene fiber by total dry weight of the sand+sludge ash mixture and the prepared samples were cured for 7 and 14 days prior to the testing. Freezing and thawing resistance of the mixture including 10% sludge ash and 0, 0.5 and 1% polypropylene fiber was also examined. On the basis of UCS testing results, it is said that sludge ash inclusion remarkably enhances UCS performance of sand. Moreover, the addition of polypropylene fiber to the admixtures including sand and sludge ash significantly improves their stress-strain characteristics and post-peak strength loss as well as UCS. As a result of this paper, it is suggested that sludge ash be successfully reused with polypropylene fiber for stabilizing sand in soil stabilization applications. It is also believed that the findings of this study will contribute to some environmental concerns such as the disposal problem of sludge ash, recycling, sustainability, environmental pollution, etc. as well as the cost of an engineering project.

Keywords: sludge ash; polypropylene fiber; sand; unconfined compressive strength; freezing and thawing resistance; soil stabilization

1. Introduction

Lately, there has been a dramatically increase in the amount of sewage sludge generated due to the environmental programs applied, rapid urbanization and population growth. Therefore, its mismanagement gives rise to some undesirable effects on the environment and public health (Dean and Suess 1985). For this purpose, some disposal techniques have been applied. Incineration is the most attractive disposal techniques because of legal hurdles on its disposal (Malerius and Werther 2003, Tantawy *et al*. 2012). Incineration has some advantages such as large reduction in the volume of sewage sludge, thermal destruction of toxic organic compounds, energy generation and minimization of odor emission (Hjelmar 1996, Khiari *et al*. 2004, Bierman and Rosen 1994,

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Tantway *et al*. 2012). However, the process of incineration produces a new waste material, namely sludge ash (SA). Its storage in landfills constitutes some environmental problems such environmental pollution and health risks for people living near. Hence, instead of landfilling, its reuse for engineering applications becomes more of an issue and thereby, the cost of an engineering project considerably decreases as well as the contribution to the recycling and sustainability.

Soil stabilization is one the most common civil engineering applications. It is often required for civil engineering constructions such as foundations of buildings, the base courses of highway and airfield pavements to improve the engineering properties of soils by mixing them with a suitable inclusion material and then compacting suitably (Murthy 2002). In recent years, few studies have been performed on the reuse of sludge ash as an additive for stabilization purposes (Lin *et al*. 2005, 2007a, b, 2016, Chen and Lin 2009). Lin *et al*. (2005) introduced sludge ash to soft soil to improve its strength characteristics. They observed that the unconfined compressive strength (UCS) of soft soil increased two or three times and its swelling properties decreased with the addition of sludge ash. In addition to this, the results showed that its cohesive parameter, *c*, was enhanced with the increase in dosage rates of sludge ash. Lin *et al*. (2007a) conducted a study to investigate the effect of the use of sludge ash and lime together on the engineering characteristics of soft soil. They found that the UCS performance of soft cohesive soil improved as much as three to seven times and its swelling value decreased due to the inclusion of both sludge ash and lime as a stabilizer. On the basis of the experimental results, they concluded that sludge ash and lime could be added to soft soil for stabilization purposes. Lin *et al*. (2007b) employed sludge ash and fly ash with soft cohesive soil and compared the results by sludge ash with those by fly ash. The results by sludge ash indicated that the UCS performance of the untreated soil was augmented up to two times. They found from the comparison of the results that sludge ash could substitute for fly ash for stabilizing soft cohesive soil. Lin *et al*. (2016) presented an effort for stabilizing soft subgrade soil with sewage sludge/lime and nano-SiO_2 additives. Their results indicated that the use of sewage sludge ash/lime mixture as a stabilizer improved the engineering properties of soft subgrade soil and caused a transformation in the soil from “poor subgrade soil” to “good to excellent subgrade soil”. With addition of nano-SiO_2, they observed that the UCS performance of soil modified with sewage sludge ash/lime increased approximately 17 kPa. Chen and Lin (2009) studied the influence of the addition of both sludge ash and cement to soft soil on its strength characteristics. The obtained experimental results denoted that the UCS and swelling properties of untreated soft soil improved approximately three to seven times and 60%, respectively. Consequently, they proposed that sludge ash and cement be employed together in soil stabilization.

In the case of the use of the materials that have pozzolanic activities as a stabilizer in soil stabilization applications, some unfavorable phenomena such as brittle behavior come into existence. Recently, many researches have been made in order to overcome this matter by means of reinforcement material (i.e., fiber) (Kaniraj and Havanagi 2001, Cai *et al*. 2006, Khattak and Alrashidi 2006, Tang *et al*. 2007, Consoli *et al*. 2009, 2010, 2011, 2012, 2013a, b, c, Park 2009, 2011, Estabragh *et al*. 2012, Olgun 2013, Correia *et al*. 2015, Rekha *et al*. 2016). The use of fiber for reinforcing soil remarkably contributes to its ductile failure characteristics and strength improvement, the former particularly in soils treated by stabilizers with pozzolanic properties (Correia *et al*. 2015, Hamidi and Hooresfand 2013, Nasr 2014, Pino and Baudet 2015). For the purposes of laboratory investigations, polypropylene fiber (PF) is largely utilized to reduce the shrinkage properties and to get through chemical and biological degradation besides ductile behavior and strength improvement (Khattak and Alrashidi 2006, Tang *et al*. 2007, Musenda 1999, Puppala and Musenda 2000, Santoni *et al*. 2001, Yetimoglu and Salbas 2003, Yetimoglu *et al*. 2005, Vasudev 2007, Viswanadham *et al*. 2009).

In the cold climates, the water within the soil medium changes into ice particles due to the temperature falling below 0°C and this phenomenon is known as freezing. As the temperature rises above 0°C, the ice particles melts and turns into water, known as thawing (Güllü and Khudir 2014). Soils in the regions where seasonal change occurs undergo repeated freezing and thawing cycles resulting from the seasonal change. These freezing and thawing (FT) cycles can negatively impact the engineering characteristics of the soils such as strength, bearing capacity (Sheng *et al*. 1995, Watanabe 1999, Simonsen and Isacsson 1999). Lately, a number of studies have been conducted in order to investigate the influence of freezing and thawing cycles on the engineering characteristics of soils (Sheng *et al*. 1995, Simonsen and Isacsson 1999, Zhang *et al*. 2004, Wang *et al*. 2007, Qi *et al*. 2008, Güllü and Khudir 2014, Güllü 2015, Arasan and Nasirpur 2015). They have depicted that the detrimental effects on the engineering properties of soils takes place due to the repeated freezing and thawing cycles. For this reason, an effort of soil stabilization under the freezing and thawing cycle could make a huge contribution to practice.

To our knowledge, there is inadequate effort on the reuse of sludge ash with sand and polypropylene fiber for stabilization purposes. For this reason, this paper aims at filling this gap in the literature through presenting an investigation on the reusability of sludge ash as an additive with polypropylene fiber to stabilize poorly-graded sand based upon the compressive strength performances from UCS tests. UCS tests can be adequately employed in order to determine the suitability of the mixtures of geomaterials for uses in geotechnical engineering applications such as pavement design (base, subbase and subgrade courses), highway embankment, foundation base of buildings, fills behind retaining walls, etc. UCS tests also provide a quick measurement of compressive strength performance of stabilized soil in an inexpensive and practical way (Park 2011). Therefore, in this study, a series of UCS tests was performed on sand treated with: (i) sludge ash only; and (ii) sludge ash and polypropylene fiber together after a curing period. In addition, in the case of using sludge ash at minimum dosage rate (10% in this study), in order to see the effect of freezing and thawing, one repeated freezing and thawing cycle was carried out on the specimens containing: (i) 10% sludge ash only; (ii) 10% sludge ash+0.5% polypropylene fiber; and (iii) 10% sludge ash+1% polypropylene fiber. The findings obtained from UCS tests indicate that sludge ash and sludge ash+polypropylene fiber mixtures can be used to increase the compressive strength of sand material in geotechnical applications such as soil stabilization, road construction, highway embankment, foundation base of buildings, etc. Furthermore, it is believed that the findings will contribute to the disposal problem of sludge ash, recycling, sustainability and environmental pollution as well as the cost of an engineering project.

2. Experimental study

An extensive experimental study covering mainly UCS tests was performed in order to investigate the reusability of sludge ash with polypropylene fiber for improving the strength characteristics of sand. Moreover, in the case of using sludge ash at its minimum inclusion rate (10% in this study), in order to understand the influence of freezing and thawing on the UCS performance, one freezing and thawing cycle were applied on the mixture including: (i) 10% sludge ash only; (ii) 10% sludge ash and 0.5% polypropylene fiber together; and (iii) 10% sludge ash and 1% polypropylene fiber together.

2.1 Materials used

The coarse-grained soil used in the present study was supplied from a local market in Gaziantep city. During the experimental work, the coarse-grained soil below 2.00 mm was employed. Preliminary tests including sieve analysis, modified proctor and specific gravity were performed to in order to define the soil. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) were calculated as 4.46 and 0.76, respectively, from the results of sieve analysis. The coarse-grained soil used was also classified as poorly-graded sand (SP) according to the Unified Soil Classification System (USCS). Its grain size distribution is given in Fig. 1. The compaction parameters of optimum moisture content and maximum dry unit weight for sand were found to be equal to 10% and 19.5 kN/m^3, respectively. The compaction curve of sand is indicated in Fig. 2. From the specific gravity test on sand, its specific gravity was computed as 2.78.

As to the sludge ash employed here, it is produced by the incineration of dewatered wastewater sewage sludge at 850^{o}C at wastewater treatment plant in Gaziantep city, Turkey. A series of tests involving chemical analysis, laser diffraction method, modified proctor and specific gravity were carried out. The chemical characteristics of the sludge ash are listed with its some physical properties in Table 1. Its grain size distribution by laser diffraction method (Malvern Mastersizer Hydro 2000MU) is shown in Fig. 1. The compaction parameters of optimum moisture content and

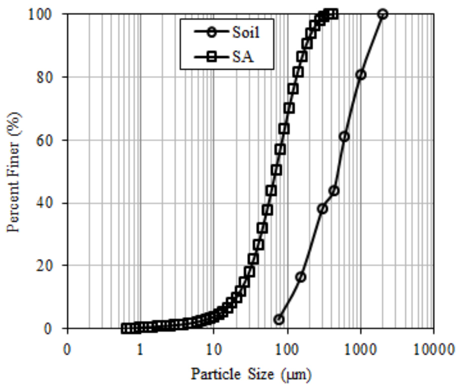

Fig. 1 Particle size distributions for sludge ash (SA) and soil used

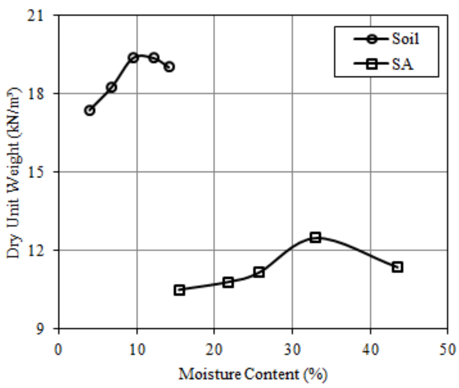

Fig. 2 The compaction curve for sludge ash (SA) and soil used

Table 1 Some chemical and physical properties of the sludge ash used

Properties	Sludge ash
CaO (%)	33.38
SiO_2 (%)	24.18
Al_2O_3 (%)	7.44
Fe_2O_3 (%)	4.29
MgO (%)	8.26
SO_3 (%)	11.17
P_2O_5 (%)	1.74
K_2O (%)	2.74
Loss on ignition (%)	4.53
Specific surface area (m^2/g)	0.199
Surface weighted mean (μm)	30.077
Volume weighted mean (μm)	86.067

Table 2 Properties of the polypropylene fiber used

Properties	Sludge ash
Length (mm)	20
Diameter (mm)	0.016
Specific gravity	0.91
Tensile strength (MPa)	300-400
Modulus of elasticity (MPa)	4000
Melting temperature (°C)	185
Ignition temperature (°C)	365
Water absorption capacity (%)	0

maximum dry unit weight for the sludge ash were determined 33% and 12.5 kN/m^3, respectively.

2.2 Testing program and configurations

The UCS tests in the present paper were conducted on poorly-graded sand for two different combinations: (i) modified with sludge ash only; and (ii) modified with sludge ash and polypropylene fiber together. The mixtures to be used for the testing were prepared at the optimum moisture content of the natural soil (10%). The inclusion rates were 10%, 15%, 20% and 30% for sludge ash and 0%, 0.5%, and 1% for polypropylene fiber by the total dry weight of sand+sludge ash mixture. An intensive testing program that included the dosage rates of sludge ash and polypropylene fiber in percentages, the mix design and the curing periods for the prepared mixtures was created. All UCS tests in this study were performed by following testing program in Table 3. In order to compare the improvements due to the addition of stabilizers (sludge ash and polypropylene fiber for this study), S0 mixture in Table 3 that contained 10% sludge ash with no curing and freeze-thaw cycle was selected as the control sample.

The literature review on fiber inclusion to stabilized soil indicates that experimental results are

Table 3 The test matrix of experimental program

Mixture name	Soil (%)	SA (%)	PF (%)	CT (Day)	FT(Cycle)
S0 (Control)	90	10	0	0	0
S1	90	10	0	7	0
S2	90	10	0	7	1
S3	90	10	0	14	0
S4	90	10	0	14	1
S5	90	10	0.5	7	0
S6	90	10	0.5	7	1
S7	90	10	0.5	14	0
S8	90	10	0.5	14	1
S9	90	10	1	7	0
S10	90	10	1	7	1
S11	90	10	1	14	0
S12	90	10	1	14	1
S13	85	15	0	7	0
S14	85	15	0	14	0
S15	85	15	0.5	7	0
S16	85	15	0.5	14	0
S17	85	15	1	7	0
S18	85	15	1	14	0
S19	80	20	0	7	0
S20	80	20	0	14	0
S21	80	20	0.5	7	0
S22	80	20	0.5	14	0
S23	80	20	1	7	0
S24	80	20	1	14	0
S25	70	30	0	7	0
S26	70	30	0	14	0
S27	70	30	0.5	7	0
S28	70	30	0.5	14	0
S29	70	30	1	7	0
S30	70	30	1	14	0

S: Sample; SA: Sludge ash; PF: Polypropylene fiber;
CT: Curing time; FT: Freezing and thawing

closely connected with the sample preparation. On this subject, Tingle *et al*. (1999) and Consoli *et al*. (2010) have reported that fiber inclusion after water prevents occurring floating and sticking throughout the mixing. For this reason, while the sample preparation for UCS testing, first of all, the sludge ash was added to dry natural sand at predetermined amounts and the obtained dry sand+sludge ash mixture was blended by hand in a plastic container until a uniform mixture was

Table 4 General relationship of consistency and UCS values (Das 2009)

Consistency	q_u (kPa)
Very soft	0-25
Soft	25-50
Medium	50-100
Stiff	100-200
Very stiff	200-400

obtained. Later, water was introduced to the dry mixture at the rate of 10% and the mixture was meticulously mixed. At the final process for the sample preparation, polypropylene fiber as a reinforcement material was added to the sand+sludge ash+water mixtures at the dosage rates of 0, 0.5 and 1%. The utmost attention while mixing fiber material was paid in order to be sure of uniform mixture. Before UCS tests, the prepared mixtures were compacted in a PVC plastic mold with a split lengthwise on side and about height to diameter ratio of two by following the procedure defined in ASTM D1557. Then, the samples were removed from the mold and wrapped with plastic bag. Later, they were cured at a room temperature prior to performing UCS. All samples tested in this paper were roughly 50 mm in diameter and 100 in height.

UCS is one of the most common laboratory tests performed in order to investigate the effect of stabilizers (sludge ash and polypropylene fiber for this paper) on the strength performance of untreated soil as well as the suitability of a mixture for geotechnical engineering applications, such as soil stabilization. All UCS tests here were carried out by following the procedure in ASTM D5102 at a load rate of 1 mm/min. In ASTM D5102, UCS is defined as either the maximum load attained per unit area or the load per unit area at 5% axial strain, whichever happens firstly in the case of performing a test. The obtained UCS testing results were compared with the approximate consistencies of clays given in Table 4 (Das 2009).

2.3 Freezing and thawing cycle

Closed system freezing was used for the repeated freezing and thawing cycle. Jones (1987) identified the closed system as a freezing process in which no source of water present when processing except for originally within the voids of the soil. This freezing system is convenient for the conditions where no noticeable variation in the in-situ moisture content is foreseen between the seasons (Güllü and Khudir 2014). Furthermore, in the soils with low hydraulic conductivity, frost penetration rate is mainly achieved greater than water transportation rate, which means that there is not enough time throughout freezing to enable a continuous water supply to arrive in the freezing front (Wong and Haug 1991). For this reason, in the present paper, a closed system freezing for the repeated freezing and thawing cycle was used. Consoli *et al*. (2009) have conducted triaxial tests in order to investigate the fiber reinforcement of cemented sand specimens. From the experimental investigation, they found that the rate of increase in strength due to the addition of fiber material decreases as the dosage rate of cement material enhances, that is, the fiber reinforcement becomes less effective. Accordingly, freezing and thawing cycle was applied to the samples containing: (i) 10% sludge ash; (ii) 10% sludge ash and 0.5% polypropylene fiber; and (iii) 10% sludge ash and 1% polypropylene fiber after curing periods (7 and 14 days here). On the number of freezing and thawing cycles, Lee *et al*. (1995) and Ghazavi and Roustaie (2010) have found that the most detrimental impact on the engineering properties of soil such as strength generally happens throughout the first cycle. Accordingly, the samples for freezing and thawing tests were exposed to one repeated freezing and thawing cycle. In the case of freezing process, the samples were exposed to the temperature of -18^{o}C for 24 h in order to get a complete frost penetration (Güllü and Khudir 2014). Afterwards, the thawing process was applied on the samples at a room temperature of 23°C for 24 h in a plastic bag to be able to obtain the relative humidity of 100%. After freezing and thawing cycle, UCS tests were conducted on the samples.

Table 5 The UCS testing results for the samples and their consistencies and contributions

Mixture name	UCS (kPa)	Consistency (Das 2009)	RC (%)
S0 (Control)	22	Very Soft	0
S1	562	Hard	2455
S2	782	Hard	3455
S3	1119	Hard	4986
S4	765	Hard	3377
S5	883	Hard	3914
S6	919	Hard	4077
S7	1125	Hard	5014
S8	625	Hard	2741
S9	1047	Hard	4659
S10	1242	Hard	5545
S11	1921	Hard	8632
S12	1277	Hard	5705
S13	455	Hard	1968
S14	1505	Hard	6741
S15	1071	Hard	4768
S16	1485	Hard	6650
S17	1001	Hard	4450
S18	1859	Hard	8350
S19	530	Hard	2309
S20	1636	Hard	7336
S21	1050	Hard	4673
S22	1417	Hard	6341
S23	945	Hard	4195
S24	1811	Hard	8132
S25	724	Hard	3191
S26	1767	Hard	7932
S27	1196	Hard	5336
S28	1274	Hard	5691
S29	932	Hard	4136
S30	1703	Hard	7641

RC: Relative Contribution

3. Results and discussion

An extensive experimental study covering UCS tests was conducted following the experimental program in Table 3. The UCS test results, their corresponding consistencies according to Das (2009) and relative contributions (*RCs*) to control sample are presented in Table 5. The formulation used for relative contribution is as follows

$$RC\,(\%) = \frac{(UCS_{treated} - UCS_{untreated})}{UCS_{untreated}} x100 \tag{1}$$

where $UCS_{untreated}$ and $UCS_{treated}$ represent the UCS values of control sample and sand treated with sludge ash and polypropylene fiber. Here, the effects of the use of sludge ash only, sludge ash and polypropylene fiber together and the application of freezing and thawing cycle on UCS are to be discussed, respectively.

The effect of sludge ash inclusion and curing periods on UCS of control sample is shown in Fig. 3. The expression of “0-7” in Fig. 3 represents polypropylene fiber content and curing time, respectively. It is clearly seen in Fig. 3 that there are significantly improvements in UCS values due to both the addition of sludge ash to sand and curing periods in comparison to that of control sample. In addition, it is evident in Table 5 that the consistency of sample improves “very soft” to “hard”. These improvements can results from the bonds formed among the solid particles through pozzolanic reactions in which either aluminum silicate hydrates or calcium silicate is constituted during the polymerization processing (Rogers and Glendining 2000, Ameri and Esfahani 2008, Rifai *et al*. 2009, Jullien *et al*. 2010, Güllü 2015). However, the magnitudes of these improvements vary with sludge ash contents. On the basis of the experimental findings Fig. 3, it can be said that the highest UCS performance for both curing times was achieved due to the sludge ash inclusion at 30%. The sludge ash inclusion at 15% and 10% yielded the lowest UCS for curing times of 7 and 14 days, respectively. In parallel with UCS results, it is obvious in Table 5 that while the addition of sludge ash at 30% provides the most relative contribution for both 7 days and 14 days of curing, 15% and 10% sludge ash inclusion yielded the least relative contribution for 7 days and 14 days, respectively. For the samples cured for 14 days, it was found that the UCS performance of the sand modified with sludge ash only enhanced with the increment in its content. Lin *et al*. (2005) have

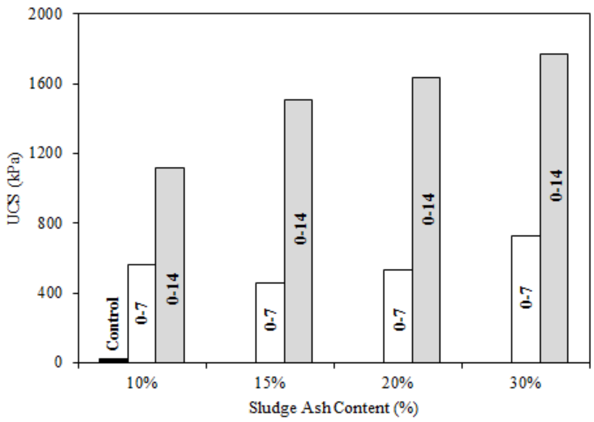

Fig. 3 The variation of UCS values with sludge ash content and curing times at 0% PF

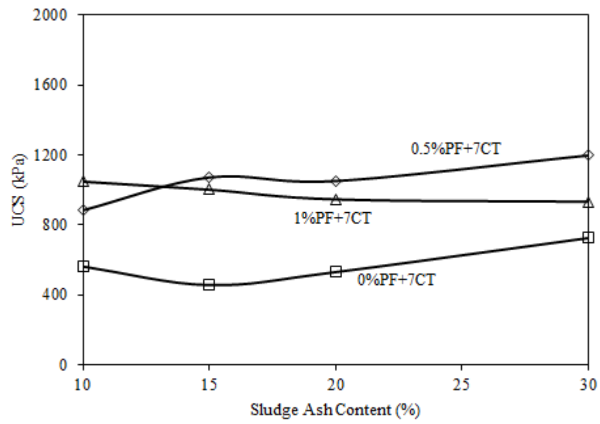

Fig. 4 The variation of UCS values with sludge ash and polypropylene fiber contents for a curing time of 7 days

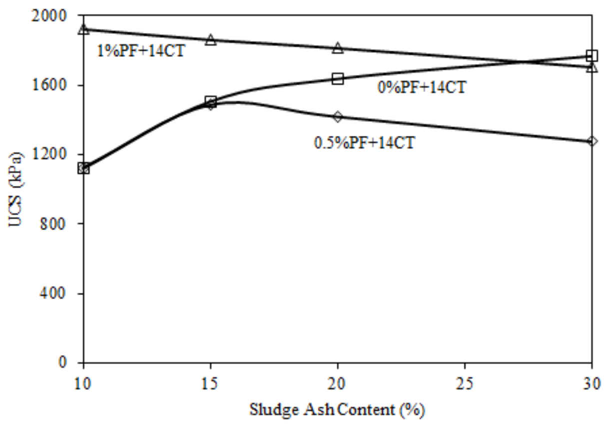

Fig. 5 The variation of UCS values with sludge ash and polypropylene fiber contents for a curing time of 14 days

found that the addition of sludge ash to untreated soft soil improved its UCS performance two to three times depending upon its inclusion rate and curing period.

The effect of the use of sludge ash and polypropylene fiber together on UCS performance of the specimens under curing periods of 7 and 14 days is demonstrated in Figs. 4-5, respectively. To be able to see the influence of addition of polypropylene fiber more clearly, the UCS performances of the samples modified with sludge ash only (i.e., inclusion of polypropylene fiber at 0%) is also included in Figs. 4-5. The expressions of “0.5-7” and “0.5-14” in these figures demonstrate the inclusion rate of polypropylene fiber and curing period. For the admixtures with 7 days of curing, Fig. 4 explicitly indicates that the addition of polypropylene fiber to soil treated with sludge ash increases its UCS value. It may be a reason of this increment that introducing fiber to cemented soil brings about bonding and friction between the fiber and soil Park (2011). Moreover, as seen in Table 5, for the samples with 7 days of curing, their consistencies improved “very soft” to “hard” due to addition of sludge ash and polypropylene fiber together. Based upon the experimental results presented in the figure, it is transparently seen that while there is an upward trend in UCS gain up to the use of polypropylene fiber at 0.5%, there is a downward trend beyond this inclusion rate except for 10% sludge ash where UCS gain enhances with the increase in polypropylene fiber content. The most relative contribution was also obtained as 5336% in the case of the use of 30% ash and 0.5% polypropylene fiber. In addition, the sample including 10% sludge ash and 0.5% polypropylene fiber gave the lowest contribution (3914%). As for the samples with a curing period of 14 days, it can be said in Fig. 5 via comparing UCS results with those of the admixtures without polypropylene fiber that for the samples with 0.5% of polypropylene fiber, their UCS performances decrease depending upon the increase in sludge ash content, even though UCS value of the sample including 10% sludge ash and 0.5% polypropylene fiber slightly enhances. Fig. 5 obviously depicts that 1% polypropylene fiber inclusion increases the UCS value of the sample with sludge ash up to the dosage rate of 20%, while slightly decreasing the UCS value of the sample with 30% of sludge ash. Moreover, this increment decreases as sludge ash content increases. Consoli *et al.* (2009) have also obtained similar results and concluded that the increment in triaxial peak strength resulting from fiber addition is less effective for higher amounts of cement. The consistencies of the samples treated with sludge ash and polypropylene fiber subjected to 14 days of curing improved "very soft" to "hard". It is obvious in Table 5 that even though the mixture including 10% of sludge ash and 0.5% of polypropylene fiber presented the lowest contribution (5014%), the mixture containing 10% of sludge ash and 1% of polypropylene fiber provided the most relative contribution (8632%).

In addition to the improvement in the magnitude of UCS, it is well known from the past studies that the use of fiber material considerably improves the stress-strain behavior and post-peak strength of cemented soils (Kaniraj and Havanagi 2001, Cai *et al.* 2006, Khattak and Alrashidi 2006, Tang *et al.* 2007, Consoli *et al.* 2009, 2010, 2011, 2012, 2013a, b, c, Park 2009, 2011, Estabragh *et al.* 2012, Olgun 2013, Correia *et al.* 2015). Fig. 6 indicates the stress-strain results of sand treated with sludge ash and polypropylene fiber obtained from UCS tests. It is obviously seen from Fig. 6 that the addition of polypropylene fiber to sand+sludge ash mixture results in a change in material behavior from brittle to more ductile one and a reduction in post-peak strength loss. It can also be said based on the results in Fig. 6 that the improvements (stress-strain behavior and post-peak strength) occurring in sand+sludge ash due to fiber inclusion highly depends upon the used fiber content and curing periods. The sand+sludge ash mixtures show more ductile behavior and less post-peak strength loss as the dosage rates of polypropylene fiber rise. This can be attributed to tensile and frictional forces developed by fiber inclusion (Güllü and Hazirbaba 2010). However, as for the curing periods, it is found that no significant improvement with regards to material behavior and post-peak strength after 0.5% polypropylene fiber takes place.

To be able to see the freezing and thawing resistance of the sample with 10% sludge ash, one freezing and thawing cycle was applied on the samples prior to performing UCS tests. In addition to this, in the present study, it was investigated whether there was an impact of polypropylene fiber content and curing time on UCS testing results. The variation of UCS value with inclusion rates of polypropylene fiber and freezing and thawing cycle is presented in Figs. 7-8. These figures indicate the experimental results obtained for curing times of 7 days and 14 days, respectively. In the figures, the expressions of "1-7" and "1-14" represent the number of freezing and thawing cycle (1 cycle) and curing periods (7 and 14 days). Based on the experimental findings shown in Fig. 7, it can be said for the samples subjected to 7 days of curing that the application of freezing and thawing cycle enhances their UCS values when compared with those of non-freezing and thawing. Zaimoglu (2010) has conducted UCS tests after applying freezing and thawing cycles to soils modified with polypropylene fiber and found that they generally increase the UCS

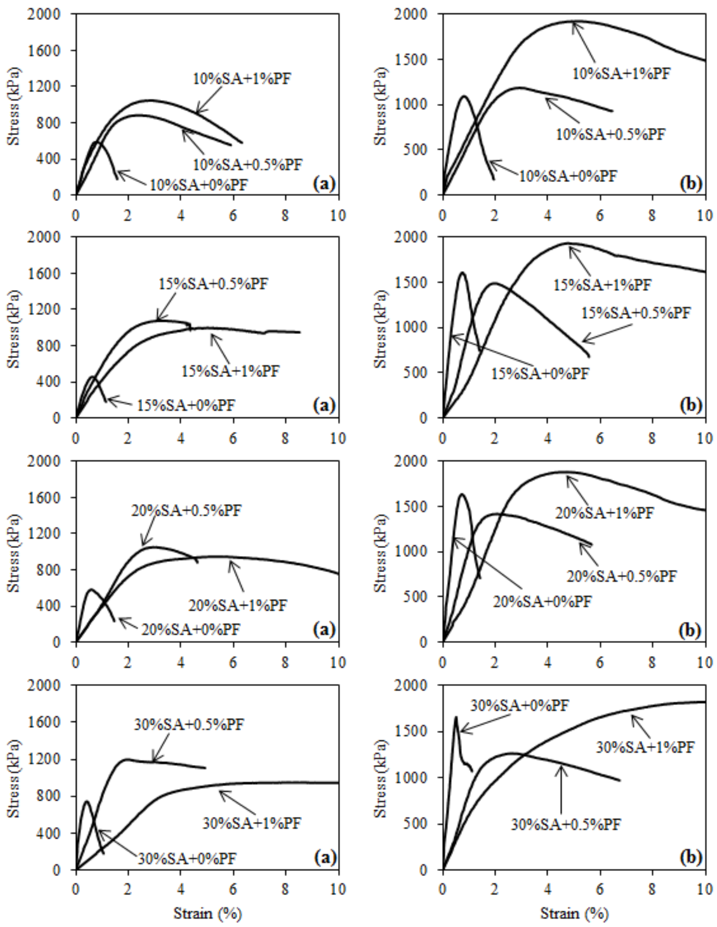

Fig. 6 Stress-Strain curves of sand+SA+PF mixtures for curing periods of: (a) 7-day; and (b) 14-day

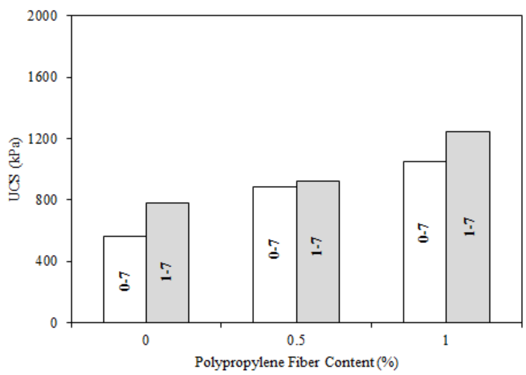

Fig. 7 The effect of the freezing and thawing cycle on UCS values for curing time of 7 days

performance with the increase in its dosage rate. Ghazavi and Roustaie (2010) has also achieved similar results and reported that the freezing and thawing cycles enhance the UCS value of soil by

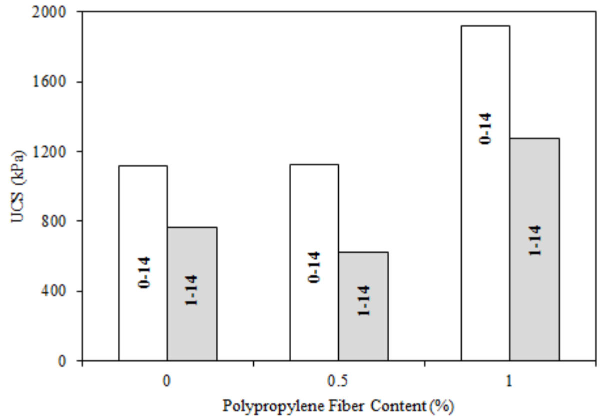

Fig. 8 The effect of the freezing and thawing cycle on UCS values for curing time of 14 days

60 to 160% due to the addition to polypropylene fiber. Nevertheless, as for the application of freezing and thawing cycle after 14 days of curing, it is found by Fig. 8 that freezing and thawing resistance of sample is detrimentally affected. Fig. 8 also denotes that the magnitude of strength loss increases depending on the increment in polypropylene fiber content. It is evident in Table 5 that the application of freezing and thawing cycle did not change the consistencies of the samples.

4. Conclusions

In this study, an experimental effort was presented on the reuse of sludge ash as a stabilizer with polypropylene fiber for improving the UCS performance of poorly-graded sand. In addition, after a curing period (7 and 14 days), one freezing and thawing cycle was applied on the samples including 10% sludge ash and 0 to 1% polypropylene fiber in order to investigate their freezing and thawing resistance. The following major conclusions could be drawn:

(1) It is found from the UCS results that the addition of sludge ash as a stabilizer remarkably improves the UCS characteristics of sand. This improvement enhances with the increase in curing period due to pozzolanic activities of sludge ash. Also, the consistencies of the samples are changed from “very soft” to “hard”. The use of sludge ash at 30% presents the most relative contribution for both 7 days and 14 days of curing with regard to UCS testing results. The lowest relative contribution for curing periods of 7 days and 14 days is achieved in case of sludge ash inclusion at 15% and 10%, respectively.

(2) For the UCS samples cured for 7 days, it is observed that polypropylene fiber inclusion to sand modified with sludge ash enhances the magnitude of UCS. However, while the addition of polypropylene fiber at 0.5% results in an increasing trend in UCS gain, polypropylene fiber inclusion at 1% causes a decreasing trend except for 10% sludge ash where UCS gain increases as polypropylene fiber content augments. In the case of using polypropylene fiber at 0.5%, the most and lowest contributions are obtained for the mixtures that contained sludge ash at 30% and 10%, respectively.

(3) As for the UCS samples cured 14 days, the magnitude of UCS of control sample increases with the increase in sludge ash content. In addition, the addition of polypropylene fiber

enhances the UCS values of sand+sludge ash mixtures. However, in case of fiber addition at 0.5%, the use of sludge ash at greater than 15% results in a decreasing trend in UCS performances of sand. Furthermore, as polypropylene fiber content augments, the improvement in UCS due to sludge ash inclusion becomes less, that is, UCS decreases with the increase in sludge ash content. It is also from this study that the admixture including 10% sludge ash and 1% polypropylene fiber yields the most relative contribution to UCS.

(4) Polypropylene fiber inclusion also contributes to the stress-strain characteristics and post-peak strength loss of sand+sludge ash mixtures. After the addition of polypropylene fiber, sand+sludge ash mixtures exhibit more ductile behavior and less reduction in post-peak strength occurs.

(5) The application of one freezing and thawing cycle after 7 days of curing enhances the UCS performance of sand+sludge ash+polypropylene fiber mixtures. But, a detrimental effect on UCS results due to one freezing and thawing cycle has been observed for the mixtures that were cured for 14 days. Furthermore, it is found from the experimental investigation that the increase in polypropylene fiber content enhances the detrimental impact on UCS.

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