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Characterization and Demonstration of Reuse Applications ofSewage Sludge Ash

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ABSTRACT: In this papersewage sludge ash (SSA) refers to ash material product of incineration of municipal and industrial sewage water. SSA from a waste water treatment plant in Eastern United States was characterized in order to investigate and demonstrate potential reuse applications for the ashes produced by this plant. To date most research on reuse applications for ash materials has focused largely on coal-sourced ashes such as fly ash or bottom ash. In contrast very little research has been reported on SSA,which typically will have important differences with coal-based ashes in terms of physical and chemical composition and cementitious properties.This paper presents the results of an elemental and morphological characterization as well as a demonstration of clay brick admixture and soil stabilization admixture reuses applications.

Keywords: Ash-based Bricks,Sewage Sludge Ash, Ground Improvement, Sewage Sludge Ash Reuse

1. INTRODUCTION

The disposal of sewage sludge presents challenges which must be met by waste water plant operators through traditional storage-type disposal methods or innovative reuse and volume reduction methods. One such volume reduction method is incineration, which removes water and much of the volatile fraction of the sludge while generating a quantity of biomass ash that is much less than the original volume of sludge. Although the net volume of waste is reduced, the resulting biomass ashes must be committed to disposal or beneficial reuse alternatives. Disposal by traditional landfilling has associated costs and permitting obstacles. Beneficial reuse offers the opportunity to reduce cost, or in some cases, generate revenue and the environmental benefit of reduced landfilling.

The work presented in this paper was undertaken to assist a Southeastern US wastewater treatment plant inidentifying and developingbeneficial reuses of their biomass ash material. Since the biomass ash is produced from incineration of sewage sludge,it will be referred to as sewage sludge ash (SSA). The paper presents results of a laboratory characterization of theSSA ashes as well as results of a feasibility study for two beneficial reuse options. The two beneficial reuse options presented are asan admixturefor fired clay bricks and as a geotechnical ground improvement soil admixture similar to lime or cement commonly used for improved strength and reduced settlement of soft clayey subgrade soils.

1.1 Background and Motivation

The plant which supplied the ashes used in this study processesabout 91,000 m^3 per day of municipal wastewater. To reduce the volume of wastewater treatment residual requiring disposal,the utility utilizes a multiple hearth furnace to incinerate the sludge. This process results in approximately 6,150 $m^3$of incinerated SSA per year. This amount isexpected to increase by about 25% as the utility undertakes capital improvementsto increase operation and treatment efficiency by taking excess sludge from other nearby wastewater facilities.

The utility desires to develop three or four permitted uses for its SSA as part of a beneficial use program. This approach is consistent with U.S. Stateand Federal initiativesto reduce, reuse and recycle materials to preserve landfill space, optimize the use of land resources and protect groundwater.Furthermore, the motivation for implementing beneficial reuse strategies for the SSA ash are in anticipation of possible new and more stringent guidelines and regulations for management and beneficial reuse of combustion residuals. These pending regulations are being developed to address concerns about possible groundwater contamination from migration of trace heavy metals that could be present in combustion residuals such as the SSA from this wastewater plant.

1.2 Beneficial Uses of Sewage Sludge Ash

Sewage sludge is produced in large quantities from residential and industrial water treatment plants. The direct use of sewage sludge in agricultural applications such as fertilizer or soil amendment is attractive due to the presence of nutrients (e.g., nitrogen and phosphorus) and organic matter, which can increase fertility of the soil. However, despite theapparent benefits of land applicationin agricultural settings, this practice has been mostly abandoned due to health and environmental concerns regarding toxins present in the sludge [1], [2]. To reduce waste volume, manywastewater treatment facilities in the U.S. incinerate the sewage sludge and the majority of the resulting SSA is disposed in controlled landfills [3]. In an attempt to avoid landfill disposal and possibly valorize the SSA, there isgrowing interest in identifying technically feasible and cost-effective reuse or recycling applications of SSA in different areas such as agriculture, construction, etc. The direct use of SSA as an agricultural fertilizer is under consideration, butsimilar to sewage sludge, itmay pose environmental and health challenges sincemany SSA ashes containpotentially hazardous heavy metals. Recently use of treated incinerated SSA as an agricultural fertilizer has been reported in Bavaria, Germany where a thermo-chemical process has been used to extract the heavy metals from the ashes below environmental regulatory thresholds [4]. Another alternative is to use SSA in non-human consumption agricultural application, such as biofuel production.

In terms of construction related reuse applications, the main focus of this paper,SSA has been reported in the literature as being viable as: (i) an additive to concrete mixtures [5], [6]; (ii) a fine aggregate for cement mortar [7], [8]; (iii) a clay substitute in the manufacture of clay bricks [9], [10]; (iv) a source material for fabricating glazed tiles [11]; (v) a filler in asphalt paving mixes [12]; (vi) a source material for fabricating lightweight aggregates [13], [14]; and (vii) an admixture with cement for stabilization treatment of soft subgrades [15].Based on the literature review and feedback from the plant management the following two reuse applications were selected for this study and described herein: (i) use of the SSA as an additive for clay bricks, and (ii) use of SSA, without the addition of cement, as an admixture for soft ground improvement. These applications are described in Section 3.

2. CHARACTERIZATION OF SSA

2.1 General Characterization

The general chemical and physical properties of SSA ashes can vary widely as they stronglydepend on the composition of the waste water being treated as well as the type of incineration system and the chemicals used during the wastewater treatment process [16]. Donatello et al. [3] and Cyr et al. [6] reported that silicon (Si), iron (Fe), aluminum (Al), calcium (Ca) and phosphorous (P) were the major elements present in the SSA materials they investigated, other elements reported as being present included potassium (K), sodium (Na), magnesium (Mg), and sulfur (S) [9]. The presence of P in SSA is mainly due to the removal of soluble P from wastewater during the wastewater treatment process [13]. According to [10], and [11] the most significant mineral phases present in SSA are silicon oxide (SiO_2), calcium phosphate ($Ca_3(PO_4)_2$), iron oxide (Fe_2O_3), calcite ($CaCO_3$), anhydrite ($CaSO_4$) and a significant amount of amorphous phases.

2.2 Characterizationof the SSA ash used in this study

The SSA ashes used in this study were collected from two access points at the incineration wastewater treatment facility. One SSA type consisted of dry ash(DA) which was sourced from the exit port of the furnace and was maintained in a dry condition prior to collection and during storage. Many plantssluice the ash into a slurry in order to pump it to settling/storageash ponds on site. The second SSA ash investigated was collected from the ash pond at the end of the process and is referred herein as sluiced ash (SA). This ash was wet when collected but oven dried for characterization and for the reuse application study.

Grain size distribution of the DA SSA revealed this ash is equivalent to a silty sand as it has about 62% of sand sized particles, 35% of silt sized particles and 3 % as clay sized particles (all percentages by weight). Atterberg limits tests on the fine fraction of the ashes revealed a non-plastic behavior. The particle characteristics for the DA and SA SSA ashes were investigated using an electronic stereo microscope. Representative photos of the particles for the DA and SA SSA ashes are shown in Figs. 1 and 2, respectively. Many ash particles are agglomerated in clusters which are 1-2mm in diameter. These agglomerations are easily broken during handling and transport, however they were found to influence the bulk volumetric characteristics of the material. Also visible in Fig. 1is a large particle of carbon. Much of the carbon in the sample seems to exist in such clusters, which range in size up to 4 mm.

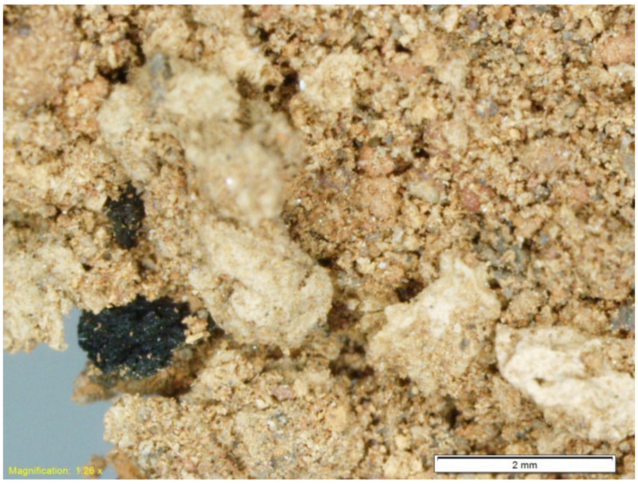


Fig. 1: Stereomicroscope image of the DA SSA ash

The chemical compositions of the two SSA ash types investigated,as measured by X-Ray fluorescence, are presented in Table 1. The results are expressed as themass percentage of the element present in each sample.The two SSA ashes contained primarily the elements, silicon (Si), iron (Fe), aluminum (Al), phosphorous (P), and calcium (Ca). The balance of constituents,reported as light elements, includes mostly unburned carbon (C) and oxygen (O). Both ashes had loss on ignition of approximately 13%. As shown in Table 1, the SASSA was found to have lower amounts of copper (Cu), titanium (Ti), calcium (Ca), phosphorus (P), aluminum (Al) and lead(Pb) compared to the DA SSA. This signifies that the sluicing process of the ash (SA) leads to reduction in the amount of these elements. It is apparent that sluicing the ash reduces the amount of most easily soluble elements present in the initial ash sample.

SEM micrographs of representative DA and SA SSA samples are shown in Figs. 3 and 4, respectively. Both images were collected at a magnification of 900X and an accelerating voltage of 7KV. Prior to imaging with the SEM, SSA samples were pulverized with a mortar and pestle and sputter coated with gold. Ashes not treated in this way tended to form agglomerations that give the appearance of much larger particles. These images show how both SSA types have irregularly-shaped particles and how the DA and SA SSA show little variation in their microstructure. This would indicate that the sluicing process has little impact on the physical structure of the ashes. The material grains can be described as having angular particles with a deeply porous, rough surface. Such surface texture is typical of combustion byproducts due to the expansion of gasses during heating.

Using the image scale provided, one can infer that most particles in the images are less than 20 microns in length (i.e., silt sizes). However these images do not include some of the sand size conglomerates that were broken up during the SEM sample preparation process.

Fig. 2: Stereomicroscope image of SA SSA ash

Table 1: ElementalAnalysis of SSA by X-ray Fluorescence

Element	DASSA (%)	SASSA (%)
Si	9.57	9.22
Fe	9.381	14.007
Al	7.37	5.76
P	7.146	4.695
Ca	6.634	4.533
Ti	0.949	0.654
K	0.895	0.808
Zn	0.486	0.272
S	0.457	<LOD
Mn	0.249	0.289
Cu	0.204	0.09
Zr	0.079	0.05
V	0.062	0.064
Cr	0.036	0.021
Ag	0.028	0.028
Co	0.022	0.023
Cd	0.02	0.024
Pb	0.013	0.007
Bi	0.013	0.008
Mo	0.012	0.004
Ni	0.01	<LOD
Sn	0.009	0.008
Sb	0.007	0.008
Mg	<LOD	<LOD
Light Elements	56.36	59.43
Total	100.012	100.002

3. DEMONSTRATION OF MATERIALS

As indicated in Section 1, this work involved a study of feasibility for construction-related reuse applications of SSA from a wastewater treatment plant in South Eastern USA. The following subsections describe the results for the two reuse applications selected.

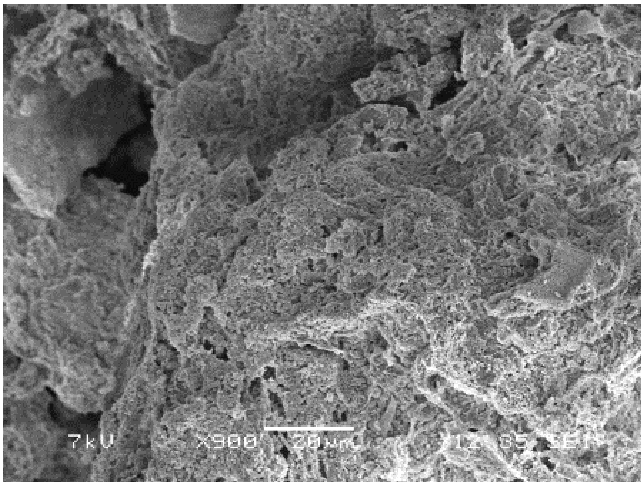


Fig. 3: SEM micrograph of the DA SSA ash

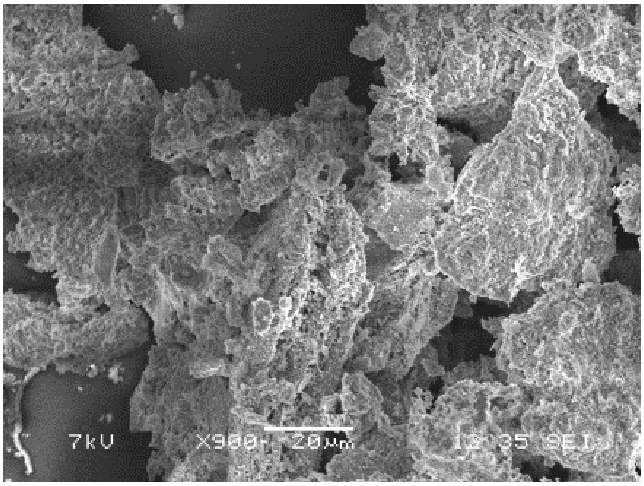


Fig. 4: SEM micrograph of the SA SSA ash

3.1 Reuse of SSA as an Admixture for Bricks

The addition of SSA influences many brick qualities in the fresh and fired states. SSA can act as an “opening” agent due to its particle size and structure. The ashes form pores, acting as fluxing agents, decrease sintering temperature of the mix, and can improve compressive strength as a result of iron and calcium content [18]. Bricks made with proportions of SSA up to 50% have achieved compressive strength of 69 MPa [19]. However, some negative impacts have been reportedand some researchers have suggested using limited amounts of ash in mixes [20]. The high water absorption capacity and possibility of significant calciumcontent of the SSA has a tendency to increase the demand for water in order to maintain workability of the brick mix in the fresh condition. Although sometimes stronger and mechanically superior to traditional bricks, SSA bricks can exhibit secondary problems including moss growth, icing surface, and whitening [18], [21].

In order to measure the compressive strength of clay bricks incorporating SSA ashes as a clay replacement, the dry SA SSA material described in Section 2.0 was mixed with a clay soil, which is described in Section 3.2.Bricks were prepared with 0%, 20% and 40% SSA ash content by weight of clay soil. Water was proportioned to the mixture so as to provide sufficient plasticity for forming and handling the bricks. The brick mixes were created by adding water, ash and clay to a Hobart mixer and churning slowly until they were thoroughly combined. The resulting fresh brick material was compactedwith a hydraulic press applying approximately 0.31MPa into a steel mold lubricated with light oil. After removing the wet brick from the press, it was air-dried for 4-6 hours. When the air-drying period was complete, the batch of bricks was oven-dried at 77°C for 24 hours. After drying in the warm oven, initial dimensional measurements were taken and the oven-dried bricks were moved to a high temperature kiln for firing.

During the brick production process changes in unit weight and volume of the bricks were observed (Fig.5).This figure shows that fresh unit weights ranged from 15.85 kN/m^{3}for the brick mix with 40% of SA SSA to about 18.3 kN/m^{3}for the control mix with 0% of SA SSA. Unit weights for bricks at the end of the kiln firing process ranged from 19.2 kN/m^{3}for the 40% DA SSA mix to 19.9 kN/m^{3}for the 0% DA SSA mix. The variation of brick unit weight from fresh to kiln fired was found to be more pronounced with increasing DA SSA content. This is due to the greater water absorption with increasing DA SSA and the associated observed shrinkage in the fired brick. The greatest increase in density from oven to after firing was observed in the 40% DA SSA mix.

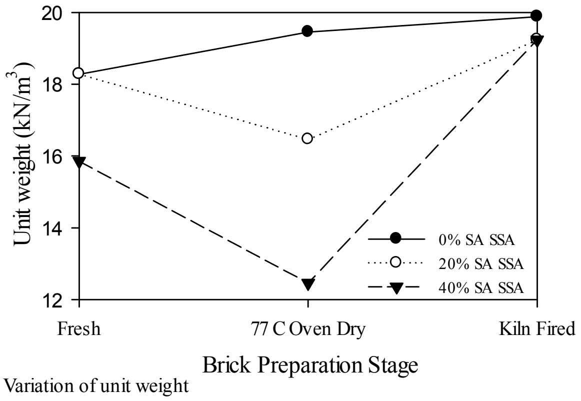
Representative photos of the bricks before and after firing are shown in Fig. 6. The compressive strength of the fired bricks was measured by testing them to failure in a Universal Testing Machine. The bricks were capped with gypsum compound and loaded in the manner consistent with ASTM C67 [22]. Table 2 gives the compressive strength results of the bricks. Each brick mixture was tested in triplicate with the exception of the 40% ash series because one of the samples was damaged prior to testing. Results indicate that increasing ash content up to 40% DA SSA results in an increase in compressive strength within the preparation and firing parameters used for this study. While strength results from this work point to positive impacts of ashes as clay substitute for brick, the commercialization of this process would require adaptation of the procedure to accommodate the observed large shrinkage.

Table 2: Compressive Strength of Bricks

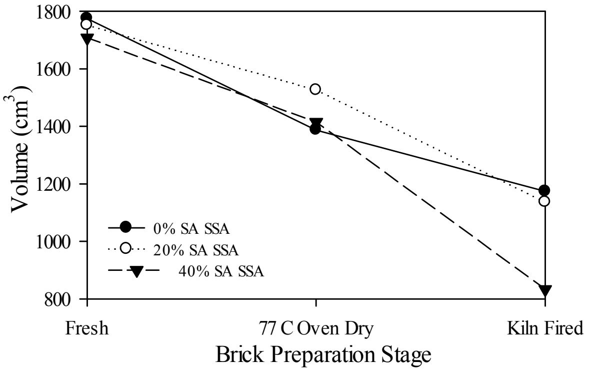
Ash Ratio	Compressive Strength (MPa)			Mean	Stand. Dev.
0%	28.4	29.6	18.5	25.5	6.1
20%	25.4	40.7	29.2	31.8	7.9
40%	47.7	49.3	-	48.5	1.1

3.2 SSA as a Ground Improvement Admixture

Soft soil improvement or stabilization has been practiced for quite some time by mixing chemical admixtures to the soft soil, such as cement and lime, to increase its strength and stiffness [23], [24]. In recent years ground improvement using Class F or C fly ash has also been reported [25], [26]. In contrast very little to no research has been found that addresses the applicability of SSA as a soil stabilization admixture. Reference [15] reports the use of SSA mixed with Portland cement. This paper presents a summary of relevant results form a pilot study conducted to assess the potential of using SSA for this kind of applications. The pilot study has two phases: i) laboratory study, and ii) field study.



a) Variation of unit weight



b) Variation of volume

Fig. 5: Brick properties during preparation stages

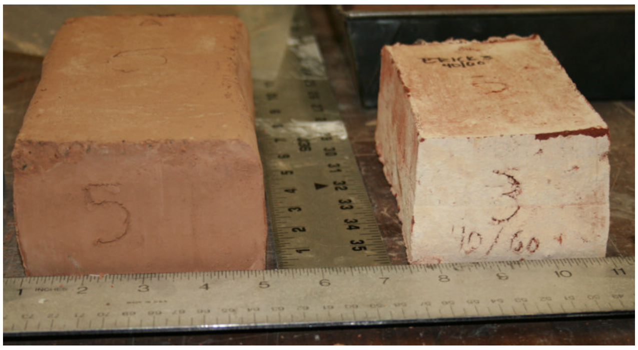


Fig. 6:Bricksbefore (left) and after (right) kiln firing

The pilot laboratory study primarily involved assessing the stabilization characteristics of a clayey soil obtained from a site located in Concord, NC, USA when blended with different percentages of DA SSA. The stabilization characteristics were evaluated with respect to a) curing time (0, 7, 14, 28, and approximately 40 days), and b) amount of SSA (5 to 20% by dry weight). The following subsections describe the materials used (i.e., base clay soil, and SSA ash), and experimental procedures (i.e., sample preparation, curing procedures, and test procedures).

3.2.1 Materials used

Two materials were used: the base clayey soil to be stabilized and the DA SSA ash described in Section 2.2. The clayey soil used for this study was obtained from a borrow site located in Concord, NC. Several 5-gallon pails of the clayey base soil were retrieved from this site. The soil at this site can be described as a reddish brown high plastic sandy silt (MH) to sandy clay (CH). From a series of grain size distribution analyses carried out following ASTM D422 [27] the Concord clay has approximately 37% sands, 27% silt sizes, and 36% clay sizes. The Atterberg limits for this soil were found to be about 65% for the Liquid Limit and 39% for the Plastic Limit. According to the Unified Classification system this soil classifies as a high plasticity silt (MH). A summary of the main index properties of the base soil is provided in Table 3.

3.2.2 Laboratory study

Prior to soil treatment, the base clay soil from the Concord, NC site was air dried for two weeks and then processed using crushing equipment. Several Standard Proctor compaction tests (ASTM D698) [28] were carried out on the base clay soil which yielded, on average, an optimum moisture content of about 20 % and maximum dry unit weight of 16.42 kN/m^3 as shown in Table 3.

Soil samples were treated with 5% and 10% DA SSA ash by weight. The effect of adding SSA to the compaction characteristics of the treated base clayey soil was assessed by comparing the corresponding Standard Proctor compaction curves as shown in Figure 7. It can be seen from this figure that the maximum dry unit weight of the treated soil decreased from about 16.5 kN/m^3 to approximately 15.85 kN/m^3 and 15.64 kN/m^3, for the clayey soil treated with 5% and 10% DA SSA ash, respectively. The optimum moisture content was about 20% for the untreated control samples and the clay treated with 5% DA SSA, and increased to about 22% for the clay treated with 10% DA SSA. Based on the Standard Proctor curve results, a uniform target moisture content of 20% was selected for the pilot laboratory study.

Before compaction of the treated samples, the initial moisture content of the air dried clay was measured to ensure the correct amount of water was added to obtain the target moisture content of 20%. The pre-moistened soil was kept in sealed bags for a minimum mellowing period of 24 hours prior to adding the appropriate amount of SSA admixture. To ensure homogeneous blends of soil and admixture the specific quantities of admixture and pre-moistened soil were mixed for 3 minutes using an electrical mixing machine at about 138 rpm.

According to Barbu [29], maximum stabilization effects are obtained when ash-treated soils are mixed quickly and immediately compacted. Based on this, all the samples in this study were immediately compacted after mixing. This procedure minimized effects related to the early hydration reaction associated when using SSA ash. The samples were compacted inside plastic molds with a 50.8mm diameter and a 102 mm height. The plastic molds were placed inside the compaction device shown in Fig.8, prior to soil filling and compaction. The soil-admixture blends were compacted by placing the mixtures in 6 equal layers and applying 13 blows to each layer using the hammer rod shown in Fig.8. This compaction procedure corresponds to the same specific compaction energy of a Standard Proctor test (ASTM D 698 [28]). Immediately after compaction, the molds of the samples were sealed with a plastic cap and stored in a curing chamber with controlled conditions of temperature and humidity. Prior to unconfined compressive testing,samples were cured for 7, 14, or 28 days.

Table 3: Index properties and Compaction Characteristics of the BaseClayey Soil

Property	Value	ASTM standard
Natural water content (in-situ when sampled)	17-25	D 2216
Liquid Limit (%)	60-65	D 3418
Plastic Limit (%)	35-39	D 3418
Plasticity Index (%)	26-28	D 3418
Specific gravity, G_s	2.66	D 854
Moist unit weight, γ_{wet} (kN/m^3) (Drive cylinder test)	18.7 – 19.7	-
Organic matter content (% by weight)	1.2-2.4	-
Maximum dry unit weight (Standard Proctor) (kN/m^3)	16.38-16.52	D 698
Optimum water content (Standard Proctor) (%)	19-20	D 698

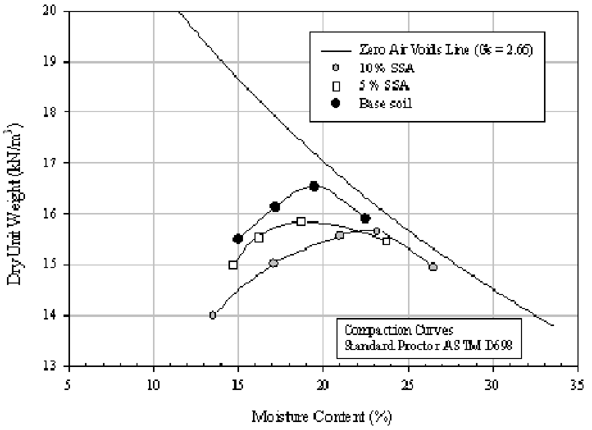


Fig. 7: Standard Proctor Compaction Curves

Unconfined compressive tests were also carried out on uncured samples which were tested immediately after compaction, (i.e., corresponding to an age of 0 days). To consider inherent sample and test result variability, at least three samples were tested at each admixture proportion level and curing time.

The assessment of the feasibility for using DA SSA ash for soil stabilization was made primarily on the basis of the results of unconfined compressive strength tests carried out on cured samples with different admixture treatments as discussed before. The unconfined compressive strength tests were carried in general accordance with ASTM Standard D2166 [30]. All unconfined compression tests were strain controlled at a rate 1% per minute. Fig. 9 shows the average unconfined compressive strength values measured for the two dosage levels of DA SSA investigated. For comparison purposes this figure also presents the baseline corresponding to average unconfined compressive strength values measured on untreated clay samples compacted using the same procedure as the one used for treated samples. All results correspond to 28 day curing time. The error bars shown correspond to the standard deviation for the total number of samples tested. This figure shows that samples of the clayey base soil treated with 5 and 10 % DA SSA ash has modest unconfined compressive strength gains of 10 to 20% with respect to the untreated control samples. These unconfined compressive strength gains although modest, did indicate that samples treated with DA SSA increased in strength and maintained the strength gained when compared to the untreated control specimens. To further investigate this beneficial reuse alternative of soft clay stabilization with DA SSA, a field study involving plate load tests was carried out as described in the following section.

Fig. 8: Miniature compaction equipment

3.2.3 Plate load test field study

The plate load test field component was designed and implemented at the same site in Concord, NC, USA where the base soil samples used for the laboratory program were collected. An area of the site where the clayey soil was exposed and had no vegetation cover was selected for the pilot field study. This section describes the main activities pertaining to this component.

A rectangular test section was cleared and divided into different subsections representing three treatment conditions: i) 5% DA SSA (by weight); ii) 10% DA SSA (by weight); and iii) Control or untreated clayey soil.Prior to tilling and adding admixtures, the in-situ field density and moisture content was measured using drive cylinders and nuclear gage field density tests. The field density and moisture results are summarized in Table 4.

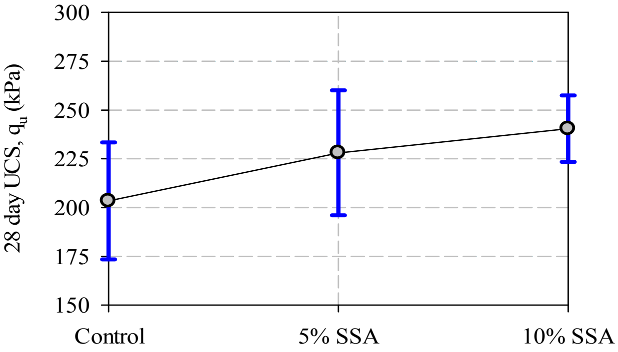


Fig. 9: 28 day unconfined compressive strengths

Table 4:Summary of Field density tests before tilling site

Test Section	Test Type	Field Density	Field Moisture
A – Control (No treatment)	Nuclear gauge	$\gamma_m = 19.67$ $\gamma_d = 16.32$	w = 20.5 %
B – 5 % SSA	Nuclear gauge	$\gamma_m = 19.56$ $\gamma_d = 16.21$	w = 20.7 %
B – 5 % SSA	Drive cylinder	$\gamma_m = 19.88$ $\gamma_d = 16.56$	w = 20.0 %
C – 10 % SSA	Nuclear gauge	$\gamma_m = 19.37$ $\gamma_d = 16.27$	w = 19.1 %

The field density testing results were used to calculate the amount of water required to achieve the target moisture content of 20% after tilling, and mixing in the different types and proportions of admixtures. After field density testing and demarcation, the test section was carefully tilled to a depth of about 19 cm. With the tiller and hand tools the admixtures were mixed at the different target proportions including addition of the corresponding amount of water to achieve the target moisture content of 20%. It should be pointed out that the control section (Sector A) was tilled using the same procedure but no chemical admixture or water was added (in-situ moisture = 20.5%).After tilling, adding water, and mixing the different DA SSA proportions, a large vibratory smooth roller compacter was used to compact the different sectors of the test section. A total of 6 passes of the roller compacter were used to achieve the desired field compaction levels.

After 28 days of curing, a series of plate load tests were carried out at each of the test subsections. The plate load tests were carried out using a circular steel plate with a 152.7 mm diameter and a 45.7 mm thickness. The plate load tests were carried out in general accordance with ASTM D1196 [31].A hand operated hydraulic jack was used to apply load on the steel plate. The applied load was recorded using a calibrated load cell and the resulting settlement of the plate was measured using electronic dial gages.The test setup is shown in Fig. 10. This figure also shows how the hydraulic jack was pushed against a bulldozer.

The possible gains in strength and stiffness of the SSA treated soil sectors was evaluated by comparing the applied pressure versus plate settlement curves obtained from the plate load tests for each test section. A summary plot showing the average pressure-settlement curve obtained for the two DA SSA treated sectors (Sectors B and C) and for the untreated control sector (Sector A) are shown in Fig.11. All tests were carried out until a settlement of at least 25 mm was measured or until the final stroke of the hydraulic jack was reached. Thesettlement curves in Fig. 11 show an increase in both bearing capacity (which is related to the soil strength) and stiffness for both the 5% and 10% DA SSA treated soil compared to the results obtained for the untreated control.For comparison purposes, this figure shows that for a plate settlement of 25 mm the applied pressures measured were 672, 765, and 885kPa for the control, 5% SSA, and 10% SSA treated soils, respectively. These values represent relative bearing capacity improvements of 13.9 and 31.7 % when the clayey soil at this test site was treated with 5 % and 10% DA SSA by weight, respectively.

Fig. 10: Photo showing plate load test setup

4. CONCLUSIONS AND RECOMMENDATIONS

Ashes from a wastewater treatment facility that incinerates its treatment sludge were evaluated physically and chemically. Dry collected and sluiced ashes were demonstrated in two possible beneficial uses in order to evaluate the potential for developing recycling alternatives. The beneficial use alternatives were partial clay substitute for brick manufacture and as a soft soil stabilizing admixture. Both beneficial use demonstrations indicate positive impacts from the ashes. In the case of the clay substitute for brick manufacture, addition of ash led to increased brick strength relative to bricks not containing ash that were fired at the same temperature. As a soil stabilizing admixture, improvement in bearing capacity and stiffness were found relative to soils which did not receive treatment with the ashes.

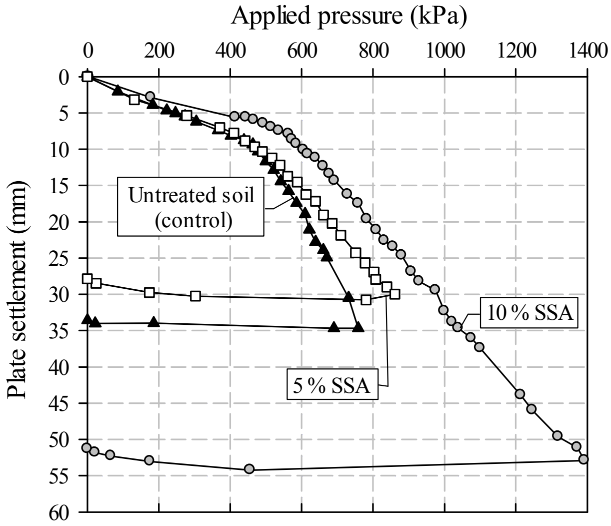


Fig. 11: Plate load test results

These results are sufficiently positive to encourage further investigation of both recycling alternatives. Due to the environmental and industrial setting of the wastewater treatment plant in the southeastern United States, stabilization of clayey soils and manufacture of bricks are both significantly attractive outlets. Further research should include rigorous study of three key features. The environmental implications of use must be carefully assessed prior to deploying either alternative on a large scale. This should include determining the leaching behavior of the stabilized soil as well as the bricks. Secondly, the variability of ash characteristics that would impact their function in both applications should be quantified and understood in order to develop specifications or standards that can separate acceptable ashes from unsuitable ashes. Thirdly, the long term durability of the ash amended materials should be evaluated. A standard set of brick durability tests is available due to the strong precedent for clay brick use in construction. The ash containing bricks should be evaluated with equivalent methods as non-ash containing bricks. For the soil amendment, long-term monitoring of the test site should be undertaken to verify that the strength gains are permanent.

5. ACKNOWLEDGMENTS

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