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Research Article

Geotechnical Properties of Wood Ash-Based Composite Fine-Grained Soil

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It is observed in Bangladesh that there is an extensive use of wood as a solid biomass for heat and electricity production, which led to increase in the amount of combustion residues known as ash. These ashes are discarded and dumped here and there, resulting in pollution of the environment. It could be managed by using wood ash as a stabilizer of soft clay. It is found that there is an enhancement of the engineering properties of existing soil in stabilized forms particularly unconfined compressive strength (UCS), shear strength parameters, workability, and compaction and compressibility characteristics. Therefore, laboratory tests associated with these properties were performed for some selected percentage of wood ash, for example, 0%, 5%, 7.5%, 10%, and 12.5%. Chemical investigation of wood ash depicts that it contains approximately 30% CaO, which directs it to behave like a pozzolanic material. Besides, the test result signifying that the soil could be made lighter with the increase of moisture content, strength, and reduction of compressibility due to the addition of ash content.

1. Introduction

During the last decades, some construction difficulties of foundation resting on soft clay have been observed. These soils are treated as problematic soils as they have high compressibility and low shear strength. They also may have a tendency to swell and shrink. One of the indications for the soft soil is undrained shear strength smaller than 40 kPa [1]. These soils pose higher strength at dry state and lose their strength when there is an increase in moisture content. These types of dispersive soils are also highly prone to erosion [2]. Therefore, these soils are not fit for the construction of infrastructure on them as they have a high risk of settlement. Moreover, the available land for construction is very limited. Hence, it has become a challenging task for a foundation engineer to design and construct a foundation on such soft soil. There are different methods practiced to improve the engineering properties of such soils such as stabilization, grouting, removal and replacement, removal and recompaction, preloading, vibroflotation, stone columns, and dynamic compaction and reinforcement using geosynthetics [3–8]. These methods improve the physical and chemical properties of soil in such a way that the soil becomes consistent; hence, the strength is increased and deformability and permeability are reduced. Although compaction and consolidation methods work very well for granular soil, it takes a long time for the soil to consolidate (months to years) especially with the cohesive soil [9]. Moreover, in the case of highly organic soft soil, it is not possible to improve the geotechnical properties of soil with these methods. Replacement methods could be the possible solution for organic soil, where the organic soil to a sufficient depth is replaced with granular soil such as sand and crushed stones or preloading to improve engineering properties [10]. Chemical stabilization is an alternative low-cost solution, where stabilizing agents such as cement, lime, fly ash, and other binders stabilize the organic soil rapidly through chemical reactions [11–13].

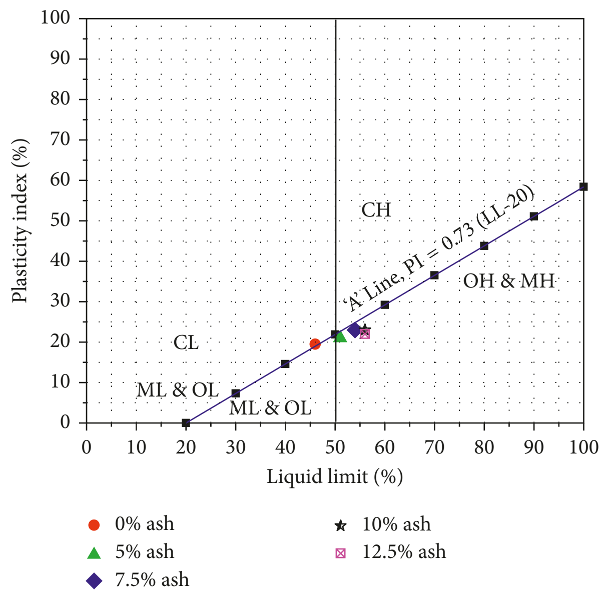

Figure 1: Plasticity chart showing the original and wood ash-treated soil.

Table 1: Physical properties of soil.

Properties	Soil
Liquid limit (%)	46
Plasticity index (%)	19
Specific gravity	2.71
OMC (%)	22
MDD (kg/m^3)	1550
Undrained shear strength, S_u (kPa)	30

Table 2: Chemical composition of wood ash.

Constituents	% in wood ash
CaO	29.80
MgO	5.25
K_2O	9.55
Fe_2O_3	0.95
Na_2O	7.50
SiO_2	25.8
Al_2O_3	14.72
P_2O_5	2.33
TiO_2	0.70
SO_3	0.70
Loss on ignition, LOI	2.70

Soil stabilization using chemical additives such as cement, rice husk ash (RHA), fly ash, and lime is widely used because of their cementitious constituents [14–18]. These cementitious constituents modify and stabilize soft soil through cation exchange, flocculation and agglomeration, and reactions [19]. However, the selection of chemical additives depends on several factors such as dry density, shear strength [20, 21], workability (in surficial improvement techniques), and durability [22]. Barends [23] categorized soil improvement techniques for soft soil according to the manner of treating the soil.

Wood that is widely used as a fuel and energy sources has led to a strong increase in the amount of combustion residue. Wood ash is a gray material produced from the combustion of wood. It is generally discarded as waste and dumped outside of house or landfill, which increase the volume of landfill. A country like Bangladesh, where population density is very high, needs to manage this waste properly in the limited landfill area. Therefore as an alternative solution, this ash can be used as a potential soil stabilizer through the chemical reaction. The chemical composition of wood ash implies that it can be used as a substitute of CaO (that contains about 30% CaO) for soil stabilization. It lacks plastic properties with particles that are mostly smaller than 0.075 millimeter in size. It is found from the literature that the concentration of heavy metals present in the wood ash is very low [24, 25]. However, this ash may be leaching heavy metals into the soil, but the movement of the metal concentration is slow. The slow movement of the leachate is attributed to the reduction of solubility of the leachate due to the contribution of the pH value from wood ash. As long as the value of pH is above 6, the metals will remain bound in the soil, chemically locked in place [26, 27].

Khulna is the southwest part of Bangladesh having fine-grained soil with some organic deposits, which, due to the lower bearing capacity, are not good for shallow foundations [28]. In the present study, wood ash is focused as a substitution of lime (CaO) to improve the compressibility and strength characteristics.

2. Materials and Methods

2.1. Materials. The soil sample was collected from KUET, Khulna, Bangladesh (758686.70 m E, 2529312.06 m N, and elevated at 3 m), in a disturbed state, by manual excavation. It was then dried and pulverized using a manual hammer. The pulverized soil was sieved through a sieve of 4.75 mm aperture. The soil could be classified as A-7-6 and is CL (clay with low plasticity) according to the AASHTO and Unified Soil Classification System (USCS), respectively (Figure 1). The physical properties of soil are summarized in Table 1.

Wood flour was collected from the locally available sawmill and was simply burned to prepare ash. In this arrangement, pulverized wood was kept in a steel box of 1.5 m × 1.5 m in dimensions. Five thermocouples with a connecting data logger were used for measuring the burning temperature. Briquettes were used as fuel to start and maintain the fire. The wood ash contained about 30% CaO, which is the key factor for improving soil properties (Table 2).

2.2. Methodology. Soils and wood ashes were kept in an oven at 105°C overnight to remove moisture and repress microbial activity. The pulverized soil and ash contents were mixed manually in a large tray in a dry state with proper care because there is a possibility of nonuniform mixing according to Table 3.

To study the influence of the wood ash on the mechanical properties of the treated samples, it is crucial to maintaining consistency between the sample preparations. It was decisive

Table 3: Combination scheme of soil samples.

Sample ID	Sample description		
	Soil (gm)	Wood ash (gm)	Ash content (%)
Original soil	6000	—	0
W1	6000	300	5
W2	6000	450	7.5
W3	6000	600	10
W4	6000	750	12.5

that consistency among the samples could be achieved by controlling the mixing water. In this investigation, samples were prepared using their corresponding optimum moisture content (OMC) in order to maintain the consistency. A series of laboratory test was conducted including index testing, compaction test, UCS test, direct shear test, and consolidation test on nontreated, as well as, ash-treated soils.

Before conducting the compaction test, the nontreated and ash-treated soils (5, 7.5, 10%, and 12.5% ash content) were mixed with water for about ten minutes by hand. After that, the mixtures were put into polyethylene bags and mixing was continued by shaking, overturning, and pressing the bag to squeeze out the air from the soil voids. A series of standard Proctor tests, specific gravity test, and Atterberg limit test on nontreated and ash-treated soils were conducted according to ASTM D 698, ASTM D854, and ASTM D-4318, respectively.

The specimen was then statically compacted in three layers inside a cylindrical split mold, which was lubricated so that each layer reached the specified dry density. The top of the first and the second layers was slightly scarified. After the molding process, the specimen was immediately extracted from the split mold. The samples were then sized as per required for different tests and placed within the plastic bags to avoid significant variations of moisture content before testing.

Unconfined compression tests have been used in most of the experimental programs to verify the effectiveness of the treated soil. The uncured unconfined compressive strength of the cylindrical specimens (36 mm diameter and 71 mm length) was determined according to ASTM D-2166. Shear strength parameters (c and φ) were determined by the direct shear test (ASTM D 3080) of the compacted soil specimens (60 mm diameter and 25 mm height). The settlement characteristics of soils were determined by performing the consolidation test (ASTM D-2435) on the samples of 63.5 mm diameter and 25 mm height.

3. Results and Discussion

3.1. Atterberg Limit Test Result. The Atterberg limits are very important for the characterization of soil within a broad category. The variations of liquid limit and plastic limit with the varying percentages of wood ash are shown in Figure 2. The Atterberg limit results show that both the liquid limit and plastic limit increase with increasing percentages of wood ash. The liquid limit ranged from 46 to 56% and the plastic limit from 27 to 40%, thus resulting in a decrease of the plasticity index values ranging from 19 to 16%. Okagbue

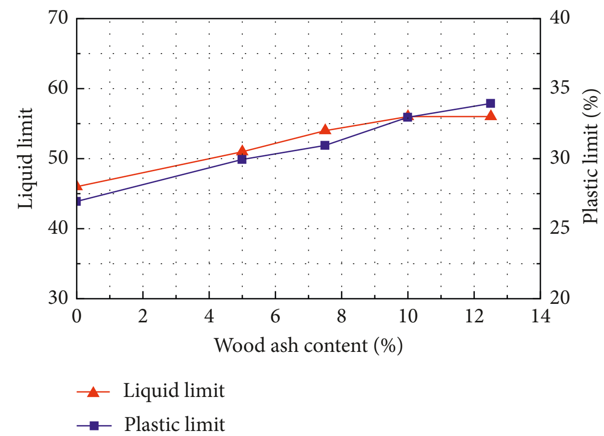

Figure 2: Variation of LL and PL with wood ash content.

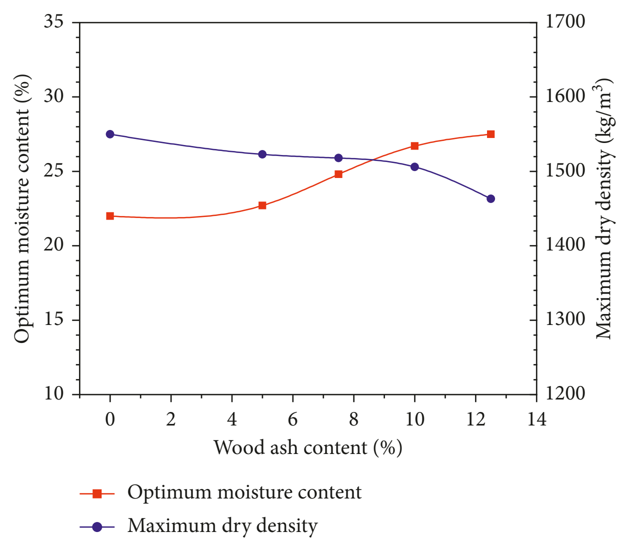

Figure 3: Variation of maximum dry density and optimum moisture content with ash content.

[29] showed the similar results and explained that these beneficial changes in engineering properties are mainly attributed to cation exchange, flocculation of the clay, agglomeration, and pozzolanic reactions. For example, rapid and immediate changes in plasticity occurred due to the cation exchange and flocculation of clay. These trends are the same as those produced when soils are treated with lime, rice husk ash, and cement [30–32].

The plasticity chart shown in Figure 1 depicts the change in form of soil grain for the addition of wood ash. This curve represents that the soil was initially containing medium plastic clay, and after being the addition of ash, it changes in form from clay to silt. This change in form is attributed to agglomeration of the clay particles due to the production of calcium silicate gel. This gel coats the clay clasts, binding them together and filling the pores, resulting in a reduction of water absorption and shrinkage as described in Okagbue [29].

3.2. Compaction Characteristics. Figure 3 shows the effect of wood ash on the optimum moisture content (OMC) and

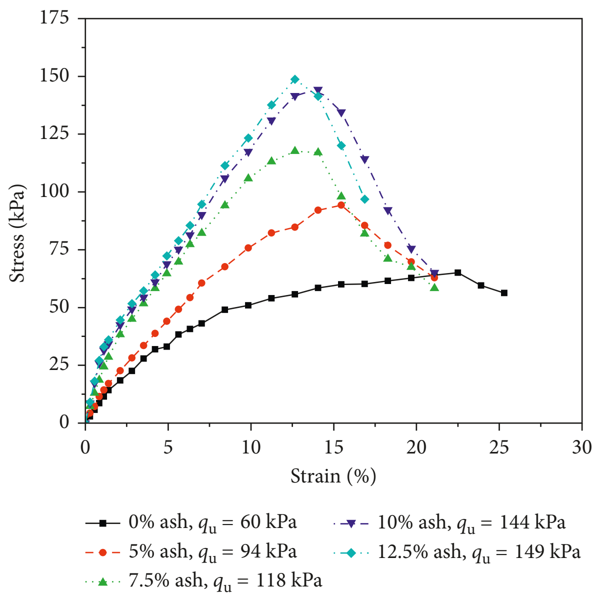

Figure 4: Stress-strain graphs from the UCS tests.

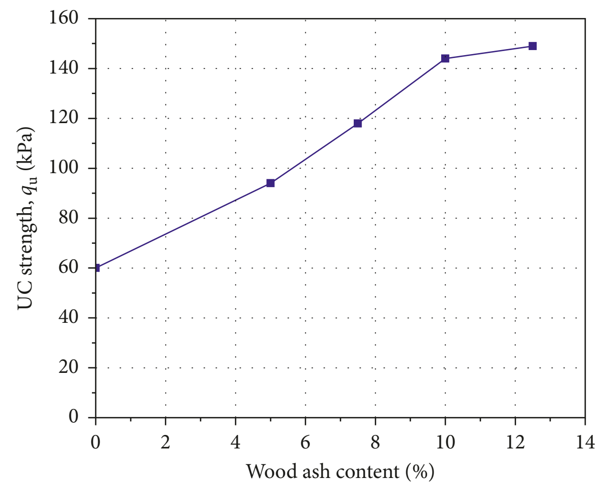

Figure 5: Variation of UCS with ash content.

maximum dry density of soil. It can be seen while maximum dry density decreasing with the increasing amount of wood ash, the optimum moisture content gradually increases from 22% to 27.1% with the addition of 12.5% ash. This trend is similar with Okagbue [29], and it described that the decrease in maximum dry density is attributed by the agglomeration and flocculation of clay particles through cation exchange reaction, leading to occupy larger space as well as reducing the weight: volume ratio. This may also be due to the replacement of the relatively same volume soil particles with wood ash having lower specific gravity (1.67). For example, the specific gravity of soil is decreased from 2.71 to 2.54 after the addition of 12.5% ash content.

On the other hand, the optimum moisture content of soil increases with the increase of wood ash content as more water is required for the formation of the lime-like product, $Ca(OH)_2$, and dissolution of this product into Ca^{2+} and OH^- ions, in order to supply more Ca^{2+} ions for the cation exchange reaction. Besides that the more the fines, the more the surface area, so more water is required to provide good lubrication. The ash content also decreases the quantity of free silt and clay fraction, forming coarser materials, which occupy larger spaces for retaining water.

3.3. Strength Characteristics

3.3.1. Unconfined Compressive Strength (UCS). For the usefulness of wood ash in improving the soil properties, unconfined compressive strength tests were conducted. Figure 4 represents graphically the stress-strain behavior of original and wood ash-treated soil under the vertical load. Initially, the stress is rapidly increasing with the increase of strain until reaching the peak value. After attaining the peak stress, it decreases with the increase of strain for both the wood ash-treated and original soils. It is also seen that the original soil failed at a higher plastic strain compared to the wood ash-treated soil.

Figure 5 illustrates the variation of UCS with the addition of wood ash. In general, as the percentage of wood increases, the percentage of UCS increases significantly in comparison with that for untreated soil ($q_u = 60$ kPa). The illustration shows that there is a rapid increase of UCS with the addition of ash content up to 10%, and for further 2.5% ash content, the UCS value is not significantly increased. Okagbue [29] also reported that 10% ash content gives the optimum value of UCS for the uncured specimens. He also estimated the UCS value for different curing days, although there is no significant improvement of strength was found. The reason for this improvement is formation cementing gels (hydrate) due to the reactions between CaO of ash with Al_2O_3 and SiO_2 of soil. This results in agglomeration in large size particles and causes the increase in compressive strength. Therefore, wood ash can be considered as the potential additives for the stabilization of soft clay.

3.3.2. Shear Strength Parameters. The Mohr–Coulomb shear strength envelops of the original soil, and wood ash-based composite soils are shown in Figure 6. This figure illustrates that shear stress increases for every increment of normal stress, and the steepness of the curve increases with the increase of ash content up to 10%. However, the curve for 12.5% ash-treated soil did not show a significant increase of steepness.

The disparity of the cohesion (c) and frictional angle (φ) with the increase of % ash content is shown in Figure 7. It is observed that the value of cohesion gradually increases from 33.43 kPa to 35.3 kPa for the addition of wood ash up to 10%. After that, this value suddenly drops to 34.02 kPa for the further increment of ash content. The similar trend can be observed in the case of the angle of friction, as it rapidly increases from 18° to 33° up to 10% of ash content and this value decreases for the further 2.5% of wood ash content. Therefore, the optimum shear strength parameters were

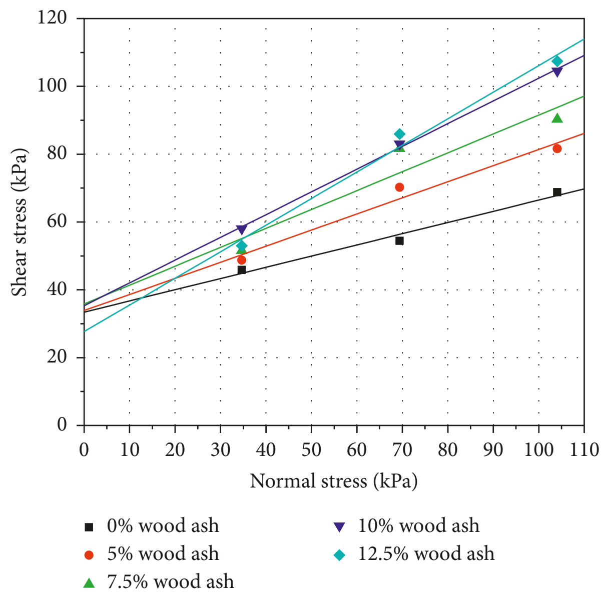

FIGURE 6: The Mohr–Coulomb failure envelops.

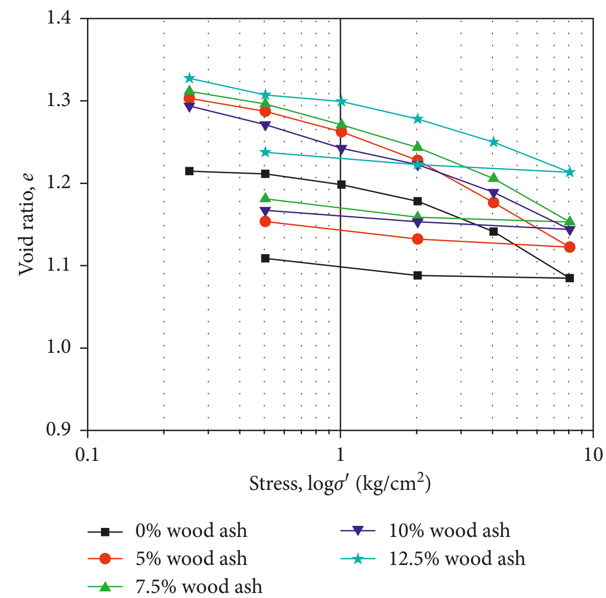

FIGURE 8: Plot of the void ratio, e, versus effective stress, σ.

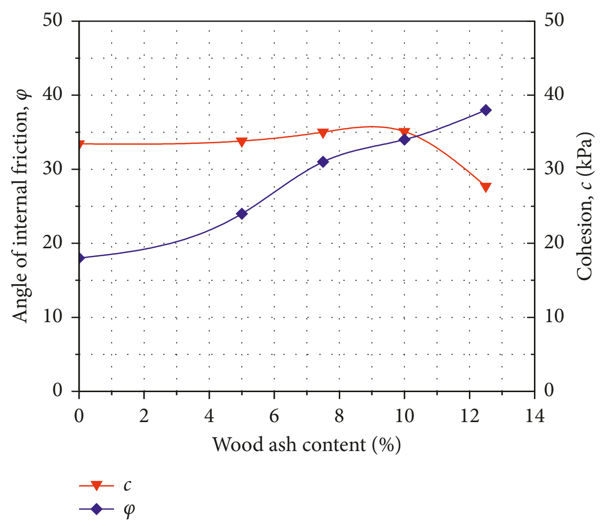

FIGURE 7: Variation of the shear strength parameters with wood ash.

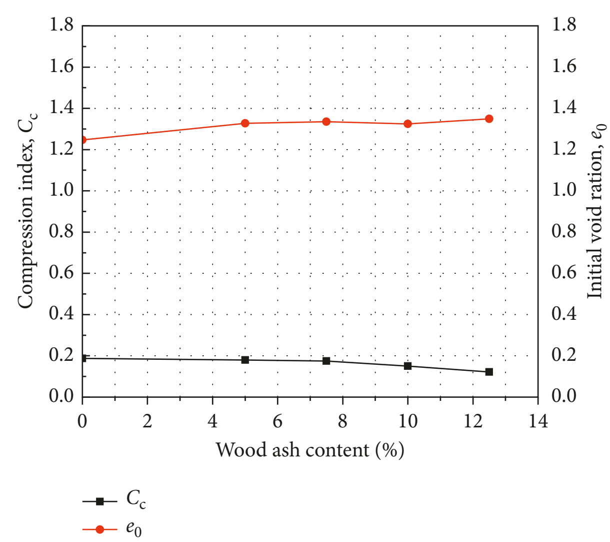

FIGURE 9: Variation of the initial void ratio (e_0) and compression index (C_c) with ash content.

found at 10% ash content, and wood ash can be a useful an additive against the shear failure of soil.

3.4. Consolidation Characteristics. The one-dimensional consolidation test was performed to determine the consolidation characteristics of both untreated and wood ash-treated soil. Figure 8 represents the relation between the void ratio and applied stress. It is seen that all the curves show a similar trend for the void ratio against applied pressure. The void ratio was found to decrease with the increase of applied pressure during the loading period, while the void ratio increases due to the release of applied pressure, but the void ratio does not get back to its original state as it undergoes plastic strain conditions.

The variation of the compression index and the initial void ratio with wood ash content is shown in Figure 9. It is observed that the compression index (C_c) is decreasing gradually from 0.19 to 0.12 for the treatment of soil with wood ash up to 12.5%. This decrease in the compression index implies that there could be a result of the increased formation of products within the pore spaces of soil from physicochemical changes which leads to a reduction in the compression index [33]. On the other hand, the value of the initial void ratio (e_0) increased gradually for the addition of wood ash content up to 7.5%, and after that, it decreases for the further amount of ash content. The decrease of the void ratio in the soil sample for the addition of wood ash content above 7.5% is attributed by the quick pozzolanic action of the soil-ash mixture.

4. Conclusions

This study has evaluated the extent to which wood ash can improve the fundamental geotechnical properties such as consistency, compaction, UCS, shear strength, and settlement characteristics of untreated and wood ash-based clayey soil. The soil was stabilized through 5%, 7.5%, 10%, and 12.5% wood ash content. It is observed that there is an improvement of geotechnical properties of the ash-treated soil. Based on the results obtained after completing the experimental program, the following conclusions can be drawn:

(i) Wood ash reduces the plasticity and maximum dry density of clay, while more water is required for the agglomeration and flocculation of clay particles through cation exchange reaction and coagulation with the consequent reduction in the amount of fines.

(ii) Ash stabilization causes an increase in unconfined compressive strength in the soft clayey soil, and 10% wood ash-clay mixture optimizes the results. The larger the ash percentage inserted, the greater the strength is.

(iii) There is a sharp improvement in the shear strength parameters with the addition of wood ash. The angle of internal friction has witnessed an improvement of about 85% for 10% cement addition, while the cohesion value has an improvement of only about 6% for 10% ash addition.

(iv) From the consolidation test result, it can be concluded that the values of the compression index decreased with the increases of wood ash content and the initial void ratio increases for the ash-treated soil.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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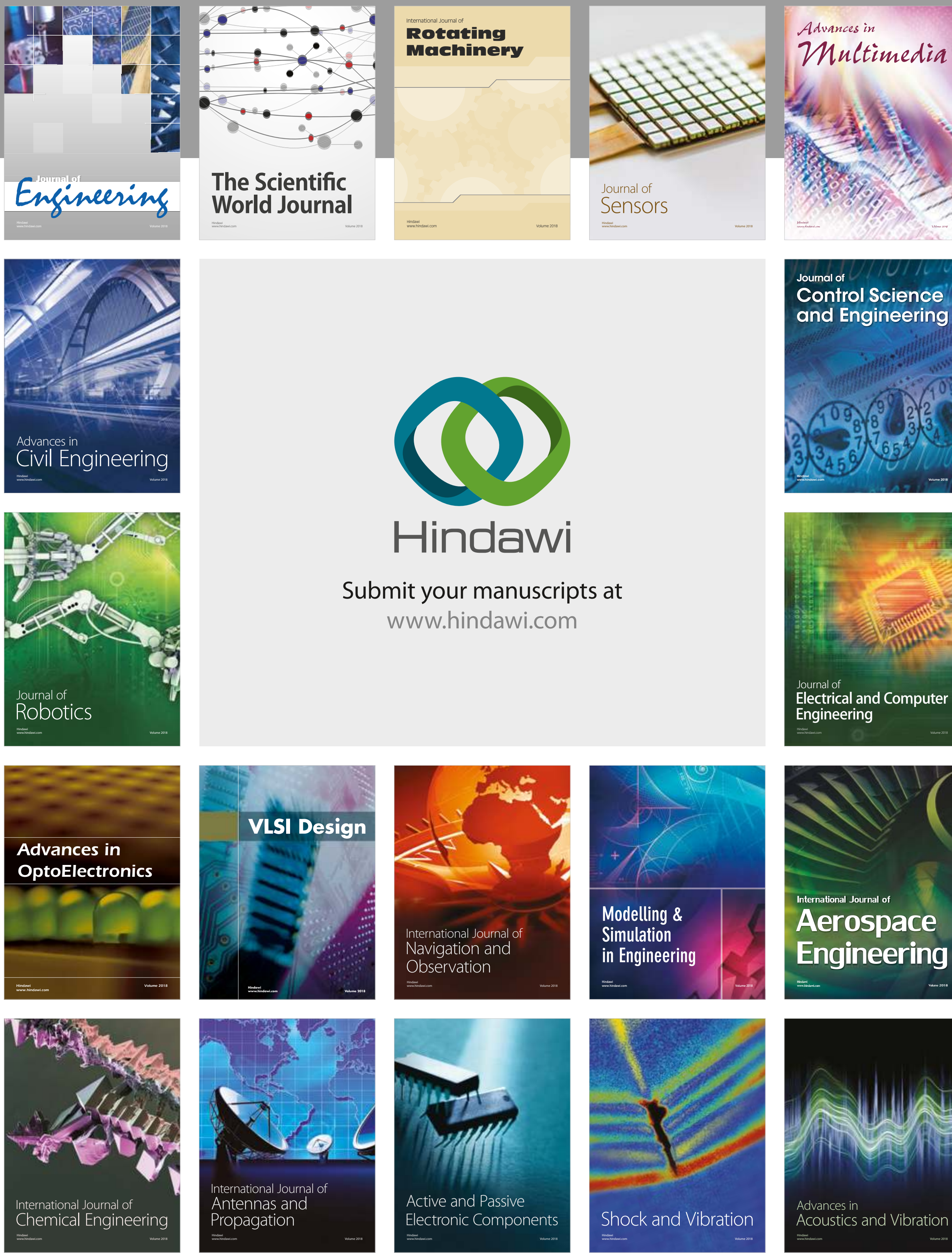
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