





Effect of Seawater on the Mechanical Strength of Geopolymer/Cement Stabilized Sandy Soils

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Abstract. Freshwater supply for stabilizing sandy soils is one of the significant challenges in coastal regions. On the other hand, Ordinary Portland cement (OPC) has several limitations in the exposure to saline environments. Geopolymers, as environmentally friendly soil stabilizers, have been widely used in soil stabilization research. In this paper, the effects of natural seawater (SW) on the mechanical and microstructural properties of Portland cement/geopolymer stabilized sandy soils were studied. The soil samples were prepared with freshwater as reference samples. The impacts of binder type, slag replacement, curing duration, and curing conditions on the mechanical strength of stabilized soil samples were investigated. SEM images were used for microstructural analysis of the geopolymer stabilized soil samples. The results indicated that the use of seawater in stabilizing soil resulted in higher strength development in short-term (28 days) compared to the distilled water-based samples. However, seawater adversely affected the soil's long-term (90 days) strength. In addition, the strength of slag-based samples was generally higher than the strength of OPC and VA-based samples. Therefore, alkali-activated slag can be a potential replacement for OPC paste in stabilizing sandy soils. The SEM images revealed that using seawater led to the alteration of cementitious gels in comparison to distilled water.

Keywords: Portland cement · Geopolymer · Soil stabilization · Seawater

1 Introduction

The lack of access to fresh water and the high cost of providing fresh water in soil improvement projects have caused researchers to consider the use of seawater as an economic option in large scale projects [1]. Recently, seawater is being used more and more in soil stabilization techniques including deep mixing and jet grouting to reduce fresh water consumption. However, some researchers have looked into how soil-cement behavior is impacted by water salinity [2]. In this line, the microstructural and mechanical characteristics of Portland cement (OPC) stabilized saline soils were investigated in previous research [3]. The impact of NaCl on the mechanical properties and elastic modulus of clayey soil was investigated [4]. This study demonstrated that when water salinity increased, the strength of cement-clay samples with cement contents of less

than 15% reduced, but no changes were found in the modulus of elasticity [4]. The strength reduction was also observed in previous research where clayey soil was mixed with different saline contents [5, 6]. Furthermore, the cemented saline clay samples with lower salinity exhibited greater strength due to the clay-chloride-cement interparticle interaction [7].

According to previous research, an eco-friendly Portland cement substitute is required due to the insufficient mechanical qualities of Portland cement in stabilizing saline soils under marine conditions [8, 9]. Geopolymers are a type of alkali activated cements used as novel construction materials in various applications [10–13]. A previous study explored the possibility of using seawater to produce alkali activated cements [14]. In the alkali activated fly ash-based cement used in this research, the alkali activation procedure captured around 86.8% of the chloride present. Theoretically, it was predicted that any sodium ions left over after the alkaline activator would react with the structure's chloride to form NaCl and deposit on the N-A-S-H gel [1]. In other words, the chloride ions in alkali activated cement with seawater formed CaCl_2 and NaCl deposits, which either settled on the surface of N-A-S-H gel or were encapsulated in the geopolymer matrix [1]. CaCl_2 was found to be helpful in speeding up the early polymerization reaction of alkali activated cements, which could lead to the extra formation of N-A-S-H [14]. Investigation of using seawater instead of distilled water in alkali activated cements showed that alkali activated slag samples had much more superior performance than alkali activated fly ash samples in absorbing chloride ions [15]. Furthermore, it was found that changing the slag/fly ash ratio resulted in a change in the amount of chloride adsorption because the reaction products changed by changing this ratio in alkali activated slag/fly ash pastes [16]. In a different research, increasing the temperature enhanced the physical and chemical absorption of chloride ions in the gel matrix [17, 18]. Because N-A-S-H gel's capacity for chloride ion adsorption increased with rising temperature. In contrast to steam curing conditions, the quick evaporation of the alkaline activator in oven curing conditions resulted in dry shrinkage and microstructural fissures, which stopped the geopolymerization process and reduced mechanical strength. On the other hand, in a steam-curing environment, the steam kept the shrinkage process from drying up, preserving the samples' strength. The results of this study contributed to the potential of using seawater as well as sea sand in the manufacture of geopolymer concretes [2, 17–19].

Although past research shows the high potential of using sea water in the preparation of geopolymeric cements, however, comprehensive research has not yet been done to use geopolymeric cements prepared from sea water to improve problematic soils. Therefore, the impacts of binder type, slag replacement, curing duration, and curing conditions on the mechanical strength of stabilized soil samples were investigated in this study.

2 Materials and Methods

2.1 Soil and Raw Materials' Characterization

Portland cement (OPC) from Tehran Cement Company and ground granulated blast furnace slag (GGBFS or slag) from Sepahan Cement Company served as the raw materials. The Taftan region in Iran provided the volcanic ash (VA). Table 1 displays the chemical

Table 1. Chemical components of VA, slag, and OPC.

Oxide composition	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	Na ₂ O	MgO	TiO ₂	SrO	SO ₃	P ₂ O ₅	MnO	L.O.I
VA [wt.%]	53.89	8.96	20.31	3.44	1.91	5.15	1.42	0.50	0.07	0.26	0.22	-	3.79
GGBFS [wt.%]	34.86	36.59	13.93	0.20	1.01	-	6.04	1.91	0.08	2.70	-	1.45	1.19
OPC [wt.%]	18.42	61.46	5.23	3.60	0.88	-	2.73	0.36	0.09	4.10	-	0.19	2.90

L.O.I = Loss on ignition

Table 2. Mixture proportion.

Binder type	Slag replacement (%)	Curing time curing condition [day]	
Geopolymer	0, 50, 100	28, 90	DC*, OC [¥] , SC [฿]
OPC	—	28, 90	DC, OC, SC

compositions of the VA, slag, and OPC. The Caspian Sea provided the seawater used in this study. To make the 8M alkaline activator for alkali activated specimens, 99% pure sodium hydroxide (NaOH) pellets (Merck corporation; CAS number: 1.06482.1000) were combined with filtered water. The sandy soil used in this research was collected from the coast of the Caspian Sea. The selected soil was classified as SM based on USCS (Unified Soil Classification system) which consisted of 83% sand and 13% silt.

2.2 Sample Preparation

Table 2 shows the mixture proportion of prepared specimens in this study. Three different curing conditions were used in the study. Dry condition (DC) was related to a condition with temperature of 50 ± 2 °C and relative humidity of $15 \pm 2\%$. Optimum condition (OC) condition was related to a condition with temperature of 25 ± 2 °C and relative humidity of $95 \pm 2\%$ and saturated condition (SC) condition refers to a submerged condition of specimens in distilled water or seawater. To prepare alkali activated/Portland cement stabilized soil specimens, the soil was mixed with initial water (10 wt.% of the soil). After mixing the raw materials and alkali activator for 1 min, the provided slurry was added to the red escribed amounts of soil (binder/soil ratio of 0.3) and mixed for 5 min by hand mixing. Three sets of material testing were performed. Set 1 was used to study the effect of seawater as initial moisture, see Table 3. Set 2 was performed to study the effect of seawater as slurry, see Table 4. Set 3 was performed to study the effect of seawater as submerging solution, see Table 5.

2.3 Mechanical Strength

According to ASTM C109 [20], a universal testing machine was used to conduct a uniaxial compressive strength (UCS) test with a 50 kN load cell attached and a constant strain rate of 0.5 mm/min. For each measurement, three specimens were used, and the average of the measured compressive strengths was reported.

Table 3. Effect of seawater as initial moisture.

Series	Initial moisture	Slurry	Curing
Geopolymer	Distilled water (D), seawater (S)	Ditilled water	Distilled water
Portland cement	Distilled water, seawater	Ditilled water	Ditilled water

Table 4. Effect of seawater as slurry.

Series	Initial moisture	Slurry	Curing
Geopolymer	Seawater	Ditilled water, seawater	Seawater
Portland cement	Seawater	Ditilled water, seawater	Seawater

Table 5. Effect of seawater as submerging solution.

Series	Initial moisture	Slurry	Curing
Geopolymer	Seawater	Ditilled water	Distilled water, seawater
Portland cement	Seawater	Ditilled water	Distilled water, seawater

2.4 Microstructure Assessment

Scanning electron microscopy (SEM) was examined using the TESCAN Vega 3 instrument.

3 Results and Discussion

3.1 Unconfined Compressive Strength (UCS) Test Results

Figure 1 presents the effect of seawater as initial moisture on compressive strength of Portland cement and alkali activated stabilized soil specimens at various curing conditions. Slag-based samples showed the highest and VA-based samples showed the lowest 28 days and 90 days' mechanical properties in varoius curing conditions. Using seawater instead of distilled water led to an increment in short-term strength and a reduction in long-term strength in both geopolymer and Portland cement samples. D and S are abbreviations of distilled water and seawater, respectively, Figs. 1–3.

Figure 2 depicts the effect of seawater as slurry on mechanical properties of Portland cement and alkali activated stabilized soil specimens at various curing conditions. Similar to the using seawater as initial moisture, slag-based samples showed the highest short-term and long-term mechanical strength in various curing conditions. The negative effect of using seawater instead of distilled water on the long-term mechanical strength of both geopolymer and Portland samples is clearly visible. However, slag-based samples showed higher strength in comparison with OPC specimens.

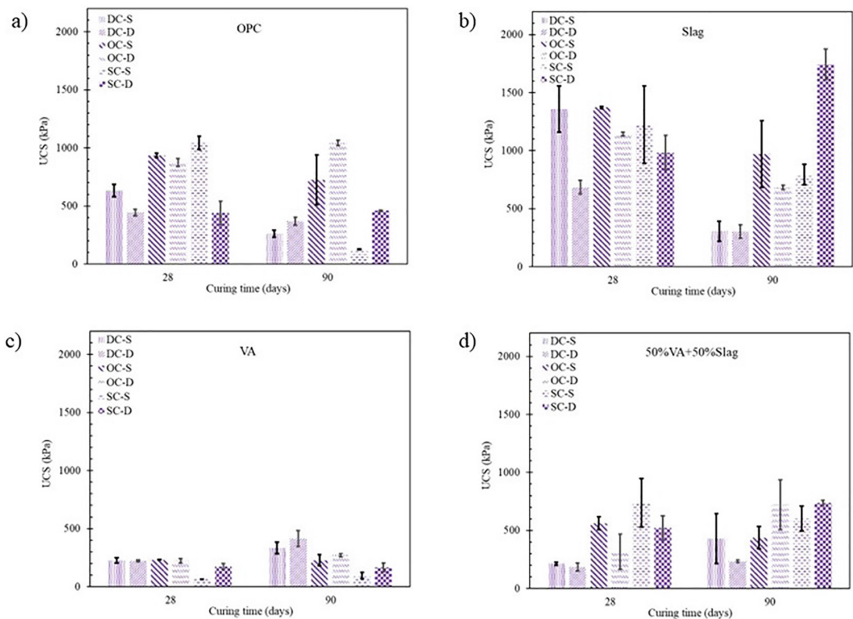


Fig. 1. Effect of seawater as initial moisture on compressive strength of a) Portland cement, b) alkali activated (100 wt.% slag), c) alkali activated (100 wt.% VA), and d) alkali activated (50 wt.% VA + 50 wt.% slag) stabilized soil samples under various curing conditions.

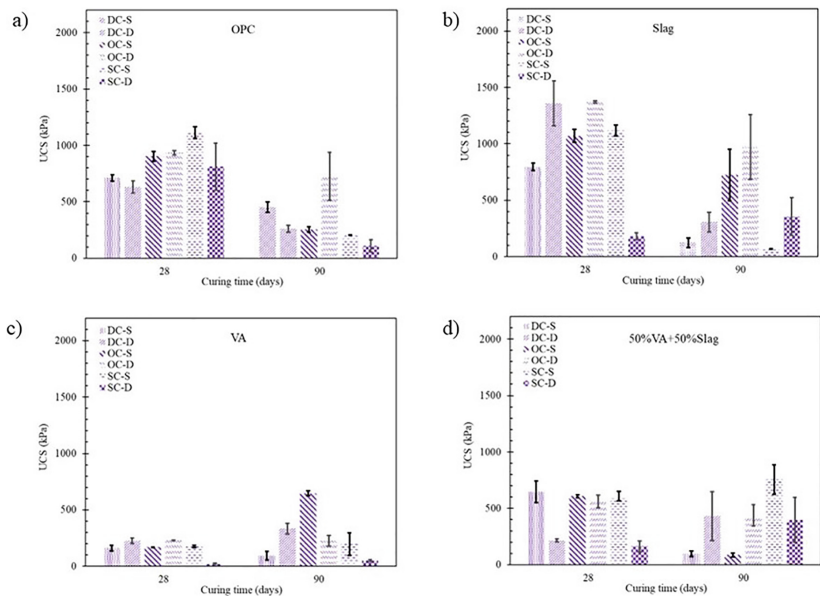


Fig. 2. Effect of seawater as slurry on compressive strength of a) Portland cement, b) alkali activated (100 wt.% slag), c) alkali activated (100 wt.% VA), and d) alkali activated (50 wt.% VA + 50 wt.% slag) stabilized soil samples under various curing condition.

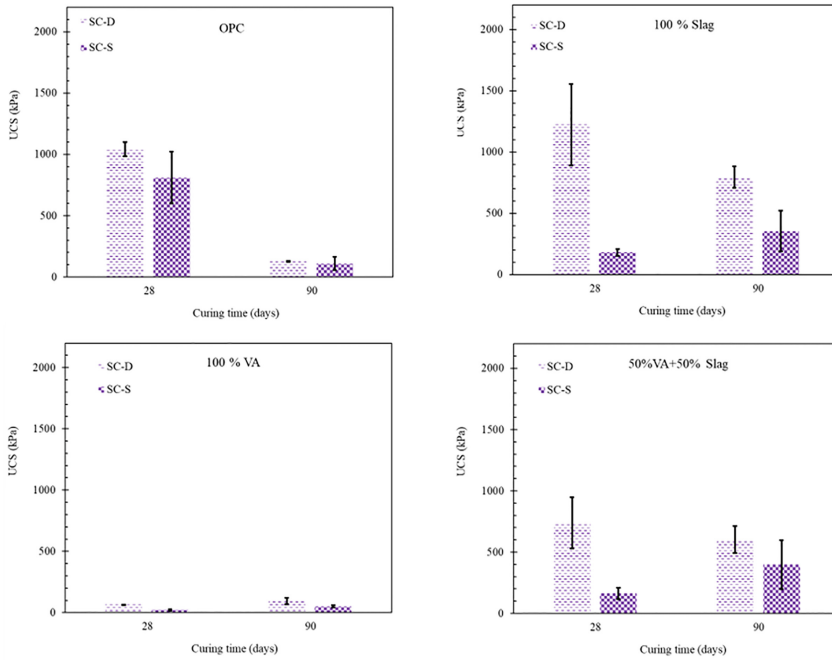


Fig. 3. Effect of seawater as curing solution on compressive strength of a) Portland cement, b) alkali activated (100 wt.% slag), c) alkali activated (100 wt.% VA), and d) alkali activated (50 wt.% VA + 50 wt.% slag) stabilized soil samples under various curing condition.

Figure 3 presents the effect of seawater as curing solution on compressive strength of Portland cement and alkali activated stabilized soil specimens at various curing conditions. Curing of geopolymer and Portland cement samples in seawater instead of distilled water resulted in a significant reduction in the samples' mechanical strength. Nevertheless, the curing of samples containing slag in seawater improved the mechanical strength over time.

3.2 Microstructural Analysis

SEM micrographs show the effect of seawater as initial moisture on microstructure of alkali activated volcanic ash stabilized soil specimens (after 90 days curing) at various curing conditions, see Fig. 4. Generally, the SEM images revealed that using seawater led to the alteration of cementitious matrix in comparison to distilled water at both curing conditions. The specimens prepared with seawater presented a porous microstructure in comparison with the corresponding samples prepared with distilled water that resulted in lower mechanical strength of samples prepared with seawater in long curing times.

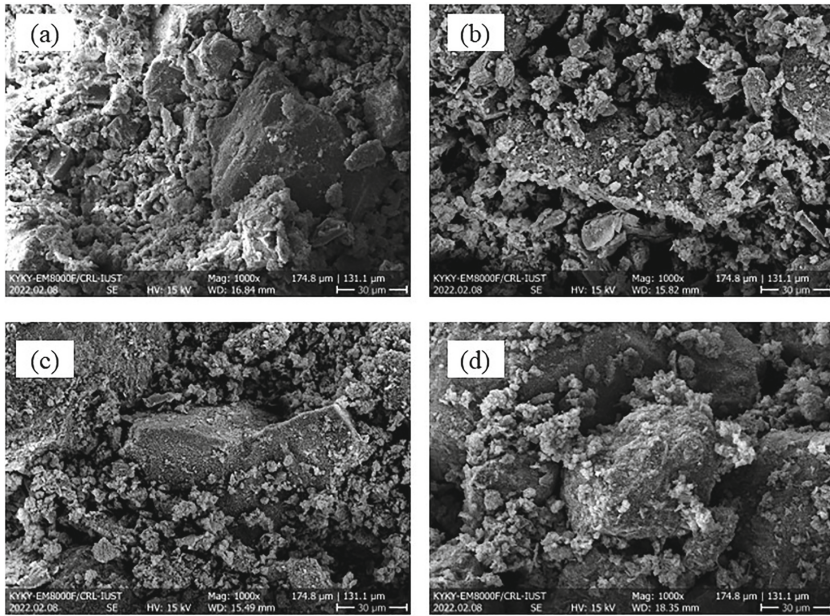


Fig. 4. SEM micrographs of alkali activated volcanic ash stabilized soil specimens (after 90 days curing) prepared with a) Distilled water at DC condition, b) Seawater at DC condition, c) Distilled water at OC condition, and d) Seawater at OC condition.

4 Conclusion

This paper studied the impact of seawater on the microstructural and mechanical properties of a sandy soil stabilized with alkali activated/Portland cement. The impacts of binder type, slag replacement, curing duration, and curing conditions on the mechanical strength of stabilized soil samples were investigated. The results indicated that the use of seawater in stabilizing soil samples resulted in extra strength development in short-term compared to the distilled water-based samples. However, seawater adversely affected the soil's long-term strength. In addition, the strength of slag-based samples was generally higher than the strength of OPC and VA-based samples. Therefore, alkali-activated slag can be a potential replacement for OPC paste in stabilizing sandy soils.

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