Avrupa Bilim ve Teknoloji Dergisi
Sayı 19, S. 484-496, Ağustos 2020
© Telif hakkı EJOSAT'a aittir
Araştırma Makalesi

www.ejosat.com ISSN:2148-2683

European Journal of Science and Technology
No 19, pp. 484-496, August 2020
Copyright © 2020 EJOSAT
Research Article

Using Sustainable Materials to Treat Free Shrinkage of Clay

Abdullah Ekinci[1*]

[1] Orta Doğu Teknik Üniversitesi, Kuzey Kıbrıs Kampüsü, İnşaat Mühendisliği Programı, Güzelyurt, Mersin 10, Türkiye (ORCID: 0000-0002-6787-9983)

(First received 8 May 2020 and in final form 15 June 2020)

(**DOI:** 10.31590/ejosat.734490)

ATIF/REFERENCE: Ekinci, A. (2020). Using Sustainable Materials to Treat Free Shrinkage of Clay. *European Journal of Science and Technology*, (19), 484-496.

Abstract

Global warming, pandemics, and poverty are the evidences of human destruction of the planet. Excavating and disposing of fertile soils destructively effect wildlife and nature and causes natural disasters such as fires and flooding leading to economic losses and casualties. This study investigates the effects of mechanical and chemical stabilization agents on the shrinkage of marine deposited clays. Three different sustainable material such as polypropylene fibers, wood ash, and copper slag were used to reduce cement usage in resisting shrinkage problem of the studied clay. The specimens were prepared in various combinations of 0.5-1% fiber, 5-7% cement and 10-20% wood ash and copper slag. Then, the prepared specimen was brought to a slurry state to produce a mix of adequate workability and erase the structure of clay to better highlight the effect of replacement materials. In a controlled environment, the specimens were subjected to free shrinkage and specimen height, diameter, and mass were measured at regular intervals until the dried condition was reached and no further change was monitored. The measurements were then averaged for each set of mix to calculate axial, radial, and volumetric shrinkage strains as well as weight loss. The obtained data were further statistically assessed by evaluating the individual impact of each controllable factor and second-order interaction of cement and fiber. The results indicated that a mix of 1% fiber and 7% cement performed best for reducing the volumetric shrinkage of the clay. Additionally, it was reported that 0.5% fiber addition is as effective as 7% cement in reducing volumetric shrinkage. Furthermore, replacing cement with 10% wood ash was observed to reduce volumetric shrinkage much more effective then other contents of wood ash and copper slag. The availability of aluminous elements in clay accelerated the chemical interaction with cement and wood ash particles, forming a densified composite structure. This interaction appears to isolate the available moisture in the particles and restrict weight loss, resulting in reduced volumetric shrinkage of wood ash treated specimens. In addition to the environmental and economic benefits of cement usage reduction, using harmful waste materials such as recycled polypropylene fiber, wood ash, and copper slag enable their safe disposal. Incorporating such materials in-situ requires no specific tools; field application is conventional and straightforward.

Keywords: Shrinkage, Clay, Analysis of variance, Cement, Wood ash, Copper slag

Sürdürülebilir Malzemelerin Büzülen Killerin İyileştirilmesinde Kullanimi

Özet

Dünyamız her geçen gün kirlenmeye devam etmektedir. Sürdürülebilir olmayan tüketim alışkanlıklarmız nedeniyle , doğal kaynaklarımız tükenirken doğaya geri dönülmez tahribatlar vermekteyiz. Bu tahribatlardan sıkça karşılaştığımız,üzerine inşası mümkün olmayan zeminlerin kazılıp doğal hayata kontrolsüzce dökülmesi ve bunun sonucunda ortaya çıkan çevre tahribatıdır. Oluşan durum, özellikle büzülen killerin varlığı üzerinde inşa edilen yapılara zarar vermektedir. Bahse konu zeminlerin büzülme problemlerinin önlenebilmesi amacıyla, bu çalışmada sürdürülebilir malzemelerin kullanımı ön plana çıkartılmıştır. Çalışma kapsamında geri dönüştürülmüş polipropilen fiber, odun külü ve bakır cürufu sırası ile fiziksel ve mekanik katkı malzemeler olarak kullanılmıştır. Yine en etkili iyileştirme yöntemlerinden biri olan çimento ile iyileştirme uygulanıp çimento kullanım miktarının

---

[*] Corresponding Author: Orta Doğu Teknik Üniversitesi, Kuzey Kıbrıs Kampüsü, İnşaat Mühendisliği Programı, Güzelyurt, Mersin 10, Türkiye (ORCID: 0000-0002-6787-9983), ekincia@metu.edu.tr

sürdürülebilir malzemeler vasıtası ile azaltılması amaçlanmıştır. Yeniden yapılandırılan kil, çimento, fiber, çimento ile fiber, çimento ile odun külü ve çimento ile bakır cürufu karışımları farklı oranlarda hazırlanıp serbest büzülme deneyine tabi tutulmuşlardır. Deney süresince hazırlanan örneklerin yükseklik, çap ve ağırlıkları kaydedilerek yatay, dikey ve hacimsel büzülme yüzdeleri yanında ağırlık kaybı yüzdeleri değerlendirilmiştir. Elde edilen veriler ışığında bir-yönlü varyans analizi ve iki-yönlü varyans analizi modelleri oluşturulmuştur. Yapılan istatistiksel analizler sonuçunda, %0.5 oranında sadece fiber katkının %7 oranında sadece çimento katkı kadar etkili olduğu bunun yanında %7 çimento ile %1 fiberlerin bir arada kullanılması ile büzülmeyi engellemede en etkili karışım olduğu gözlemlenmiştir. Söz konusu iyileşmenin çimento ile fiberlerin bir arada kullanılması sebebi ile çimentonun fiber yüzeyini kaplaması ve yüzeyde oluşan gerilmeleri fiberlerin parlak yüzeylerine nazaran artırmasından dolayı olduğu görülmüştür. Kulanılan çimento mikatarını %10 ve %20 oranlarında azaltarak, odun külü ve bakır cürufu olarak değiştirilmesi neticesinde odun külünün %10 oranında, bakır curufuna nazaran daha etkili olduğu gözlemlenmiştir. Odun külü ile kildeki alüminin kimyasal etkileşimi hızlandırarak yoğunlaştırılmış kompozit bir yapı oluşturarak parçacıklar içindeki mevcut nemi izole edilerek ağırlık kaybını engelleyip hacimsel büzülmeyi azalttığı görülmüştür. Odun külü ve bakır cürufunun çimento iyileştirmeye nazaran etkisinin az olmasına rağmen çimento kullanımının azaltılması ve bahse konu malzemelerin atık oldukları ve bertaraf edilecekleri düşünüldüğü zaman, killerin büzülmesinin önlenmesinde kullanımları mümkündür.

Anahtar Kelimeler: Büzülme, Kil, ANOVA, Çimento, Odun külü, Bakır curufu.

1. Introduction

Global warming, pandemics, and poverty are evidence of human destruction of the planet. The rate of construction is causing destruction of nature through the excavation and disposition of fertile soils because they are unsuitable for construction activity. This causes natural disasters such as fires and flooding, which in turn yields economic losses and casualties. Construction meets the basic human need for shelter. Similarly, human consumption generates mountains of waste that contaminate clean water resources, cause disease, and lead to economic loss. Due to technological advancement, humans need electricity for daily life. Nowadays, biomass power plants are replacing coal and fuel oil in power generation plants. These biomass power plants generate wood ash (WA), which contaminates resources and endangers humankind. And finally, humankind open mines to obtain this valuable material to use in electronic consumables wherein return this hazardous waste of copper slag (CS) is produced that endanger humankind. It is quite clear that all those activities not just destroying humankind, but it also endangers all living organisms on planet earth. Therefore, our generation must find more sustainable construction materials and methods. In this study, the abovementioned waste materials recycled polypropylene fiber, WA, and CS will be incorporated into unsuitable, highly shrinking clay to enable its use in the construction sector.

Problematic soils exist worldwide; particularly, soils with shrinkage and swell potential cause major problems. Keskin et al. (2006) reported that these soils cause structural damage when changes in water content through environmental variations cause swelling and shrinkage beneath structures. Buhler and Cerato (2007) stated that damage to structures caused by the swelling and shrinkage response of soils exceed the annual average combined damage caused by other natural hazards such as floods, earthquakes, and storms. Such volumetric changes in structures are known to cause settlement and heave. Cheng (1988) evaluated the effects of expansive clays on structures through several case studies. Similarly, Clayton et al. (2010) studied damage to infrastructure assets such as pipelines and roads due to seasonal swelling and shrinkage of clay.

Ample research has been conducted on overcoming the damages caused by swelling and shrinkage of clay. Fibers were reported to be the most performance-effective, cost-effective, and environmentally acceptable option. Miller and Rifai (2004) and Abdi et al. (2008) used the discrete polypropylene fibers and reported that fiber usage resulted in reduced crack formation and volumetric change. Similarly, Puppala et al. (2000) used free swelling and swell pressure tests to study the effects of two types and ratios of polypropylene fiber incorporation on volumetric shrinkage. It was concluded that the addition of fibers decreased the swell pressure and volumetric shrinkage. Furthermore, Rifai & Miller (2004) and Tang et al. (2007) reported that fiber incorporation reduced crack formation. The authors also stated that, as the cracks start to form in fiber-reinforced specimens, fibers across the cracks stretch and develop tension through frictional force developed between the soil and fiber interface, which resists crack development. Ziegler et al. (1998) reported that above a certain limit, fiber content causes void development and encourages crack development. Furthermore, Fatahi et al. (2013) investigated the responses of recycled carpet and monofilament polypropylene on the three-dimensional shrinkage properties of cement-stabilized bentonite and kaolinite clays and reported that fiber and cement blending is effective for reducing volumetric change in clayey soils subjected to drying.

The two other additives used in this study are WA and CS; few studies have used these materials as cement replacements for reducing shrinkage of problematic soils. Nevertheless, researchers have extensively utilized CS for applications in the concrete industry. Siddique (2012) used WA in concrete manufacturing. Authors have reported that the WA quality is largely dependent on tree species, burning temperature, and available moisture content during cutting operations. The authors further stated that the factor governing composite behavior is related to the calcium–silica (Ca/Si) ratio. As this ratio increases, so does expansion. Furthermore, it was determined that crack growth is minimized as the Ca/Si ratio is reduced (Lothenbach and Nonat, 2015; Kunther et al., 2015). Based on previous findings, Siddique et al. (2019) and Lothenbach and Nonat (2015) stated that a high amount of silica reduces the system pH by reducing the Ca/Si ratio while creating higher density when the ratio is high. Moreover, Shi and Lothenbach (2019), Lothenbach and Nonat (2015) and Kunther et al. (2015) reported that the adding WA to concrete increased the water demand, thus ensuring internal curing and facilitating better bond formation later. Due to poor pozzolanic activity and the filler effect of WA, the strength was improved beyond 90 days. The silica/alumina (Si/Al) ratio also plays an important role in strong bond development by increasing the structure stability. Many studies have indicated the presence of Portlandite and ettringite needles. Crystalline phases are mostly dominated by calcium atoms and show pozzolanic activity, which facilitates densification and stabilizes the microstructure with fewer cracks. Tobermorite gel in WA can be considered semicrystalline and calcium silicate hydrate gel is considered amorphous. Mullite crystals affect the durability properties of the composites (Stolz et al., 2019; Mehta and Monteiro, 2017; Kunther et al., 2015; Siddique, 2014). The incorporation of WA increases water demand and creates internal pressure inside the matrix. If this pressure continues to increase, the structure of the composite deteriorates.

More recently, Ekinci et al. (2019) studied the strength and microstructural behavior of CS used as a cement replacement in cement-stabilized marine clay and reported relative pozzolanic activity of CS over long term. Al-Rawas et al. (2002) investigated the swelling potential of CS to treat expansive clay and monitored a substantial increase in the swelling potential of the specimens. The authors further reported that the high Na^+ content in CS probably increased the swell potential of soil. Mobasher et al. (1996), Taha et al. (2004), Pavez et al. (2004), Al-Jabri et al. (2006), De Rojas et al. (2008), and Bharati and Chew (2016) reported that CS can be used as a partial cement replacement in concrete; strength increases due to the pozzolanic property of CS. In contrast, Zain et al. (2004) and Shi et al. (2008) investigated the leachability of heavy metals from CS as bulk and reported that it was lower than the Malaysian Environmental Quality Orders and USEPA standard limits.

This study investigated the effects of mechanical and chemical stabilization activities on shrinkage. This is the first study to evaluate the shrinkage behavior of high calcium carbonate content marine clays by investigating the individual impact of each controllable factor and the second-order interaction of cement and fiber. Besides the environmental and economic contribution of cement usage reduction, using waste material such as recycled polypropylene fiber, WA, and CS will enable safe disposal of those harmful materials. Onsite incorporation of these materials does not require any specific tools; field application is conventional and straightforward.

2. Experimental Program

The adopted methodology and the details of the used materials are provided herein. Three different sustainable materials were used to reduce the cement used in resisting the shrinkage problem of studied clay. These materials are polypropylene fiber, WA, and CS. For this study, clay only and clay treated with 5 and 7% cement were tested first. Following those specimens, quantities of 0.5 and 1% polypropylene fiber, WA, and CS in 10 and 20% quantities were used as replacements for cement to treat the clay; 51 specimens (three specimens per mix) were produced for free shrinkage testing. The quantities of all replacing materials were expressed as percentages of the dry weight of the cement. The chosen quantities were determined in accordance with previous studies on micromechanical and strength behaviour of similar materials (Ekinci et al 2020; Ekinci 2020). Table 1 summarizes the mixes used in this study. Designations were also determined as CA-Clay, CF- Clay + Fibre, CC – Clay+Cement, CCF- Clay+Cement+Fiber, CCWA – Clay+Cement+Wood Ash and CCCS- Clay+Cement+Copper Slag.

Table 1. Specimen details

Mix	Designation	No. of specimens	Cement content (%)	Fiber content (%)	Wood ash content (%)	Slag content (%)
Clay	CA	3	0	0	0	0
Clay/0,5%Fiber	CF0.5	3	0	0.5	0	0
Clay/1%Fiber	CF1	3	0	1	0	0
Clay/5%Cement	CC5	3	5	0	0	0
Clay/7%Cement	CC7	3	7	0	0	0
Clay/5%Cement/0,5%Fiber	CC5F0.5	3	5	0.5	0	0
Clay/5%Cement/1%Fiber	CC7F1	3	5	1	0	0
Clay/7%Cement/0,5%Fiber	CC7F0.5	3	7	0.5	0	0
Clay/7%Cement/1%Fiber	CC7F1	3	7	1	0	0
Clay/5%Cement/10%Ash	CC5WA10	3	5	0	10	0
Clay/5%Cement/20%Ash	CC5WA20	3	5	0	20	0
Clay/7%Cement/10%Ash	CC7WA10	3	7	0	10	0
Clay/7%Cement/20%Ash	CC7WA20	3	7	0	20	0
Clay/5%Cement/10%Slag	CC5CS10	3	5	0	0	10
Clay/5%Cement/20%Slag	CC5CS20	3	5	0	0	20
Clay/7%Cement/10%Slag	CC7CS10	3	7	0	0	10
Clay/7%Cement/20%Slag	CC7CS20	3	7	0	0	20

2.1. Materials

2.1.1. Soil

The soil used in this study is widely found in marine deposit clays around the Eastern Mediterranean and Northern Cyprus coasts. Marine clays are well known to be poor for engineering applications. The identifying geotechnical properties of marine clays are high shrinkage/swelling potential, low unconfined compressive strength, low shear strength, high compressibility resulting in extensive settlements, structural damages, and engineering performance uncertainty (Rajasekaran & Rao, 1997; Rao, Anusha, Pranav & Venkatesh, 2012; Venkateswarlu, Kumar, Raju & Prasad, 2014; Al-bared & Marto, 2017; Ekinci, Filho & Consoli, 2019). Table 2 describes the physical properties of the clay, WA and CS used in this study. Atterberg limit, sieve analysis, specific gravity, and unified soil classification were performed in accordance with the ASTM D 4318 (ASTM, 2017a), ASTM D6913 / D6913M-17(2017), ASTM D 854 (ASTM, 2014), and ASTM D2487 (ASTM, 2017b) standards, respectively. To check the consistency of the performed specimens, the abovementioned tests were performed for every other batch of specimens.

Table 2. Physical properties of marine deposited clay, wood ash, and copper slag

Properties	Marine clay	Wood ash	Copper slag
Liquid limit (%)	40	-	-
Plastic limit (%)	20	-	-
Plasticity index (%)	20	-	Nonplastic
Specific gravity	2.62	1.71	3.45
Fine gravel, 4.75 mm < diameter < 20 mm (%)	-	-	0
Coarse sand, 2.00 mm < diameter < 4.75 mm (%)	3	-	10
Medium sand, 0.425 < diameter < 2.00 mm (%)	2	-	82
Fine sand, 0.075 mm < diameter < 0.425 mm (%)	26	100	8
Silt, 0.002 mm < diameter < 0.075 mm (%)	20	-	0
Clay, diameter < 0.002 mm (%)	49	-	0
Mean particle diameter (mm)	0.0036	0.19	0.9
USCS class	CL	SM	SP

Figure 1 shows the grain size distribution of marine clay, WA, and CS. It is apparent that marine clay comprises 49% of the clay fraction, whereas the remaining portion is mainly composed of fine sand.

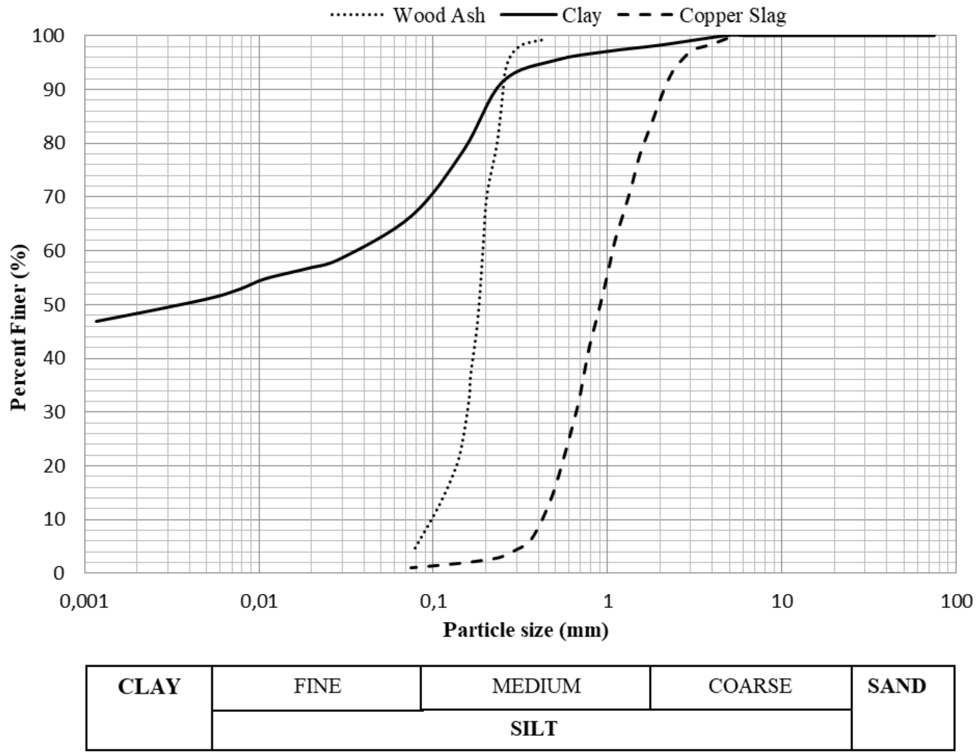

Figure 1. Grain size distribution of studied clay, copper slag, and wood ash.

2.1.2. Cement

The cement used in the study was Portland cement (C) Type I, as specified in C150 (ASTM, 2018). The Blaine fineness of cement is 289 m^2/kg. The X-ray fluorescence spectrometry (XRF) enabled the chemical composition identification of the Portland cement, WA, and CS used, as shown in Table 2. The main components of the cement are calcium oxide and silica.

Table 3. Chemical analysis of Portland cement, wood ash, and copper slag

Compound	Portland cement (%)	Wood ash (%)	Copper slag (%)
SiO_2	20.72	18.1	32.8
Al_2O_3	5.02	3.3	8.3
Fe_2O_3	3.5	2.8	43.5
CaO	63.94	44.4	4
MgO	1.21	2.8	3.5
K_2O	0.2	5.2	0. 4
SO_3	1.5	0.9	2.3
Loss on ignition	2.5	22.1	5.1

2.1.3. Copper Slag

CS was taken from the Lefke region of Northern Cyprus, which was once famous for its copper mine that was abandoned in the 1970s. A residue of the copper extracting process, the CS deposits were haphazardly dumped around the region, creating environment hazards due to the heavy metal content and leaching characteristics. However, using small percentages of CS in low-permeability soil would not cause any harm. Figure 1 shows that the incorporated CS was granulated to medium-sized sand with poorly graded particles. Furthermore, as shown in Table 2, similar to marine clay and WA, CS has a high percentage of silica but mainly composed of iron oxide.

2.1.4. Wood Ash

The WA used in this study was obtained from the remnants of pruned and burned olive trees. Tombesi (2013) stated that tree pruning enables light penetration and air circulation, preventing fungal and bacterial diseases that develop easily in humid environment. Furthermore, Rodrigues et al. (2018) stated that pruning helps to remove dead and unproductive wood, boosting the growth of new productive branches and preventing aging of the tree. Moreover, Lodolini et al. (2019) reported that controlled pruning both decreases the alternation of production that naturally affects the olive and also helps to manage the plant size to maintain safe harvest conditions. Using WA as a soil stabilization agent will reduce ash disposition in the landfill and will offer new economic benefits and employment opportunities. Currently, approximately 70% of WA is landfilled, whereas 20% is used as an agricultural soil supplement and 10% is employed in other uses, mainly metal recovery and pollution control (Campbell 1990; Etiegni and Campbell 1991).

The WA used in this study can be classified as silty sand (SM) and consists of mostly uniform silt size particles having a mean particle size of D_{50} = 0.19 mm (Figure 1 and Table 1). The chemical composition results presented in Table 2 show that, like cement, WA mainly consists of calcite and silica. The specific gravity can vary depending on the source and heat of combustion, as explained by Naik et al. (2003). Therefore, specific gravity tests were performed on each portion of provided WA, and an average value of 1.7 was considered (variation of $G_s < 0.02$).

2.1.5. Fiber

The fiber used in this study was waste recycled polypropylene type tape fiber, which is the commonly used synthetic material because of its low cost and environmental acceptability. The fibers are 4 mm wide, 63 mm long, and approximately 0.021 mm thick. The physical properties are shown in Table 4.

Table 4 – Physical properties of fibers

Properties	***Values***	***Properties***	***Values***
Melting point	*165 °C*	*Breaking tensile strength*	*350 MPa*
Moisture absorption	*0%*	*Specific gravity*	*0.91 g/cm3*
Dispersibility	*Excellent*	*Burning point*	*590 °C*
Elastic Modulus	*3500 MPa*	*Linear mass density*	*60 Denier**

2.2. Methods

2.2.1. Molding and Curing of Specimens

Clay specimens brought to the laboratory were dried at 60 °C and granulated with a mortar and pestle down until they were able to pass through a No. 20 sieve.

For the cement-only treated specimens, cement was added in the percentage of the dry weight of clay. Specimens with fibers as cement replacement required extra attention to avoid flocculation and lumping of fibers. Fiber, WA, and CS-replaced specimens were considered to be replacing a percentage of cement and specific gravity differences were considered during the calculation of replacing material weights. All specimens were prepared in batches for three specimens and were first thoroughly hand- mixed in dry conditions to ensure homogeneous mixing.

The prepared blend was then thoroughly hand mixed by adding 75% water, which is nearly 60% more than the liquid limit, bringing the specimen to a slurry state (Burland, 1990). This process was necessary for producing an adequately workable mix and erasing the clay structure to better highlight the effects of replacement materials.

The resulting mixtures with reasonable workability were placed in cylindrical split molds with 150 mm diameters. Specimens were 45 mm height in layers and flattened with a spatula. Molds were placed on a vibration table to expel the trapped air. Subsequently, the tops of the split molds were covered with stretch film to minimize moisture loss and assist the cement hydration process. Finally, specimens were cured for seven days in a humidity chamber with relative humidity of approximately 95% and 24 ± 2 °C (ASTM C511, ASTM 2013). After curing and just before the shrinkage tests, the weights and dimensions of the specimens were recorded. Notably, no significant volumetric or weight change was measured after the curing period, as the specimens were fully saturated prior to curing. Figure 2 shows the specimens after molding and casting.

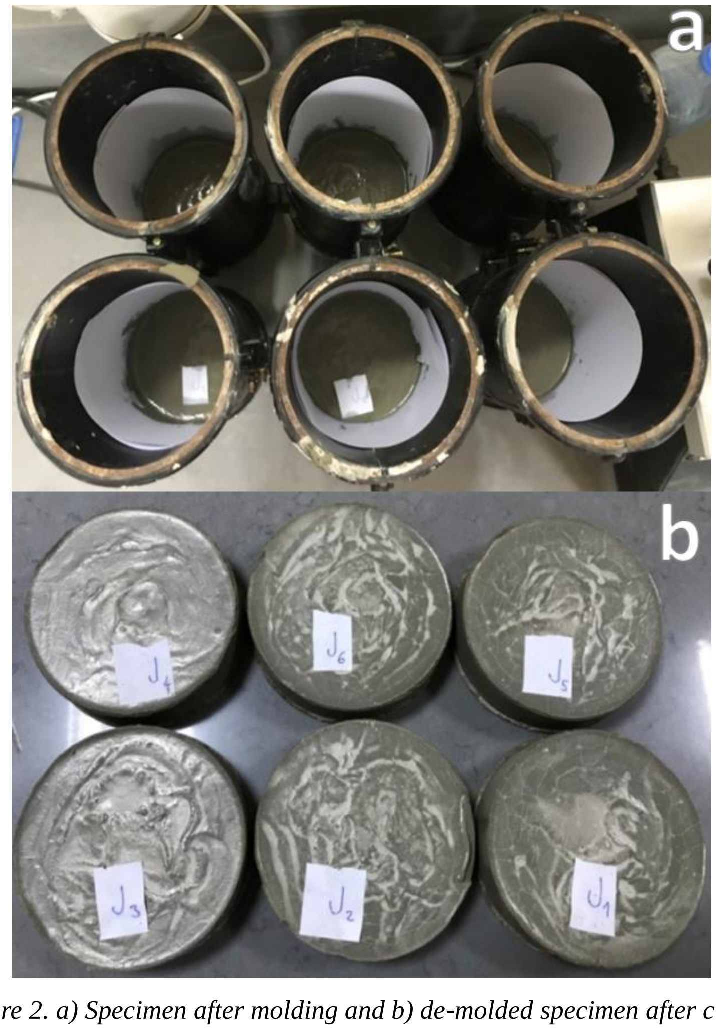

Figure 2. a) Specimen after molding and b) de-molded specimen after curing

2.2.2. Free Shrinkage Measurement

Once cured, the de-molded specimens were allowed to dry in accordance with ASTM C 157 (2008). Specimens were stored in a cabinet where humidity and temperature were retained at 45% and 24 ± 2 °C, respectively. At regular three-day intervals, the height, diameter, and mass of each specimen was measured until reaching a dried condition, after which no further change was monitored. To obtain precise measurements, 45 measurements of diameter and height of the specimen were taken at 10 mm intervals using a digital Vernier caliper. To improve accuracy, specimen dimensions were measured at the same location for each observation. The obtained measurements for each set were then used to calculate the axial, radial, and volumetric shrinkage strains using Eqs. 1, 2, and 3, respectively. Furthermore, the specimen weight loss was calculated using Eq. 4.

Axial Shrinkage Strain:

$$\varepsilon_{as} = \frac{h_i - h_f}{h_i} \tag{1}$$

Radial Shrinkage Strain:

$$\varepsilon_{rs} = \frac{D_i - D_f}{D_i} \tag{2}$$

Volumetric Shrinkage Strain:

$$\varepsilon_{vs} = \frac{V_i - V_f}{V_i} = \varepsilon_{as} + 2\varepsilon_{rs} \tag{3}$$

Weight Loss (%):

$$WL = \frac{W_i - W_f}{W_i} x100 \tag{4}$$

where, h_i, D_i, V_i, and W_i are initial volume, height, diameter, and weight of the specimens, respectively; h_f, D_f, V_f, and W_f are the final (dry condition) height, diameter, volume, and weight of the specimens, respectively.

3. Results and Discussion

3.1. Influence of the Replacement Material on the Shrinkage of the Mixes

In this study, two different replacing agent sets were adopted to treat the shrinkage of the clay. In the first approach, a mechanical material such as a fiber was used to enable the development of friction between the fiber surface and clay, which then provides tensile strength. In the second approach, chemical stabilization agents, such as WA and CS, have been incorporated as cement replacements that have pozzolanic nature.

3.1.1. Mechanical Replacement Material

Figure 3 shows axial, radial, and volumetric shrinkage percentages of CA, CF, and CC used as control mixtures, as well as those of CCF mixes, which represent a newly proposed blend to treat subjected clay. Figure 3 shows that the addition of fiber substantially reduced the shrinkage of clay, with 0.5% fiber addition seems to be more effective in comparison to 1% addition. This might be due to increase of fiber content resulting in loss of fiber soil contact area where in return result in restricted friction development. Furthermore, the addition of 5% cement proved to be not as effective as the fiber alone treatment. However, increasing the cement content to 7% revealed to be as effective as adding fiber. In contrast, mixing both fiber and cement seems to further reduce clay shrinkage. Thus, it can be determined that adding any percentage of fiber to 5% cement produces the same volumetric shrinkage response. Compared to the volumetric changes of the fiber and cement only treatments, it is clear that the shrinkage reduction effect in 5% CCF mixes is due to the effect of adding fibers rather than cement. However, further increase of cement content to 7% positively altered the behavior and resisted the clay shrinkage. Clearly, a 1% fiber and 7% cement mix performed best for reducing the volumetric shrinkage of the clay. As stated by Atiyeh and Aydin (2020), it is believed to be due to the coating of cement on fibers, producing extra bonding strength between the fibers and clays, as fibers have shiny surfaces and might end up sliding.

As expected, radial and axial shrinkages showed parallel trends to volumetric changes. Figure 3 shows that reduction in volume is more pronounced in the radial direction, compared to axial direction shrinkage. This is because the major principal axes of the specimens are radial (150 mm) whereas the minor axis is (45 mm) axial. Furthermore, inspecting the specimens during preparation and after testing demonstrated that the fibers are mostly aligned horizontally. Therefore, this has restricted the shrinkage of specimens in radial direction. This can also be proven by comparing the CC specimens with CCF specimens where radial shrinkage of the specimens was double that of the CC specimens.

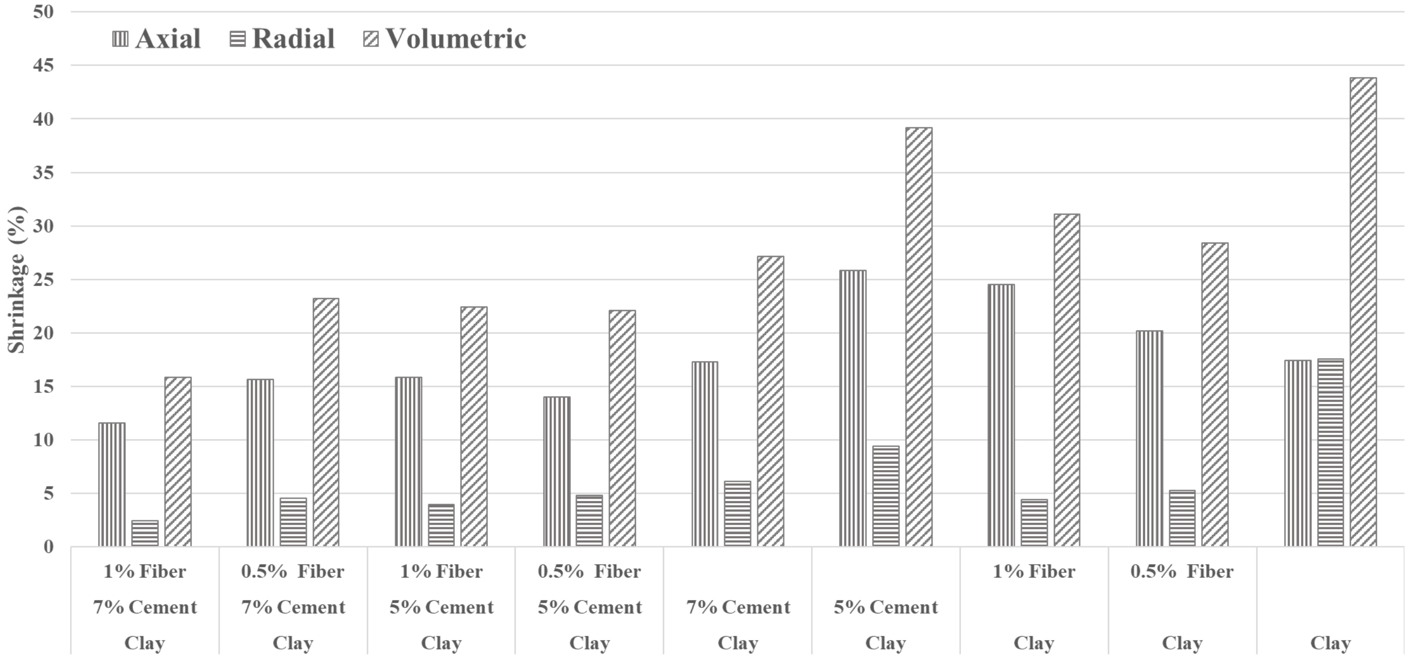

Figure 3. Axial, radial and volumetric shrinkage of CA, CF, CC, and CCF mixes.

Figure 4 shows the weight loss percentage of CA, CF, CC, and CCF mixes. Evidently, the clay only specimens experienced the most weight loss. Unlike the shrinkage behavior, the effect of this treatment on mass loss was minimal; the weight loss percentage ranged from 38.2–39.2%. However, it is interesting that increased fiber content leads to increased weight loss whereas the opposite is observed for cement. It seems that fibers function like a drainage line, leading moisture transfer from the specimens. Furthermore the trapped water between the pores were used in later reactions and lead to better bonding at fiber/soil interface. This effect was also confirmed in the CCF specimens, where increased fiber content caused increased weight loss of specimens regardless of cement content.

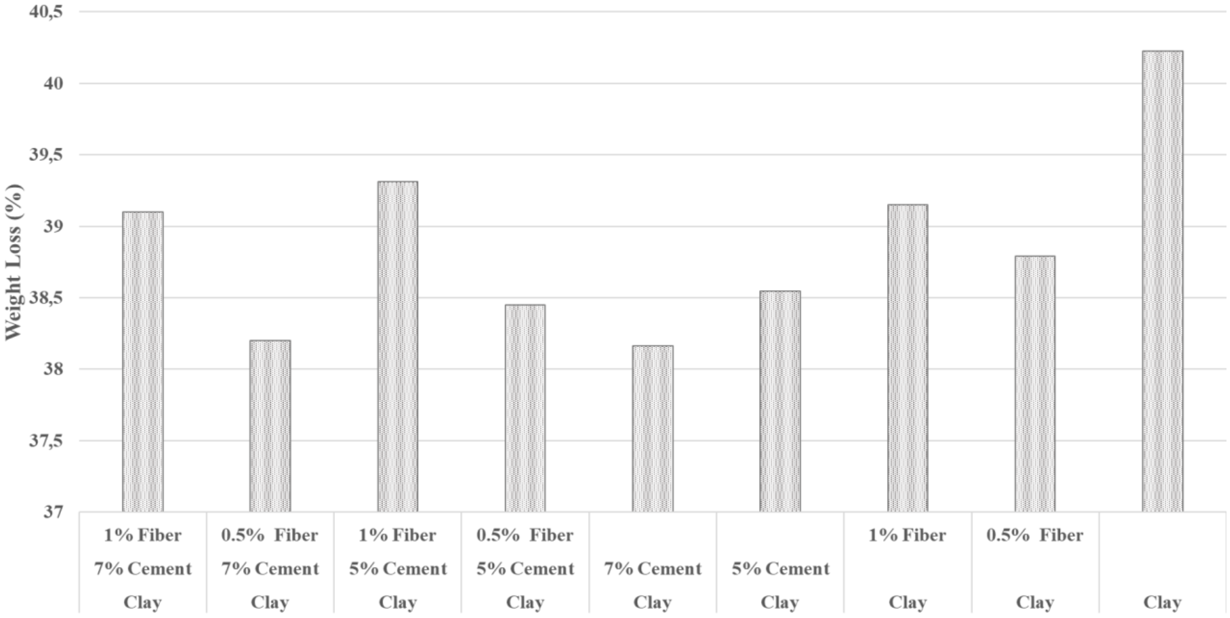

Figure 4. Weight loss percentage of CA, CF, CC, and CCF mixes.

3.1.2. Chemical Replacement Material

Axial, radial, and volumetric shrinkage of CS and WA-treated clay specimens are shown with control mixes in Figure 5. Clearly, the WA and CS-treated specimens are less effective than those treated with fiber; the addition of WA and CS caused only 5% variation in shrinkage. Interestingly, CS and WA replacement at 5% cement content seems to reduce the volumetric shrinkage of specimens, where an adverse effect is observed in 7% cement specimens. Therefore, the increase in additive content results in reduction of shrinkage prevention. It is important to limit the amount of WA and CS content to obtain the optimum performance. Moreover, the literature provides evidence that both WA and CS are pozzolanic materials; however, their contributions are greater as they age. It is also apparent from Figure 5 that there is more evidence of radial shrinkage than axial, although not as much as in the fiber-reinforced specimens. This observation further supports the earlier finding that fibers are the cause of the observed extensive shrinkage reduction in the radial direction.

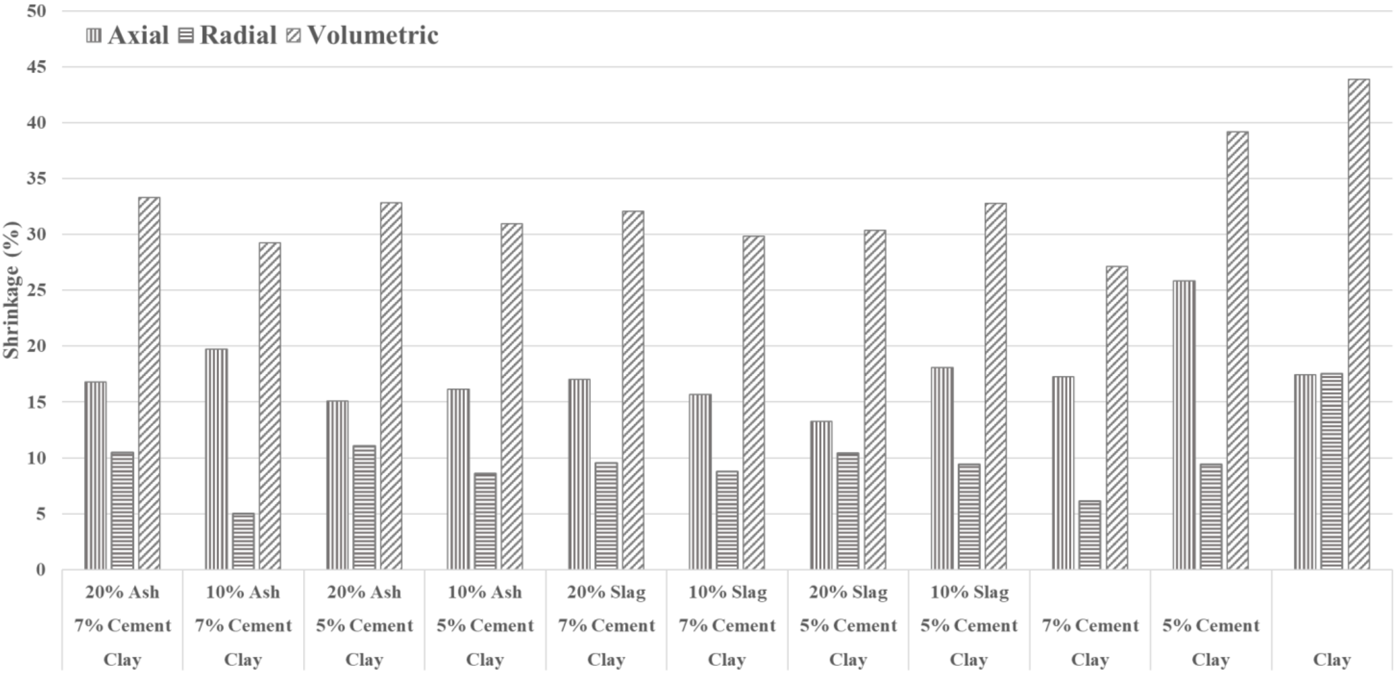

Figure 5. Axial, radial, and volumetric shrinkage of CA, CC, CCCS and CCWA mixes.

Figure 6 shows the weight loss percentage of CA, CC, CCCS and CCWA mixes. As reported earlier, the incorporation and increase of cement content encouraged weight loss. Figure 6 also shows that WA replacement reduced weight loss more than CS at the same percentage. Notably, increasing content resulted in increased weight loss for all percentages of replacement with CS and WA. However, WA resulted in the least weight reduction where such findings agreed with the volumetric responses of the specimens. Based on the XRF data, the clay particles used in this study contained mainly calcite ($CaCO_3$) and quartz (SiO_2) with some alumina and iron. The availability of aluminous elements in clay accelerates the chemical interaction with cement and WA particles to form a densified composite structure. Such occurrence seems to isolate the moisture available within the particles and restrict weight loss and result in the reduction of volumetric shrinkage. Moreover, Shi and Lothenbach (2019), Lothenbach and Nonat (2015), and Kunther et al. (2015) reported that the addition of WA increases the water demand to ensure internal curing and help to form better bonds in later stages, leading to increased stability of the structure.

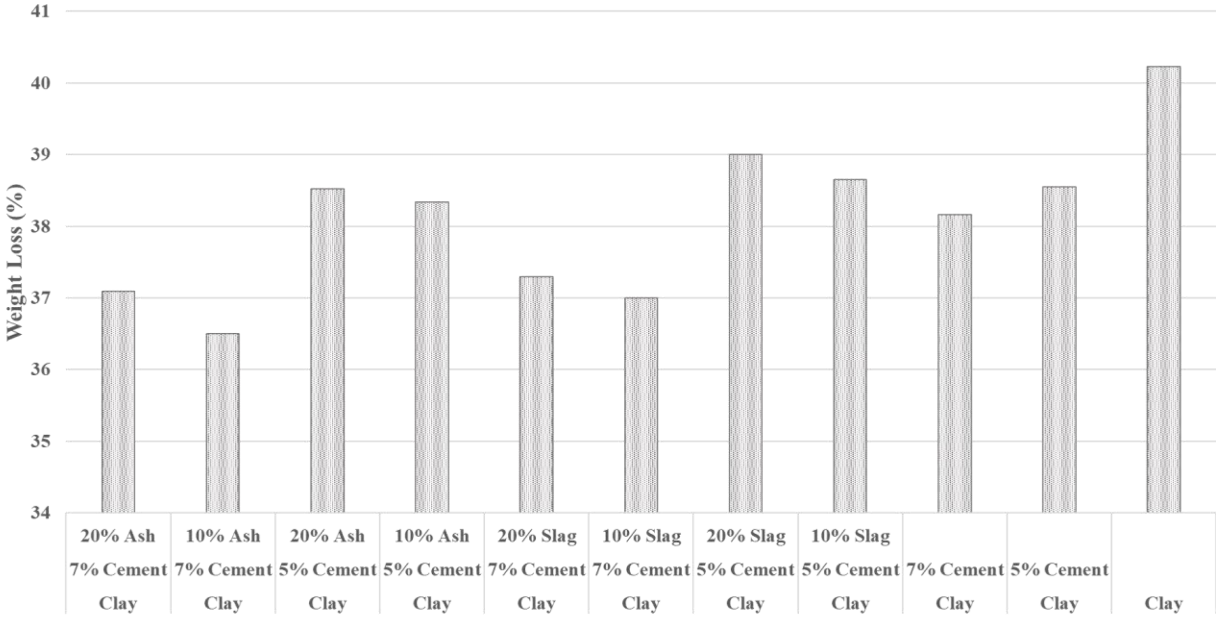

Figure 6. Weight loss percentage of CA, CC, CCCS and CCWA mixes.

3.2. Influence of Controllable Factors on the Shrinkage of the Mixes

To statistically assess the shrinkage behavior of each mix, the effect of individual controllable factors are evaluated corresponding to volumetric, radial, and axial shrinkage percentages. Controllable factors analyzed are cement, fiber, ash, and slag content where cement is added in percentage dry weight of clay but fiber, WA, and CS are mixed as replacement of cement. The analysis of variance (ANOVA) performed on each individual controllable factors and two-factor interaction of cement and fiber, were statistically significant at a significance level (α) equal to 5% (p-value < α).

Figure 7 shows the individual impact of each controllable factor on the shrinkage. Increased cement content is directly proportional to the reduction in volumetric shrinkage. In contrast, fiber incorporation is as effective as using only cement for the treatment. However, increasing the fiber-only content above 0.5% does not promise further effect. Furthermore, Figure 7 clearly shows that the 10% WA replacement offered a small, noticeable impact on the volumetric shrinkage compared with the cement and fiber only treatments. The incorporation of CS as cement replacement seems to have a null effect up to 20%. Although there was no improvement with 20% WA or 10/20% CS used as a cement replacement, such mixes still present shrinkage reduction, which can have economic and environmental benefits.

The axial and radial shrinkage responses of each controllable factor are parallel with the volumetric shrinkage behaviors. It can be determined from the axial shrinkage that the deviation of the measured values greatly exceeds the radial shrinkage values. This is because shrinkage in the axial direction was uneven compared to radial shrinkage measurements.

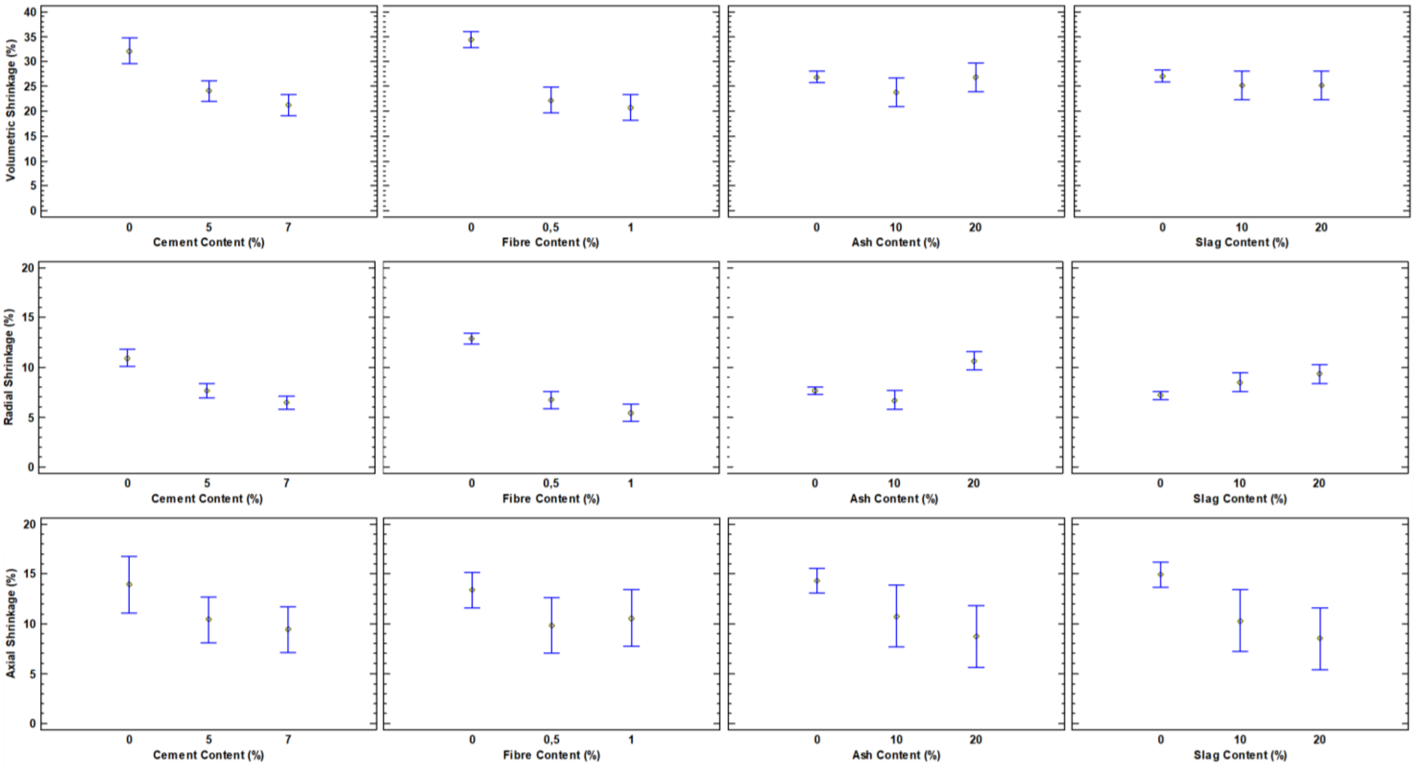

Figure 7. Main effects plot for volumetric, radial, and axial shrinkage percentage of cement, fiber, wood ash, and copper slag.

As previously mentioned, fiber replacement is much more effective for volumetric shrinkage reduction than WA and CS. One may argue that the replacement ratio is much lower in fiber-replaced mixes than in ash and slag. However, fiber incorporation is clearly more effective than any percentage of cement alone. Figure 8 further highlights the effect of fibers through investigating the second-order interaction of CCF mixes. With regard to the volumetric shrinkage response, as soon as fiber is incorporated into cement there is at least a 25% reduction in the shrinkage. Furthermore, it was observed that a 0.5% fiber addition did not result in any further contribution above 5% cement, whereas a 1% fiber addition contributed effectively with a cement content up to 7%. Although fiber inclusion was reported to influence radial shrinkage more than axial shrinkage, the same applies to the observations shown in Figure 8. Further, the increased fiber content resulted in stable reduction of radial shrinkage, whereas in the axial direction, increased cement content combined with fiber incorporation sharply reduced the axial shrinkage, with the exception of the 0.5% fiber, in which the adverse behavior was measured above 5% cement content. This proves that cement content must be increased in parallel with fiber content to obtain the optimum fiber inclusion efficiency.

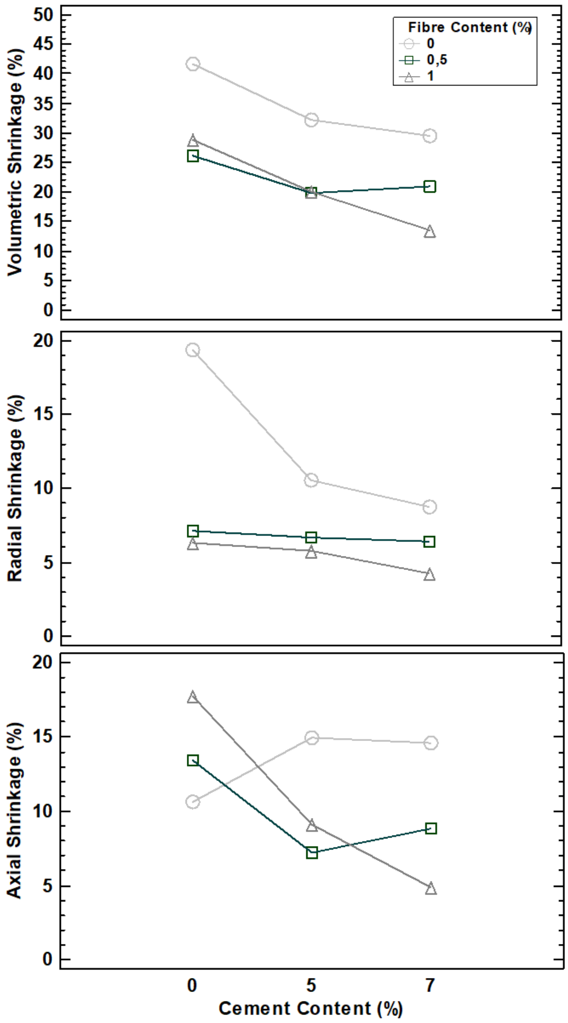

Figure 8. Second-order interaction of CCF mixes.

4. Conclusions and Recommendations

The present study investigated the impacts of polypropylene fiber, WA, and CS replacements on the shrinkage behavior of marine clay. The following conclusions can be drawn from the results of this study:

- 1% fiber with 7% cement mix performed best for reducing the volumetric shrinkage of clay. Cement-coating produces extra bonding strength between fibers and clays. Fibers alone have shiny surfaces that can slide, which degrades the frictional resistance available at the fiber–clay interface.
- The availability of aluminous elements in clay accelerates the chemical interaction with cement and WA particles to form a densified composite structure. Such occurrence seems to isolate the available moisture in the particles and restricts weight loss, resulting in reduced volumetric shrinkage.
- The 10% WA replacement had a noticeable impact on volumetric shrinkage. In turn, using CS as a cement replacement seems to have a null effect up to 20%. Even though there is no improvement of volumetric shrinkage reducing cement by replacing it with 20% wood ash or 10/20% copper slag will result in economical and environmental benefits.
- Even though fiber solely promises shrinkage reduction on problematic soils, the cement–fiber blend is the best alternative. The cement content should be increased along with fiber content to obtain the optimum efficiency of fiber inclusion.
- Reusing of unsuitable soil and hazardous wastes will reduce environmental and financial impacts. Improving soil with additives will facilitate the use of the available soil on site. In addition to the environmental contribution of cement usage reduction, using waste material such as WA and CS will enable safe disposal of those harmful materials.
- Incorporation of such material on site does not require any specific tool; field application is conventional and straightforward. Furthermore, there is no cost of obtaining wood ash, copper slag as they are waste generated from biomass powerplants and copper mines, respectively.
- As earlier studies show that WA and CS activate the pozzolanic reaction at extended curing periods, it is recommended for further study to investigate the behavior of studied mixes at older ages (28 and 60 days of curing). Furthermore, the

microstructure of the tested specimens was studied under scanning electron microscopy to highlight the interactions between clay, cement, fiber, WA, and CS.

5. Acknowledgements

The author greatly appreciates the discussions and help from Assoc. Prof. Dr. Ertuğ Aydın from the European University of Lefke. The author also thanks his graduate student, Mr. Doğan Gülaboğlu, for his support in laboratory experiments.

References

[1] Abdi, M.R., Parsapajouh, A. & Arjomand, M, A. (2008) Effects of random Finer Inclusion on Consolidation, Hydraulic Conductivity, Swelling, Shrinkage Limit and Desiccation Cracking of Clays. International Journal of Civil Engineering, 6, (4) 23-45

[2] Al-Bared, M. A. M., & Marto, A. (2017). A review on the geotechnical and engineering characteristics of marine clay and the modern methods of improvements. Malaysian Journal of Fundamental and Applied Sciences, 13(4), 825-831.

[3] Albright, W. H., Benson, C. H., Gee, G. W., Roesler, A. C., Abichou, T., Apiwantragoon, P., Lyles, B. F., and Rock, S. a. (2004) Field water balance of landfill final covers." Journal of environmental quality, 33(6), 2317–2332.

[4] Al-Jabri, K. S., Taha, R. A., Al-Hashmi, A., and Al-Harthy, A. S. (2006). "Effect of copper slag and cement by-pass dust addition on mechanical properties of concrete." Construction and Building Materials, 20(5), 322–331.

[5] Al-Rawas, A. A. (2002). Microfabric and mineralogical studies on the stabilization of an expansive soil using cement by-pass dust and some types of slags. Canadian geotechnical journal, 39(5), 1150-1167.

[6] Al-Rawas, A. A., Taha, R., Nelson, J. D., Al-Shab, B. T., & Al-Siyabi, H. (2002). A comparative evaluation of various additives used in the stabilization of expansive soils. Geotechnical Testing Journal, 25(2), 199-209.

[7] ASTM (2013). "Standard specification for mixing rooms, moist cabinets, moist rooms, and water storage tanks used in the testing of hydraulic cements and concretes." ASTM C511. West Conshohocken, PA: ASTM.

[8] ASTM (2014). "Standard test methods for specific gravity of soil solids by water pycnometer." ASTM D854. West Conshohocken, PA: ASTM.

[9] ASTM (2017a). "Standard test methods for liquid limit, plastic limit, and plasticity ındex of soils." ASTM D4318, West Conshohocken, PA: ASTM.

[10] ASTM (2017b). "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." ASTM D2487, West Conshohocken, PA: ASTM.

[11] ASTM (2018). "Standard specification for Portland cement." ASTM C150, West Conshohocken, PA: ASTM.

[12] ASTM (2008). "Standard test method for length change of hardened hydraulic-cement mortar and concrete." C157-08, West Conshohocken, PA: ASTM.

[13] ASTM (2017), "Standard Test Methods for Particle-Size Distribution (Gradation) of Sands Using Sieve Analysis." D6913 / D6913M-17, West Conshohocken, PA: ASTM.

[14] Bharati, S. K., and Chew, S. H. (2016). "Geotechnical Behavior of Recycled Copper Slag-Cement-Treated Singapore Marine Clay." Geotechnical and Geological Engineering, Springer International Publishing, 34(3), 835–845.

[15] Buhler, R. L., & Cerato, A. B. (2007). Stabilization of Oklahoma expansive soils using lime and class C fly ash. In Problematic soils and rocks and in situ characterization (pp. 1-10).

[16] Burland, J. B. (1990). On the compressibility and shear strength of natural clays. Géotechnique, 40(3), 329-378.

[17] Campbell, A. G. (1990). Recycling and disposing of wood ash. Tappi Journal, 73(9), 141-146.

[18] Chen, F., H. (1988) Foundation on Expansive Soils. New York: Elsevier.

[19] Clayton, C, R., Xu. M., Whiter, J, T., Ham, A,. & Rust, M. (2010) Stresses in cast-iron pipes due to seasonal shrink-swell of clay soils. Proceedings of the Institution of Civil Engineers - Water Management 163(3):157–162.

[20] Ekinci, A. (2019). Effect of preparation methods on strength and microstructural properties of cemented marine clay. Construction and Building Materials, 227, 116690.

[21] Ekinci, A., Filho, H. C. S., & Consoli, N. C. (2019). Copper Slag-Hydrated Lime-Portland Cement Stabilized Marine Deposited Clay. Proceedings of the Institution of Civil Engineers-Ground Improvement, 1-30.

[22] Ekinci, A., Scheuermann Filho, H. C., & Consoli, N. C. (2019). Copper Slag-Hydrated Lime-Portland Cement Stabilized Marine Deposited Clay. Proceedings of the Institution of Civil Engineers-Ground Improvement, 1-30.

[23] Etiegni, L., & Campbell, A. G. (1991). Physical and chemical characteristics of wood ash. Bioresource technology, 37(2), 173-178.

[24] Fatahi, B., Le, T. M., Fatahi, B., & Khabbaz, H. (2013). Shrinkage properties of soft clay treated with cement and geofibres. Geotechnical and Geological Engineering, 31(5), 1421-1435.

[25] Harianto, T., Hayashi, S., Du, Y. J., & Suetsugu, D. (2008) Effects of Fibre Additives on the Desiccation Crack Behavior of the Compacted Akaboku Soil as A Material for Landfill Cover Barrier. Water, Air, & Soil Pollution, 194, (1) 141-149.

[26] Keskin, S.N., Uzundurukan, S., Goksan, T.S., Korkmaz, A., & M.Ç. (2006). Estimation of Swelling Treatment of Flag Soils by Anfi Analysis. Soil Mechanics and Foundation Engineering Eleventh National Congress. Karadeniz Technical University.

[27] Kunther, W., Lothenbach, B., & Skibsted, J. (2015). Influence of the Ca/Si ratio of the C–S–H phase on the interaction with sulfate ions and its impact on the ettringite crystallization pressure. Cement and concrete research, 69, 37-49.

[28]Lodolini, E. M., Polverigiani, S., Cioccolanti, T., Santinelli, A., & Neri, D. (2019). Preliminary Results about the Influence of Pruning Time and Intensity on Vegetative Growth and Fruit Yield of a Semi-Intensive Olive Orchard. Journal of Agricultural Science and Technology, 21(4), 969-980.

[29]Lothenbach, B., & Nonat, A. (2015). Calcium silicate hydrates: Solid and liquid phase composition. Cement and Concrete Research, 78, 57-70.

[30]Mehta, P. K., & Monteiro, P. J. (2017). Concrete microstructure, properties and materials.

[31]Miller, Carol, J. & Sami, Rifai. (2004) Fibre reinforcement for waste containment soil liners. Journal of Environmental Engineering 130, (8): 891-895.

[32]Mobasher, B., Devaguptapu, R., and Arino, A. . (1996a). “Effect of copper slag on the hydration of blended cementitious mixtures.” ASCE, Materials Engineering Conference, Materials for the New Millenium, ed., K. Chong, ed., 1677–86.

[33]Naik, T. R., & Kraus, R. N. (2003). A new source of pozzolanic material. Concrete international, 25(12), 55-62.

[34]Naik, T. R., Kraus, R. N., & Siddique, R. (2003). Controlled low-strength materials containing mixtures of coal ash and new pozzolanic material. Materials Journal, 100(3), 208-215

[35]Omidi, G, H., Thomas, J, C. & Brown, K, W. (1996) Effect of desiccation cracking on the hydraulic conductivity of a compacted clay liner. Water, Air, & Soil Pollution, 89, (1) 91-103.

[36]Özkul, Z. H., & Baykal, G. (2006). Shear strength of clay with rubber fibre inclusions. Geosynthetics International, 13(5), 173-180.

[37]Pavez, O., Rojas, F., Palacious, J., and Nazer, A. (2004). “Pozzolanic activity of copper slag.” VI international conference on clean technologies for the mining industry, University of Concepcion, Chile.

[38]Puppala, A. J., & Musenda, C. (2000). Transportation Research Record. (1736), 134-140.

[39]Rajasekaran, G., & Rao, S. N. (1997). Lime stabilization technique for the improvement of marine clay. Journal of Japanese Geotechnical Society: Soils and foundations, 37(2), 97-104.

[40]Rao, K. D., Anusha, M., Pranav, P. R. T. & Venkatesh, G. (2012). A laboratory study on the stabilization of marine clay using saw dust and lime. International Journal Of Engineering Science & Advanced Technology, 2(4), 851-862.

[41]REMR Technical Note (1998). Influence of Short Polymeric Fibres ib Crack Development of Clays.

[42]Rifai, S. & Miller, C. (2004). Fibre Reinforcement for Waste Containment Soil Liners. Journal of Environmental Engineering, 130, (8)

[43]Rodrigues, M. A., Lopes, J. I., Ferreira, I. Q. and Arrobas, M. 2018. Olive Tree Response to the Severity of Pruning. Turk.J. Agric. For., 42: 103-113.

[44]Rojas, M. I. S., Rivera, J., Frías, M., and Marín, F. (2008). “Use of recycled copper slag for blended cements.” Journal of Chemical Technology & Biotechnology, Wiley-Blackwell, 83(3), 209–217.

[45]Shi, C., Meyer, C., and Behnood, A. (2008). “Utilization of copper slag in cement and concrete.” Resources, Conservation and Recycling, 52(10), 1115–1120.

[46]Shi, Z., & Lothenbach, B. (2019). The role of calcium on the formation of alkali-silica reaction products. Cement and Concrete Research, 126, 105898

[47]Siddique, R. (2012). Utilization of wood ash in concrete manufacturing. Resources, conservation and Recycling, 67, 27-33.

[48]Steinberg, M. (1998) Geomembranes and the Control of Expansive Soils in Construction. New York: McGraw-Hill.

[49]Stolz, J., Boluk, Y., & Bindiganavile, V. (2019). Wood ash as a supplementary cementing material in foams for thermal and acoustic insulation. Construction and Building Materials, 215, 104-113.

[50]Taha, R., Al-Rawas, A., Al-Jabri, K., Al-Harthy, A., Hassan, H., and Al-Oraimi, S. (2004). “An overview of waste materials recycling in the Sultanate of Oman.” Resources, Conservation and Recycling, 41(4), 293–306.

[51]Tang, C., Bin, S., Wei, G., Chen, F., & Cai, Y. (2007). Strength and mechanical behavior of short polypropylene fibre reinforced and cement stabilized clayey soil. Geotextiles and Geomembranes, 25, 194-202

[52]Tombesi A (2013). Advances in harvesting and pruning of olive trees. La Rivista di Scienza dell’Alimentazione (J Food Sci Nutr) 1:97-103.

[53]Venkateswarlu, D., Kumar, M. A., Raju, G. P., & Prasad, D. (2014). A Study On The Lime–Cement Stabilized Marine Clay. Asian Journal of Microbiology, Biotechnology & Environmental Sciences, 16(2), 439-444.

[54]Vipulanandan, C. & Leung, M. (1991) Seepage Control in Contaminated and Permeable Houston Clay: A Laboratory Study. Hazardous Waste and Hazardous Materials, 8, (1) 17-32.

[55]Zain, M. F. M., Islam, M. N., Radin, S. S., and Yap, S. G. (2004). Cement-based solidification for the safe disposal of blasted copper slag. Cement and Concrete Composites, 26(7), 845–851.

[56]Ziegler, S., Leshchinsky, D., Ling, H.I., & Perry, E.B. (1998). Effect of short Polymeric Fibres on Crack Development in Clay. The Japanese Geotechnical Society, 38, (1)

[57]Atiyeh, M., & Aydin, E. (2020). Carbon-Fiber Enriched Cement-Based Composites for Better Sustainability. Materials, 13 (8), 1899. https://doi.org/10.3390/ma13081899