Effect of Nano-Additives on the Strength and Durability Characteristics of Marl

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Abstract: Low bearing capacity soils may pose serious construction concerns such as reduced bearing capacity and excessive hydro-associated volume changes. Proper soil remediation techniques must be planned and implemented before commencing any construction on low bearing capacity soils. Environmentally friendly soil stabilizers are gradually replacing traditional soil stabilizers with high carbon dioxide emissions such as lime and cement. This study investigated the use of an alternative pozzolanic mix of nano-additives (i.e., nano-silica and nano-alumina) and cement to reduce the usage of cement for achieving competent soil stabilization outcomes. A series of unconfined compressive strength (UCS), direct shear, and durability tests were conducted on marl specimens cured for 1, 7, and 28 days stabilized with nano-additives (0.1~1.5%), 3% cement, and combined 3% cement and nano-additives. The UCS and shear strength of stabilized marl increased with nano-additives up to a threshold nano-additive content of 1% which was further intensified with curing time. Nano-additive treated cemented marl specimens showed long durability under the water, while the cemented marl decomposed early. The microfabric inspection of stabilized marl specimens showed significant growth of calcium silicate hydrate (CSH) products within the micro fabric of nano-silica treated marl with reduced pore-spaces within aggregated particles. The results confirmed that nano-additives can replace cement partially to achieve multi-fold improvement in the strength characteristics of the marl.

Keywords: marl; nano-silica; nano-alumina; cement; UCS; shear strength; durability

1. Introduction

Soil stabilization incorporates processes to alter one or more properties of soil to achieve overall improved mechanical characteristics and engineering performance under ongoing and future stress conditions. There are three types of soil stabilization techniques including mechanical, chemical, and biological soil stabilization. The mechanical soil stabilization targets the soil particle size distribution, porosity, and interparticle friction by using external actions (compaction and pre-stressing) or by incorporating soil reinforcement techniques (nailing or the use of geosynthetics) to improve the physical characteristics of the soil. Chemical stabilization improves the engineering characteristics of soil by mixing the soil with additives such as lime, cement, bitumen, and fly ash. This method of soil stabilization results in altering the chemical composition of the soil upon exposure to water through short-term and long-term chemical reactions such as cation exchange, flocculation, agglomeration, pozzolanic reaction, and carbonate cementation. In biological

soil stabilization, microbes and bacteria are grown in the soil to produce natural binding materials within the soil particles. The outcome includes one or many of the following: free swell/swelling pressure reduction, shear/compressive strength improvement, and resistance to repeated wetting and drying.

The default choice for soil stabilization amongst most engineers is the use of traditional calcium-rich additives, such as cement or lime and, to some extent, fly-ash, which all have been traditionally proved to work well for improving the mechanical behavior of reactive clays, soft clays, and other low bearing capacity soils (i.e., high compressibility and heave, insufficient stiffness, and shear/compressive strength) [1–10]. The improvement in geotechnical properties of such soils using innovative techniques and environmentally friendly materials is a recent trend in civil engineering research and practice. Several non-traditional soil additives have been studied recently such as biopolymers, sulfonated oils, polymers, cement kiln dust, ground-granulated blast furnace slag, pulverized coal bottom ash, and steel slag [11–20].

Although the goal of soil stabilization is to make the soil stable when it is subjected to externally destabilizing fluctuations, such as repeated axial loads and/or seasonal rainfall and drought, the selection of a soil admixture is highly important to cause less carbon dioxide emission and environmental pollution. The production of traditional calcium-rich additives, such as cement and lime, requires considerable energy and water and also generates harmful gases such as CO_2, SO_2, and NO_x. Nearly one ton of carbon dioxide is emitted for producing one ton of cement and lime. Fly ash also adversely affects the plant ecosystem by reducing nutrient access to plants due to its high pH [21–23]. Therefore, commonly trusted soil admixtures, such as cement and lime, are being gradually replaced with green additives such as biopolymers [11,24–27]. Soil stabilization may be carried out on a shallow layer for road construction or for providing a working platform for machinery access. For stabilizing deep layers, techniques such as jet grouting, injection, and deep mixing are used. Shallow mixing is used when a large area is to be treated at a shallow depth (i.e., roads). Deep mixing is used for stabilizing deep layers on a limited working plan area. In deep mixing, the injection performance of calcium-rich additives is limited to the soil with a pore size larger than 3–5 times the size of the cement particles (i.e., 20 microns). Therefore, it is difficult to inject such additives into fine-grained soils [28–34]. Owing to the development of nanotechnology, nano-materials, such as nano-silica, nano-alumina, and nano-titania, have been recognized as effective soil additives to increase the stiffness of clays and to reduce their free swelling potential [35–40]. Nano-additives with nano dimensions and high specific surface area can enter soil pore-spaces easily [41–43]. In contrast with cement and lime, many nano-materials require less energy for production and are generally environmentally friendly, non-toxic, and do not cause any pollution in soil and groundwater when used for soil improvement [44–47].

The combination of cement/lime with nano-materials forms a pozzolanic environment during the hydration of lime/cement and soil. Nano-materials react chemically with cement and lime to form hydrated compounds (calcium–silicate and calcium–aluminate hydrates, CSH/CAH) [48–51] and, therefore, contribute to improvement in the shear strength of the soil and, hence, reduction in lime/cement consumption [51–56]. Gallagher and Mitchell (2002) investigated the triaxial shear strength of loose sand stabilized with 5%, 10%, 15%, and 20% silica colloids [57]. It was reported that the axial strain of the sample subjected to cyclic stresses decreased gradually with the increase in silica colloid content and, therefore, the liquefaction potential of the soil was reduced. Nano-materials can also improve the properties of the cement by controlling the distribution of hydration products through the nucleation effect whereby nano-materials act as templates for crystal growth [37–39,49]. Taha and Taha (2012) showed that the addition of nano-materials leads to a decline in the hydraulic conductivity, shrinkage, and heave of the clay [58]. Upon hydration of nano-materials within the soil structure, a gel is formed that fills in the soil micro-pores and transforms the pore fluid to a viscous liquid with a shear resistance. The formed viscous gel delays the excess pore pressure generation process and mitigates the

liquefaction risk under dynamic loads, enhances the cementation between sand particles, improves the shear strength, and decreases the hydraulic conductivity of the soil [45].

Marl soils, due to their abundance, may be used as backfill materials for road construction [59]. Marls are carbonate-rich, fine-grained soft soils that pose engineering concerns including settlement, low bearing capacity, instability, and water sensitivity [60]. This type of soil is frequently found in Iran especially in the northwest. Therefore, the geotechnical properties of this soil must be improved before construction. Cement has been commonly used in practice to stabilize marl soils [61–66] to meet the minimum strength requirements for road construction. However, nano-materials have not been used to stabilize the local marl in the northwest of Iran yet. Therefore, the current study investigated the impact of the proportionate amount of two different nano-additives (i.e., nano-silica and nano-alumina) on the compressive and shear strength of cemented marl.

2. Materials

Marl soil was collected from a construction site in Tabriz, northwest Iran. The geological formation of this region ranges from the Cenozoic to the Quaternary periods with unconsolidated river deposits and glacial sediments [67,68]. Tabriz is in the center of East Azerbaijan Province with a population of more than 2 million. East Azerbaijan is in the western Alborz–Azerbaijan structural zone adjacent to the Caspian Sea. Tabriz marl has been reported as the most occurring soil in earthworks within the area with adverse properties like high plasticity and low workability. The main chemical constitutions of Tabriz marl are typically 35% calcite, 40% quartz, 10% feldspar and 4% dolomite [62]. The basic characteristics of the soil used in this study, including physical, index properties and chemical compositions are presented in Table 1.

Table 1. Properties of the marl soil.

Physical Properties	Value
Gravel (%)	0
Sand (%)	4
Silt (%)	55
Clay (%)	41
Liquid limit (LL) (%)	42.0
Plastic limit (%)	17.0
Plasticity index (%)	25.0
Shrinkage limit (%)	12.7
Specific gravity (Gs)	2.73
Soil classification (USCS)	CI
Activity (%)	0.61

In this study, nano-silica, nano-alumina, and cement were used as soil additives to stabilize the collected clay. Table 2 presents the specifications of the nano-additives and the cement provided by the manufacturer. The nano-additives used in this study were procured from the Iranian Nanomaterials Pioneers company (Iran), and ordinary Portland cement (Type II) in compliance with ASTM C150 (2021) [69] was provided by Sardar Bukan Cement (Iran). The cement properties are listed in Table 3.

Table 2. Physical properties of nano-silica and nano-alumina.

	Physical State	APS * (nm)	SSA ** $(m^2 g^{-1})$	Color	Particle Density (gcm^{-3})	Morphology
Nano-silica (SiO_2)	Solid	11–13	200	white	2.40	Amorphous
Nano-alumina (Al_2O_3)	Solid	20	138	white	3.89	Nearly spherical

* Apparent particle size; ** specific surface area.

Table 3. Physical and chemical properties of cement.

Chemical Properties	Value	Physical Properties	Value
SiO_2 (%)	23.13	Fineness (%)	1.54
Al_2O_3 (%)	5.53	Specific gravity	3.00
Fe_2O_3 (%)	3.51		
CaO (%)	58.95		
MgO (%)	1.18		
Na_2O (%)	0.33		
K_2O (%)	0.85		
SO_3 (%)	2.19		
Insoluble Residue			
LOI	6.36		
Free Lime	3.41		

LOI: loss on ignition.

3. Experimental Program and Methods

This study reports the effect of nano-additives on the unconfined compressive strength (UCS) and shear strength of the stabilized marl cured for 1–28 days. Standard Proctor compaction tests were carried out on marl treated with 0.1%, 0.5%, 0.9%, 1.2%, and 1.5% nano-additives using automatic compaction testing equipment to determine the maximum dry unit weight and the optimum moisture content of different mixes. Specimens were prepared at their maximum dry unit weight and optimum moisture content. Additives' amounts (i.e., cement and nano-additives) were calculated based on the total dry mass of the soil (inclusive of marl and additives).

There are different methods for obtaining a homogeneous distribution of nano-additives in the soil. One such method is ball milling to properly disperse nano-materials in the soil using the milling process, where the balls of the mill disperse the nano-materials homogeneously in the soil. However, the main concern with this method is the breakage of soil particles during the milling process which may change its particle size distribution [70] unless the milling time is very short. Another technique to prepare the nano-stabilized soil is to create a liquid solution of nano-materials to mix with the soil. In this study, the latter technique was used. Nano-additives were dispersed in water using a magnetic stirrer at a velocity of 120 rpm, and the specimens were prepared using the prepared liquid solution. The static compression method was used to prepare UCS specimens with a diameter of 38 mm and a height/diameter ratio of 2:1. The remolded specimens were kept in a vinyl bag at the room temperature of 23 °C and humidity of 90% and cured for 1, 7, and 28 days. The UCS test was carried out at a vertical displacement rate of 1.5%/min on triplicate specimens to eliminate errors due to the fact of specimen and test condition differences, and the average values were published.

A series of direct shear tests were also undertaken on 1, 7, and 28 days cured prismatic 60× 60 × 25 mm (B × L × H) specimens as per ASTM D3080 [71]. The shear strength of the specimens was measured under axial stresses of 50, 100, and 150 kPa. The direct shear test specimen was prepared by pushing the soil cutter into a remolded soil using a hydraulic extruder. The specimen was kept under the water in the shear box container for 24 h. The scanning electron microscopy (SEM) technique was used to investigate the effect of nano-additives and cement on the microfabric of the marl using a Hitachi 4100 field emission scanning electron microscope. Three specimens of untreated marl, 3% cemented marl (Marl-3C), and 3% cemented marl treated with 1% nano-silica (Marl-3C-1.0NS) were prepared and cured for 28 days to investigate the microfabric changes in the marl after stabilization with cement and nano-silica. The durability of the stabilized samples was investigated by submerging the 28-day cured stabilized specimens under the water to

mimic the extremely high moisture content conditions such as what may happen to the pavement subgrade during the wet season. Therefore, cylindrical 38 mm (D) × 76 mm (H) specimens were prepared at the optimum moisture content and were submerged under the water until they disintegrated structurally.

4. Results and Discussion

4.1. Effect of Nano-Additives on the Compaction Properties of Marl

Figure 1 shows the effect of nano-additives on the maximum dry unit weight (MDU) and optimum moisture content (OMC) of the marl. The maximum dry unit weight of the marl decreased with the addition of nano-additives. Nano-additives bind soil particles and make edge-to-edge flocculated aggregates that increase the void ratio of the soil, while the strength of the soil increases. Therefore, with the increased void ratio, the modified soil structure can hold more water within the pores, while the unit weight of the soil drops [37,48,49]. The maximum dry unit weight of the marl was reduced by 4.7% and 3.8% with the addition of 1.5% nano-silica and 1.5% nano-alumina, respectively. However, the optimum moisture content of the 1.5% nano-silica and 1.5% nano-alumina treated marl was 57% and 46% more than that of the marl, respectively. Nano-silica treated marl achieved a slightly higher dry unit weight compared to the nano-alumina treated marl that can be linked with the lower particle size and high specific surface of nano-silica particles compared to those of nano-alumina particles (Table 2). Although both nano-additives are hydrophilic, the water absorption capacity of nano-silica is higher than that of nano-alumina due to the fact of its higher specific surface area (i.e., 200 m^2g^{-1} compared to 130 m^2g^{-1} for nano-alumina). Therefore, higher optimum moisture content was expected for nano-silica treated marl.
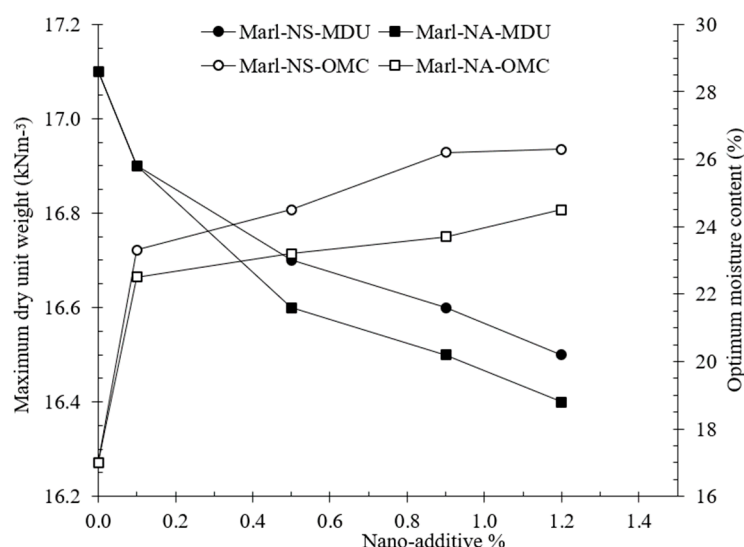

Figure 1. Maximum dry unit weight and optimum moisture content of nano-additive treated marl.

A previous study by the authors showed that the optimum cement content for stabilizing the studied soil is 3% [72]. The authors also reported the standard Proctor compaction test results for 3% cemented nano-additive stabilized clay with 0.1%, 0.5%, 1%, and 1.5% nano-silica (NS) and nano-alumina (NA). Table 4 shows the compaction properties of the stabilized clay. The addition of nano-additives to 3% cemented marl also resulted in a similar trend with a gradual reduction of the maximum dry unit weight and an increase in the optimum moisture content with the increase in nano-additive content. Cement addition did not have an obvious impact on the compaction properties of nano-additive treated marl. This may be related to the omission of mellowing/curing time that lets soil particles bond together effectively in the compaction test.

Table 4. Standard Proctor compaction properties of the nano-cement stabilized marl. Adapted from [72].

Mix Name	Cement (%)	Nano-Silica (%)	Nano-Alumina (%)	OMC * (%)	MDU ** (kNm^{-3})
Marl	0	0.0	0.0	17.0	17.1
Marl-3C	3	0.0	0.0	19.6	17.2
Marl-3C-0.1NS	3	0.1	0.0	21.6	16.8
Marl-3C-0.5NS	3	0.5	0.0	22.2	16.7
Marl-3C-1.0NS	3	1.0	0.0	22.4	16.4
Marl-3C-1.5NS	3	1.5	0.0	23.8	16.3
Marl-3C-0.1NA	3	0.0	0.1	22.3	16.9
Marl-3C-0.5NA	3	0.0	0.5	23.0	16.7
Marl-3C-1.0NA	3	0.0	1.0	25.0	16.6
Marl-3C-1.5NA	3	0.0	1.5	26.0	16.4

* Optimum moisture content; ** maximum dry unit weight.

4.2. Effect of Nano-Additives on the UCS of Marl

Figure 2 compares the UCS of treated marl with 0.1%, 0.5%, 0.9%, 1.2%, and 1.5% nano-additive. The UCS of the marl increased with nano-additive content up to a threshold content of 1.2% at which a further increase in nano-additive content to 1.5% did not yield a surplus UCS. The compressive strength of untreated marl was determined as 194 kPa. At 28 days of curing, the UCS values of 1.2% nano-silica and 1.5% nano-alumina treated marl were almost 2.7 and 2.0 times of the UCS of marl. Nano-silica treated marl achieved comparatively higher UCS than nano-alumina treated marl. The 28-day UCS of nano-alumina treated marl was less than that of the 1 day cured nano-silica treated marl up to 0.9% nano-additive content, and this trend was reversed beyond this threshold value. This can be attributed to the higher specific surface of nano-silica particles that provides an effective pozzolanic reaction over time with the available calcium ions of the hydrated clay and, hence, a quick UCS improvement.
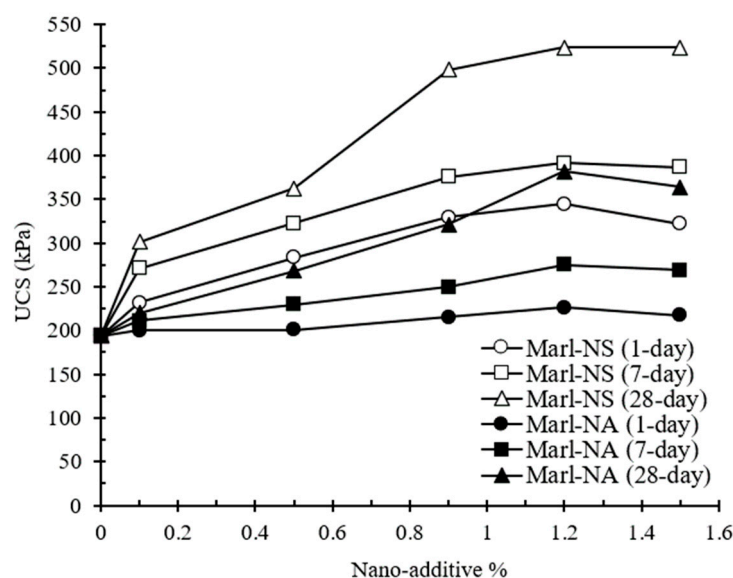
Figure 2. UCS of nano-additive treated marl.

In order to stabilize the 3% cemented marl, nano-additive contents of 0.1%, 0.5%, 1.0%, and 1.5% were selected. Figure 3 shows the UCS values of nano-additive and cement stabilized marl cured for 1, 7, and 28 days. The addition of cement increased the UCS of the marl by 22%, 78%, and 144% at 1, 7, and 28 days of curing, respectively. Nano-additives accelerate the hydration of cement due to the fact of their high surface energy [5,43,48,73–76]. The addition of both nano-additives to the cemented clay from 0.1% to 1.5%, increased the UCS of the marl gradually up to 1% nano-additive content

and then declined slightly at 1.5% nano-additive content. The 1 day UCS values of 1% nano-silica and nano-alumina cemented clay were 112% and 82% higher than that of the marl, respectively.
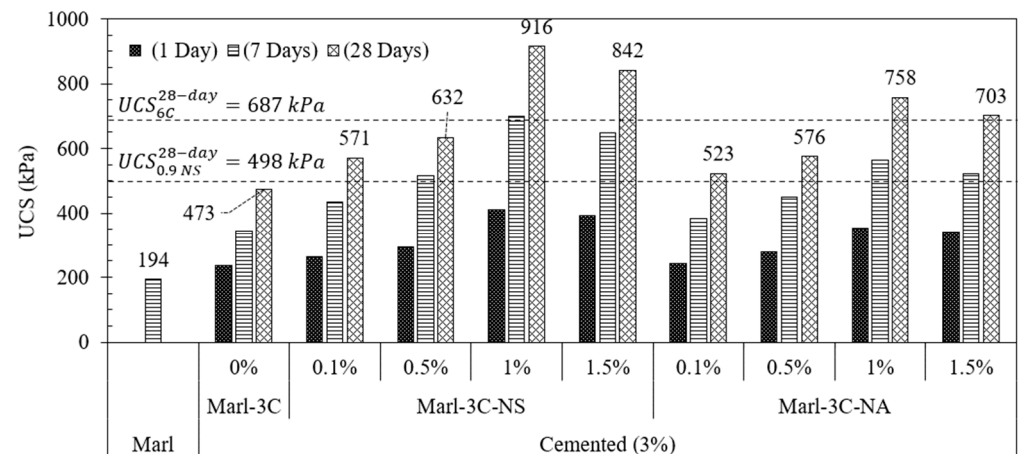

Figure 3. Unconfined compressive strength of stabilized marl.

The 28-day UCS of stabilized marl with 3% cement and 1% nano-silica was 1.94 times that of the 3% cement stabilized marl. Therefore, although cement is primarily a common additive for soil stabilization projects, the combination of cement and nano-additives yielded nearly double UCS of the cemented clay (i.e., at 28 days of curing).

The 28-day UCS of 6% cement stabilized marl is also shown in Figure 3 as a reference to compare the relative UCS gain due to the partial replacement of cement with nano-additives. As shown in Figure 3, the 28-day UCS values of 0%, 3%, and 6% cement stabilized marl were 194, 473, and 687 kPa, respectively. However, the 28 day UCS values of 3% cement stabilized marl with 0.5% and 1% nano-silica were 0.92 and 1.32 times that of the 6% cement stabilized marl. Therefore, nano-additives can replace cement partially to achieve similar or higher UCS values.

Nano-materials with nano-sized particles fill gaps between the micro-sized clay particles and, therefore, increase the surface area of the clay matrix. Upon initiation of pozzolanic reactions between the silica/alumina of the nano-additive and the hydrated calcium of the cement, a strong bond is formed between the clay particles. However, beyond an optimum nano-additive content, the extra nano-particles accumulate within the soil matrix with a weak bonding strength and prevent the cementitious products to hydrate effectively. Therefore, the strength of the specimen is reduced [49,50,77]. The UCS improvement of nano-additive treated cemented marl increased significantly with curing time, where the 28-day UCS of the 1% nano-silica and 1% nano-alumina cemented marl were 4.72 and 3.91 times that of the cemented marl, respectively.

The Young's modulus (E) of the treated marl was estimated from the slope of the UCS stress–strain curve that can be used for design purposes conservatively since the UCS test produces smaller values of Es over field values by a factor of four or five [78]. The secant modulus (E_s) is reported to be more appropriate for the estimation of E in the general range of field loading [78]. The E_s was estimated following the procedure suggested by Holtz et al. (2011) [79]: determined from the slope of the straight line drawn from the origin to the predetermined stress as 50% of the UCS value. Figure 4 shows the secant modulus of stabilized marl with cement and nano-additives. The E_s of the marl increased significantly with the addition of nano-additives to the cemented soil which was further intensified with curing to 28 days. The addition of 3% cement increased the E_s of marl by four times. However, adding 1% nano-silica and 1% nano-alumina to the 3% cemented marl, increased the E_s of the marl by 18.8 and 10.0 times, respectively. Therefore, it was expected that the cemented marl with nano-silica was extremely stiffer than the marl or

cemented marl, which leads to less deformation upon similar axial loading. This can be realized by comparing the axial strain of the treated marl at failure.
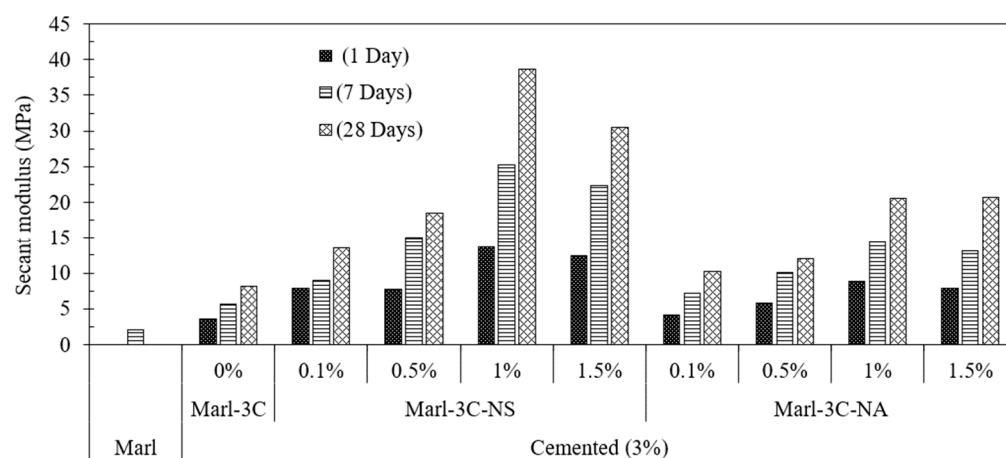

Figure 4. Secant modulus of stabilized marl.

Figure 5 compares the failure strain at the peak stress for nano-additive+cement stabilized marl. A higher failure strain is a relative indication of the specimen's ductility with the lagged formation of failure plane(s) when it is subject to a monotonic axial stress increase. Figure 5 shows that in all cases, the failure strain decreased with the increase in nano-additive content as well as with the curing time. Nevertheless, it should be noted that the strength of a hardened body with a dense structure originates from particle bonding. When a structure is rigid, its brittleness also increases [58].
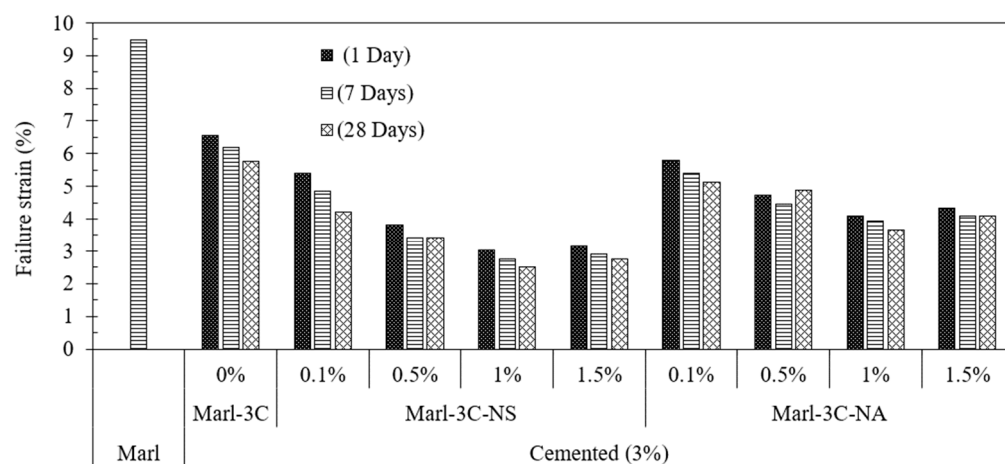

Figure 5. Axial failure strain of stabilized marl.

4.3. Effect of Nano-Additives on the Shear Strength of Marl

Figure 6 presents the shear strength parameters of the uncemented/cemented marl treated with 0.1%, 0.5%, 0.9%, 1.2%, and 1.5% nano-additives. The cohesion intercept and internal friction angle of the marl increased with nano-additive content to a threshold nano-additive content of 1.2%. The 28-day cured cohesion intercept and internal friction angle of 1.2% nano-silica treated marl were 19% and 36% higher than those of the marl, respectively. The addition of 3% cement to the nano-additive treated marl resulted in a significant improvement in the cohesion intercept and internal friction angle of the marl. The cohesion intercept and internal friction angle of the 3% cemented marl were 1.48 and 1.45 times those of the uncemented marl. However, the 28-day cohesion intercept and internal friction angle of cemented marl treated with 1.2% nano-silica were 3 and

2.4 times those of the uncemented marl, respectively. The effect of individual additives (either cement or nano-silica) on the shear strength parameters of the marl was insignificant. However, the combination of both additives improved the shear strength parameters of the marl significantly. Nano-alumina treated marl yielded lower shear strength compared to nano-silica treated marl. The higher specific surface area of nano-silica avails more silica for reaction with the calcium ions of the hydrated clay and, therefore, achieves a higher strength compared to nano-alumina treated marl. The shear strength parameters of 1 day cured nano-silica treated marl were as much as those of 7-day cured nano-alumina treated marl.

4.4. Microfabric of Nano-Additive Stabilized Marl

Figure 7 shows the SEM micrographs of the specimens. The microfabric of the marl consists of intra-assemblage pore-spaces as large as 7.9 μm and groups of small intra-pores between clay particles. However, with the addition of cement, clay particles were flocculated to form uniform large aggregates with fewer intra-assemblage pore-spaces. Cementitious calcium silicate hydrate (CSH) products were also visible within the fabric of the cemented marl (Figure 7b). The pores between particles were filled with cementitious gels, resulting in smaller pores and a denser soil matrix. Figure 7c shows the microfabric of the cemented marl treated with 1% nano-silica that includes a dense matrix with pores filled to a considerable extent with CSH gel. Nano-silica with a nano-dimension of 11–13 nm (Table 2) can effectively fill inter- and intra-assemblage pore-spaces of the marl and, therefore, speed up the pozzolanic reactions. Reactions between hydrated cement and nano-silica produce CSH gel that envelopes soil particles and strengthens the soil matrix. Furthermore, the nucleation effect of nano-silica particles contributes to the distribution of the CSH gel throughout the soil matrix efficiently. Therefore, the microstructure modification of the base marl leads to the subsequent improvement in the mechanical properties and durability of the soil.

4.5. Durability of Nano-Additive Stabilized Marl

Figure 8 shows the visual state of the specimens after 7 days of being submerged under the water. Stabilized marl specimens with 3% cement and 1% or 1.5% nano-silica or nano-alumina withstood well under the water for 7 days without ant failure. However, the untreated marl, cemented marl, and cemented marl treated with 0.1% and 0.5% nano-additives disintegrated earlier. Therefore, although the compressive and shear strength of 3% cement stabilized clay were superior to those of the untreated marl, it did not last long under unconfined water soaking conditions. However, treating the cemented marl with at least 1% nano-additive resulted in significant durability under unconfined water soaking conditions.

In low road embankments, the toe of the embankment may be subjected to unconfined water soaking during the flooding events and, thus, proper soil stabilization is essential to protect the road embankment against environmental impacts such as gradual erosion and short-term flooding events. Therefore, the inclusion of nano-additives in the calcium-based soil additives may prolong the lifespan of the improved soil significantly, especially within harsh climatic conditions.
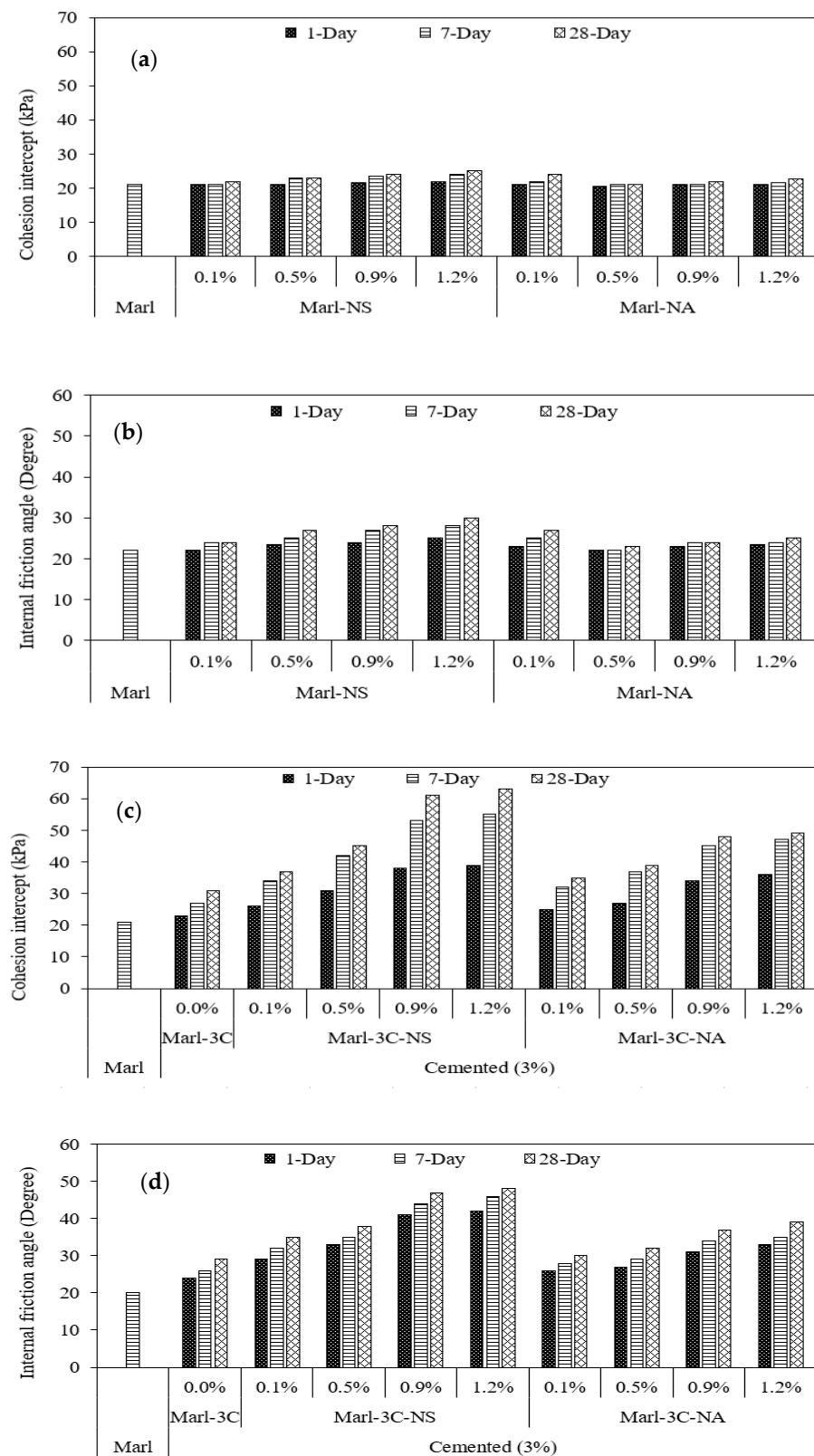
Figure 6. The shear strength parameters of stabilized marl: (**a**) cohesion intercept of nano-additive stabilized marl; (**b**) internal friction angle of nano-additive stabilized marl; (**c**) cohesion intercept of nano-additive+cement stabilized marl; (**d**) Internal friction angle of nano-additive+cement stabilized marl.
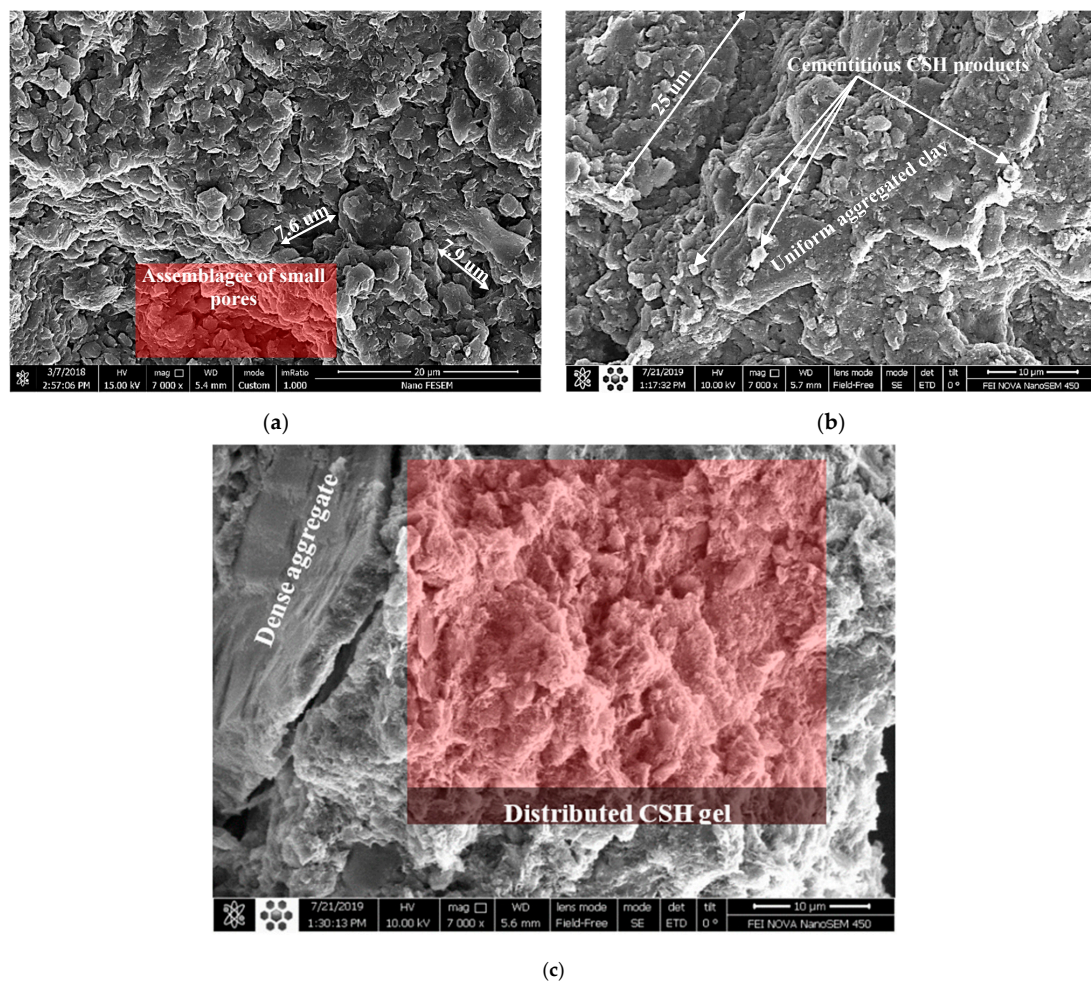
Figure 7. Scanning electron micrographs of treated marl cured for 28 days: (**a**) untreated marl; (**b**) 3% cemented marl; (**c**) 3% cemented and 1% nano-silica treated marl.
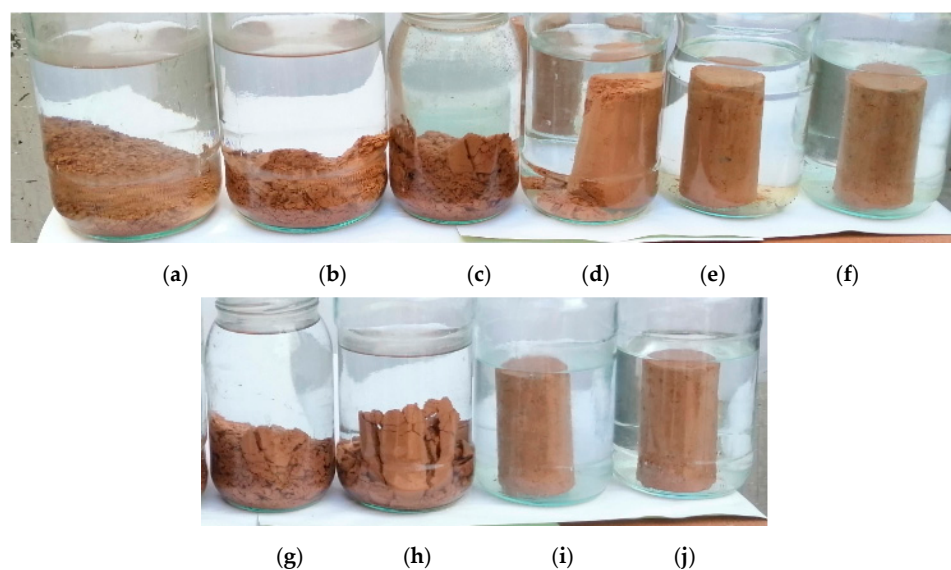

Figure 8. Durability of stabilized 28 day cured stabilized specimens under water after 7 days: (**a**) Marl; (**b**) Marl-3C; (**c**) Marl-3C-0.1NS; (**d**) Marl-3C-0.5NS; (**e**) Marl-3C-1.0NS; (**f**) Marl-3C-1.5NS; (**g**) Marl-3C-0.1NA; (**h**) Marl-3C-0.5NA; (**i**) Marl-3C-1.0NA; (**j**) Marl-3C-1.5NA.

5. Conclusions

This study investigated the use of two nano-additives (i.e., nano-silica and nano-alumina) with high specific surfaces to stabilize intermediate plastic marl. The compaction efficiency, unconfined compressive strength, shear strength, and durability of the untreated, 3% cemented, nano-additive treated marl (i.e., 0.1%, 0.5%, 0.9%, 1.2%, and 1.5%), and nano-additive cemented marl (i.e., 0.1%, 0.5%, 1.0%, and 1.5% nano-additive + 3% cement) were determined after curing periods of 1, 7, and 28 days. The results showed that nano-additives controlled the mechanical behavior of the marl significantly. Nano-additive particle size and curing time were the major factors affecting the strength and durability characteristics of nano-additive treated marl. The following conclusions were addressed in this study:

1. The addition of nano-additives resulted in an increase in the optimum moisture content and a decrease in the dry unit weight of the marl due to the hydrophilicity and high specific surface of nano-additives used in this study.
2. The UCS of the nano-additive treated marl increased with an increase in the concentration of both nano-additives to a threshold nano-additive content of 1%.
3. The 28-day UCS of 3% cemented marl was slightly less than the 28-day UCS of treated marl with 0.9% nano-silica, which suggests 3% cement can be replaced with 0.9% nano-silica for achieving similar improvement results.
4. Stabilizing marl with combined 3% cement and 1% nano-silica achieved 94% surplus UCS to the 3% cement stabilized marl. Nano-additives accelerate the hydration of cement due to the fact of their high surface energy. Therefore, although cement is primarily a common additive for soil stabilization projects, the combination of cement and nano-additives can yield nearly double UCS of the cemented clay (i.e., at 28 days of curing).
5. The 28-day UCS values of 3% cement stabilized marl with 0.5% and 1% nano-silica were 0.92 and 1.32 times that of the 6% cement stabilized marl. Therefore, nano-additives can replace cement partially to achieve similar or higher UCS values.
6. Stabilizing marl with 1% nano-silica and cement resulted in an intensified secant modulus that was 18.8 times that of the marl. However, cemented marl achieved only a secant modulus four times that of the marl.
7. Stabilizing the marl with nano-additives or with a combined mix of cement and nano-additives improved the shear strength parameters (i.e., cohesion intercept and internal friction angle) of the marl. The 28-day cohesion intercept and internal friction angle of cemented marl treated with 1.2% nano-silica were 3 and 2.4 times those of the uncemented marl, respectively. Although, the effect of individual additives (either cement or nano-additives) on the shear strength parameters of the marl was insignificant, the combination of both additives improved the shear strength parameters of the marl significantly.
8. Nano-alumina treated marl yielded lower UCS and shear strength than nano-silica treated marl at all curing times.
9. SEM micrographs of the stabilized marl showed an increase in the growth of CSH products within the microfabric of the clay with the addition of nano-silica.

The authors believe that the findings of this study contribute to the inclusion of nano-additives to the cement for soil stabilization applications. Therefore, not only the strength characteristics of the soil improves significantly, but also the consumption of cement is reduced with the hope towards zero carbon dioxide emission soon. The proposed solution to partially replace cement with nano-additives will prolong the lifespan of the improved soil significantly, especially within harsh climatic conditions.

Additionally, as a future endeavor, the authors intend to examine other characteristics such as altered rheology and environmental impacts of nano-additive treated marl.

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