sustainability

MDPI

Article

The Sustainability of Using DuraCrete as Cement Additive to Estuarine Soft Soil Stabilization

Ali N. Al-Gemeel [1], Noor Al-Hayo [2], Dominic E. L. Ong [2] and Yan Zhuge [3,*]

[1] College of Engineering, University of Babylon, Babylon 51002, Iraq; eng.ali.nassir@uobabylon.edu.iq
[2] Griffith School of Engineering, Griffith University, Brisbane 4215, Australia; noor.al-hayo@griffithuni.edu.au (N.A.-H.); d.ong@griffith.edu.au (D.E.L.O.)
[3] UniSA STEM, University of South Australia, Adelaide 5095, Australia
* Correspondence: yan.zhuge@unisa.edu.au

Abstract: Large areas of estuarine deposits exist on the coastal plains of the southeast Queensland coast with a countered depth of up to 30 m. These deposits are categorized as sediments that originated during the Holocene Age. The sediments have not been consolidated or subjected to considerable pressure since the end of the Ice Age. The structure of these deposits consists of large ratios of porosity, causing high soil compressibility, which lowers the bearing capacity of the soils. Therefore, the soils of the region cannot maintain sufficient support for construction loads, and consequent malfunctions could occur in short-term and long-term periods. The objective of this paper is to investigate the suitability of new soil stabilization additives in the southeast Queensland region and the optimum additive content of cementitious materials and an advanced mixing modifier branded as DuraCrete. A combination of Portland cement and DuraCrete was used as a soil additive. Three DuraCrete-to-cement ratios were used: 2%, 3%, and 4% by weight. Soil collected from the Port of Brisbane region was treated by adding the additives as a percentage of its weight; four percentages were considered: 10%, 20%, 25%, and 30% for each combination of additives. The performance of the treated soils was examined under unconfined compression after 28 days of curing. The results revealed that increases in the unconfined compressive strength were detected as DuraCrete was added to the mixtures. For 30% additives, increases of about 15%, 34%, and 17% were detected when DuraCrete was added as 2%, 3%, and 4%, respectively. The results also revealed that 3% DuraCrete content provided significant stabilization compared to 2% and 4% for 25% and 30% additive-treated soils; such behavior was also observed for the specimens of 25% content of additives. Additionally, DuraCrete can be considered a promising material that can be combined with cement to obtain the desired stabilization of soft soils.

Keywords: DuraCrete; EvoCrete; stabilization; unconfined; additives; southeast Queensland

check for updates

Citation: Al-Gemeel, A.N.; Al-Hayo, N.; Ong, D.E.L.; Zhuge, Y. The Sustainability of Using DuraCrete as Cement Additive to Estuarine Soft Soil Stabilization. *Sustainability* **2024**, *16*, 231. https://doi.org/10.3390/su16010231

Academic Editor: Hosam Saleh

Received: 19 November 2023
Revised: 11 December 2023
Accepted: 12 December 2023
Published: 26 December 2023

1. Introduction

Worldwide, the scarcity of soil and land sources is a major issue and a challenge corresponding to the expansive growth of the population and a rapid increase in urbanization. This issue is even more significant in regions with soils with poor engineering characteristics, for example, those surrounding estuaries.

Southeast Queensland (SEQ) refers to the area along the coast of Queensland State in Australia, which is geographically located between latitudes 26° and 28° south. The area has a subtropical climate with temperatures in the range of 10 to 35 °C year round and rainfall peaks in summer. The recorded climate data show that the average temperature in SEQ is about 19.4 °C, seasonal rainfall is 1135 mm/year, and evaporation is around 1553 mm/year, as reported by [1]. There are three distinct geographical regions in SEQ: the coastal areas, the floodplains and estuaries, and the other areas, which include mountains, foothills, and hinterlands. The coastal areas encompass shallow layers of narrow plains broken by estuaries and rock outcrops, such as the Redcliff area. Shoreline areas, such as Moreton Bay, dominate the coastal regions. The floodplains in SEQ are slender and meander in their capacities and reaches. The hinterland areas back the coastal plain areas and comprise foothills and cliffs containing ranges of mountains trending north to south [2].

Large areas of estuarine deposits exist on the coastal plains of the southeast Queensland coast, with a countered depth of up to 30 m. These deposits are categorized as sediments that originated during the Holocene Age. The sediments have not been consolidated or subjected to considerable pressure since the end of the Ice Age. A geological map of southeast Queensland is presented in Figure 1, in which areas of Holocene sediments are notated by the letter (Q), as represented in [3]. This map can be a useful guide indicating where the soft soils and estuarine are.

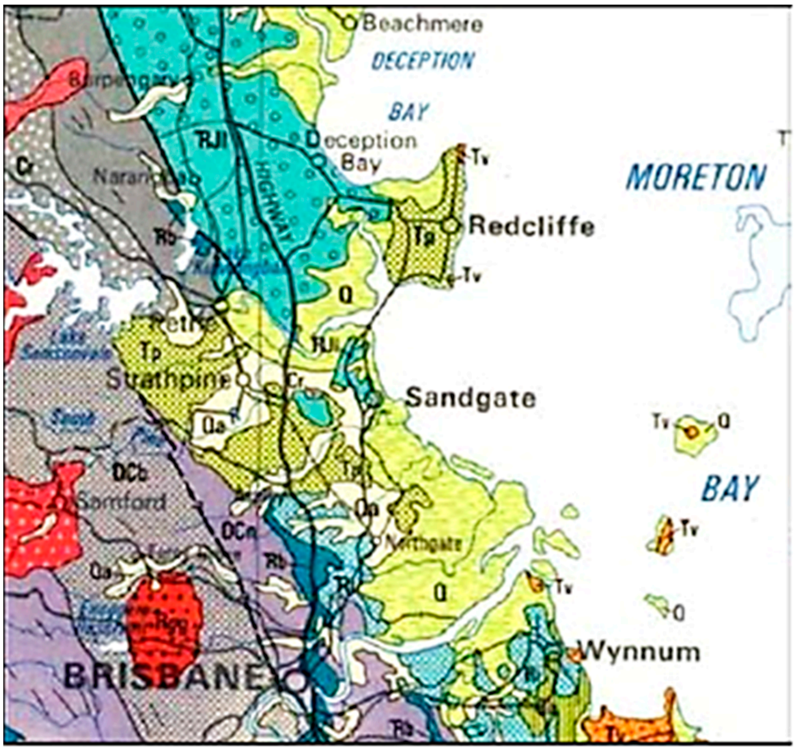


Figure 1. Holocene deposits distribution in the Brisbane area [3].

Meta-sedimentary and metamorphic types of rocks can be considered the main rock formations that dominate the basement layers of SEQ. Formations such as "Neranleigh-Fernvale beds and Bunya Phyllites (quartzite, greywacke, argillite, jasper, greenstone, and phyllite)" are the main geological formations within SEQ. It has been assumed that what is called a "Brisbane tuff unit" is overlaying ignimbrites of welded volcanic layers of ash that were formed in the Triassic period. Volcanic eruptions occurred in different periods, and enormous masses of basalt and rhyolite lava were produced. These consequently led to the formation of ranges of volcanic formations of shale, dolomite, basalt, and agglomerate and the formation of the Mount Warning complex, which includes volcanic units of microgranite, peralkaline granite, rhyolite, syenite, and trachyte. The continuous erosion and disposition processes that occurred throughout long ancient periods formed sedimentary deposits that coated the basement rock layers. The transmitted products of the abovementioned processes accumulated in valleys and natural basins and formed surface sediments of rocks such as sandstone, conglomerate, siltstone, shale, and mudstone [4,5].

Based on field data, the shear strength of undrained soft clays of southeast Queensland soils is found to be in the range of 10–15 kPa. Water content is found to vary from 60 to 120%. The data indicate that liquid indices for such soils are with the range of 1.5–2.5, indicating high sensitivity. Additionally, laboratory results indicate that compressibility as high as 0.4–0.5 was detected for the soft clays of the area, indicating that the effect of strain rates can be significant regarding the soils [6]. In regard to the distribution of the soft clay deposits, they can be found at depths of 1 to 30 m close to the coastline in low-lying areas, and this varies depending on the geological patterns of the areas [7].

Improving soil properties is essential when planning infrastructure on problematic soils. Cement is one of the most effective additives commonly used to stabilize soils using an in situ mixing method. It has been proven to be an effective additive in enhancing the engineering characterizations of soft soils [8]. The geotechnical characterization of soils can be strengthened through the combined actions of aggregation, flocculation, and reticulating interaction between the cement particles and surrounding soil particles. These processes can result in increased strength and stiffness, reduced permeability and compressibility, and deceased moisture content [3].

Construction materials have undergone noticeable developing in recent years, including the introduction of additives that can enhance cement binding properties. One such advanced material is DuraCrete, which is approved as a cement and concrete modifier that increases the bonding strength of cement and the surrounding matrix. It is known for its ability to enhance the cement hydration process and the durability of concrete. From an economic point of view, it can reduce the use of quarry materials, machinery, labor costs, and construction time. The material is applicable on-site and non-toxic, comprising 100% natural contents. Furthermore, it is fully recyclable, making it an environmentally friendly construction material: for instance, it helps reduce the CO_2 emission [9]. DuraCrete can be notated as a cement modifier that can eventually improve binding characteristics of cement-admixed soils with the presence of mixing water; and this can eventually improve the stabilization of treated soils throughout developing their nanostructure. The material restrains the actions of the carbonic acid and fluvic acid, which are natural compounds of soils and types of organic acids that remain as a solution in soils after soil acidification. In a cement–soil base, DuraCrete induces the formation of hexagonal nanostructure of crystalline formations. This structure is more sophisticated compared to that forming by cement–soil stabilization. This will eventually develop extra interlocking connectivity, resulting in soils with high compressive and tensile strength and developed static and dynamic elasticity [9].

During the soil preparation solicitation processes, DuraCrete, when combined with hydrating cement and soil particles, creates a modified bearing layer of treated soil with the desired load capacity that can substantially assist with eliminating the requirements of traditional bearing bases and excavation technologies to modify bearing capacities. From a sustainability perspective, reducing the volumes of bearing layers of infrastructures and road works result in eliminating consuming traditional construction materials and achieving financial and time savings of construction projects.

This study is motivated by the exploration of mixing a combination of traditional and advanced construction materials in a new way for the solidification and stabilization of soft soils. Specifically, the research focuses on the effect of using hybrid additives containing cement and DuraCrete materials on the unconfined compressive strength of treated southeast Queensland soils. The scope of the study encompasses optimizing the DuraCrete content along with the total additives content to reach satisfactory stabilization and examine the performance of the additives' treated clay under unconfined compressive strength conditions after 28 days of curing such as the ultimate load and the stress–strain behavior. The soft compressible estuarine deposits utilized in this study were collected from the Port of Brisbane, which is located near the Brisbane River. This soil is categorized as soft compressible estuarine deposits with high potential of settlement and low strength.

2. Methodology

To achieve the main objective of this study, various additive contents comprising a combination of DuraCrete and cement were employed as stabilizing additives to southeast Queensland clays. A range of DuraCrete to cement ratios was systematically investigated.

A qualitative methodology was undertaken by conducting experimental tests to study the geotechnical characteristics of additives treated soft soils. Key experimental tests, including assessments of water content, liquid limit, plastic limit, and unconfined compressive strength tests were undertaken on a series of samples with different contents of additives and different values of DuraCrete to cement ratio.

The experiments were conducted at the Geotechnical laboratory at the Gold Coast campus of Griffith University. The clay utilized in this study was sourced from the Port of Brisbane (as shown in Figure 2), and its mechanical properties are detailed in Table 1. Ordinary Portland cement has been used in this study. The cement used fully complies with the requirements of type GP cement in Australian standards (AS-3972) [10]. The properties of cement as provided by a local supplier are presented in Table 2.

Figure 2. The soil collected from Port of Brisbane (southeast Queensland).

Table 1. The properties of the used soil.

Percentage of Sand	Percentage of Silt	Percentage of Clay	Natural Moisture Content	Liquid Limit	Plastic Limit
27%	16.1%	56.9%	131.49%	64.99%	31.26%

Table 2. Mechanical properties of used cement.

Properties	Limits	AS3972-1997 Type GP	Typical GP
Setting Time	Min	45 min	60–150 min
	Max	10 h	2.0–3.5 h
Soundness	Max	5 mm	<3 mm
SO_3	Max	3.50%	<3.5%
ISO Mortar Compressive Strength	3 Day (min)	-	30–42 MPa
	7 Day (min)	25 MPa	43–54 MPa
	28 Day (min)	40 MPa	54–65 MPa

DuraCrete, an advanced construction material, is anticipated to influence the behavior of additives-treated soils. In this study, the material was integrated with cement to serve as a cement modifier, and the resulting combination was employed as a soil stabilizer. The material is donated by Shamrock GeoScience Ltd. located in Mahe–Seychelles, Germany, as shown in Figure 3.

Figure 3. A 2.5 kg bag of DuraCrete packed and imported from Germany.

2.1. Research Plan

The treatment of the soft soil involved blending a specific quantity of additive with the soil. The treated soil was then utilized to prepare necessary samples for experimental tests.

In this study, the total content of additives encompasses a combination of cement and DuraCrete with specific ratios. For each percentage of total additives (10%, 20%, 25%, and 30% by weight), four DuraCrete to cement ratios (0%, 2%, 3%, and 4% by weight) were investigated. This resulted in 16 mixes of additive-treated soils; and for each mix, two samples for the unconfined compressive tests were prepared, resulting in a total of 32 samples. The investigation was built on a complete set of groups ranging from a low to high rate of DuraCrete content to optimize the cement–soil modifier. It is noteworthy that DuraCrete content exceeding 4% may impact treatment feasibility. This recommendation is based on the manufacturer's guidance derived from project experiences in Germany and other countries. Table 3 provides details for each tested group, including the additives content and DuraCrete content. Each group is assigned a code with two terms. The first term represents the additive content, and the second term represents the DuraCrete content with the two terms separated by a hyphen. For example, the code 20A-2D represents a soil mix with 20% additives comprising a combination of cement and 2% weight content of DuraCrete, where the letters A and D stand for the words Additives and DuraCrete, respectively.

The preparation of these samples adhered to the guidelines outlined in the Australian Standard (AS-5101.4) [11]. After preparation, the samples underwent a curing period of 28 days before the unconfined compressive test was conducted. Preliminary tests were also undertaken on the soil to find the geotechnical properties of the soil.

Table 3. Research plan and mixes' details.

Mix Code	DuraCrete (%)	Total Additive (%)	No. of Samples
10A-0D	0	10	2
20A-0D		20	2
25A-0D		25	2
30A-0D		30	2
10A-2D	2	10	2
20A-2D		20	2
25A-2D		25	2
30A-2D		30	2
10A-3D	3	10	2
20A-3D		20	2
25A-3D		25	2
30A-3D		30	2
10A-4D	4	10	2
20A-4D		20	2
25A-4D		25	2
30A-4D		30	2

2.2. *Experimental Tests*

2.2.1. Preliminary Tests

To assess the geotechnical characteristics of the selected soil, preliminary tests such as the soil moisture content, liquid limit, and plastic limit tests are necessary. All these tests were conducted in this study according to corresponding Australian Standards [12–15]. For plastic and liquid limits tests, a process involving washing the slurry soil through a 425 µm sieve was employed. This process entailed taking 1000 g of natural soil, and then the washed soil had been dried in an oven at 105 °C for 3 days at the laboratory before the methods were conducted.

2.2.2. Unconfined Compressive Strength (UCS) Tests

This testing method is applied to compacted materials and is employed to evaluate the strength of the samples that have undergone a 28-day curing period. All UCS samples must be produced from the field in accordance with (AS-1289.1.2.1) [16]. Laboratory samples shall be obtained from a curing container in accordance with (AS-5101.4) [11]. In this study, all the processes for soil preparations were involved such as moisture contents, additives weight, samples preparation and curing.

The required content of additives was calculated for each sample as a specified weight percentage of the dry soil. The total additives in this study refer to a combination of cement and DuraCrete specific amount, as presented in Table 3. Initially, cement and DuraCrete were first mixed in their dry conditions for about 10 min. Subsequently, the dry combination was mixed with water to obtain a slurry mix by using a water–cement ratio of 1:2. The wet mixing processes were performed manually and lasted about 10 minutes for each batch. The samples were poured in three portions, which were compacted with standard effort for each layer using PVC molds. These specimens were then left to cure for 28 days before the unconfined test was conducted. A total of 32 samples were cast, compacted, and cured for the unconfined strength test, as shown in Figure 4.

Figure 4. The UCS sample preparation.

The compactive effort involved taking one portion of additives-treated soils and compacting it into PVC molds in three layers, resulting in a sample with 100 mm length and 50 mm in diameter. For one side of the mold, a 5 mm thickness and 50 mm diameter Porous stone was used for one side of the mold, and filter papers were placed on both sides of the samples. To avoid moisture loss, all samples were wrapped with cling wrap and waxed. After the 28 days of curing, the samples were extruded from the molds without any damages to the surfaces. Additionally, the samples were measured for 0.01 mm accuracy to be precisely prepared for the UCS standard test.

The test setup adhered to the standards outlined in (ASTM-D2166/D2166M-16) [17] on a LoadTrac II load frame, which was manufactured by Geocomp (Morton Grove, IL, USA) with a rate of strain set at 1.0 ± 0.1 mm/min, as illustrated in Figure 5. Before testing, all samples underwent through examination to detect any defects, and measurements were taken with a precision of 0.01 mm for both height and the diameter, which were used for stress and strain determinations.

Once all specimens were prepared for testing, they were individually placed on the lower bearing block of the apparatus. To ensure uniform seating, the upper bearing block to bear on the test sample was meticulously adjusted, aligning the vertical axis of the test specimen with the center of the upper bearing block. The load was increased at a uniform rate of 60 ± 6 kN/min after the loading ram was lowered to the point of contact with the sample. The loads were recorded at failure (P) to the nearest 0.5 kN of the test specimen. The load–displacement data of each test were recorded from the machine through a data acquisition system and stored in a connected computer.

Figure 5. The setup of the UCS test.

3. Results and Discussion

3.1. Preliminary Tests

Preliminary tests were conducted to the untreated soils to find out the characteristics of the used soft soil.

3.1.1. Moisture Content

The moisture content for Port of Brisbane soil was calculated by using the average of six samples. The experimental results of the tested specimens are presented in Table 4. The results showed that the water content of the utilized soil was found to be 131.49%. This value was used for the rest of the experimental tests and sample preparation.

Table 4. Water content test data.

No.	Tin (g)	Tin + Wet Soil (g)	Tin + Dry Soil (g)	Moisture Content (%)
1	13.03	21.2	16.6	128.852
2	21.6	31.38	25.84	130.660
3	21.81	34.87	27.54	127.923
4	23.3	37.04	29.11	136.489
5	21.6	32.37	26.3	129.149
6	21.8	31.07	25.73	135.878
Average %				131.49

3.1.2. Liquid Limit

Moisture content was calculated after drying processes for five samples, as shown in Table 5. The moisture content values were then plotted as a function of the number of blows obtained from the test, as shown Figure 6. The best fitting line was employed on the scattered points (represented by the blue points) to derive an equation expressing the relationship between the two variables (represented by the dotted line).

According to AS-1289.3.1.1 [14], the moisture content corresponding to 25 blows on the X coordinate presents the liquid limit of the soil (the orange point). Using the best fit with the point corresponding to 25 blows (orange points), the liquid limit of the soil was determined to be 64.99%.

Table 5. The experimental results of the liquid limit test.

Try	1	2	3	4	5
No. of blows	32	26	28	20	12
Weight of container (W0)	7.31	5.99	7.2	6.97	6.1
Weight of container + Wet soil (W1)	11.35	9.89	12.03	12.6	12.38
Weight of container + Dry soil (W2)	9.81	8.38	10.12	10.33	9.79
W1 − W2	1.54	1.51	1.91	2.27	2.59
W2 − W0	2.5	2.39	2.92	3.36	3.69
Moisture Content %	61.6	63.179	65.41	67.5	70.189

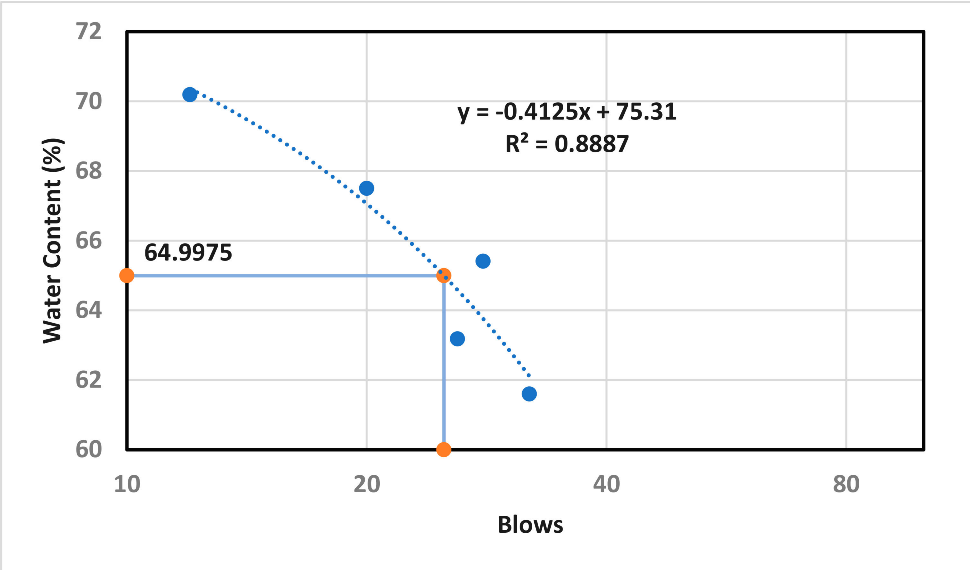


Figure 6. Linear fitting of the experimental data for liquid limit calculation (semi-log diagram).

3.1.3. Plastic Limit

Three samples were scaled after drying processes. According to AS-1289.3.2.1 [15], the average of the moisture content values of the samples was evaluated as the plastic limit of the soil. The experimental results of this test are presented in Table 6, and the plastic limit was determined to be 31.26%.

Table 6. The experimental results of the plastic limit test.

Sample	Weight of Empty Container (g)	Weight of Container + Wet Soil (g)	Weight of Container + Dry Soil (g)	Moisture Content %	Moisture Content Average %
Tin 1	6.19	9.69	8.87	30.60	31.26
Tin 2	6.33	8.36	7.89	30.13	
Tin 3	6.57	8.18	7.78	33.06	

3.2. Unconfined Compressive Strength (UCS)

The unconfined compressive strength test was conducted on each of the 32 prepared samples after a 28-day curing period. The tests were performed using a LoadTrac II machine (manufactured by Geocomp), and the resulting data were collected and stored in a computer through a data acquisition system. This system facilitated the transmission of raw data from the machine to the connected computer. For each group of specimens, the average of the compressive strength of two samples was calculated, and the average strain of each group was determined. The largest load of each specimen was used to calculate the compressive strength, and the correspondent displacement was used to calculate the strain. The results of the tested specimens are presented in Table 7.

Table 7. Experimental results of unconfined compressive strength.

Group	DuraCrete %	Samples	Average Stress (kPa)	Average Strain (%)
10A-0D	0	2	75.32	2.80
20A-0D		2	287.83	1.80
25A-0D		2	419.90	1.47
30A-0D		2	506.33	2.09
10A-2D	2	2	56.32	3.40
20A-2D		2	309.08	1.90
25A-2D		2	435.32	2.40
30A-2D		2	580.31	2.15
10A-3D	3	2	76.83	2.80
20A-3D		2	305.36	1.98
25A-3D		2	499.15	1.90
30A-3D		2	679.06	1.98
10A-4D	4	2	102.73	2.25
20A-4D		2	365.57	2.05
25A-4D		2	480.05	2.30
30A-4D		2	593.58	1.70

3.2.1. The Effect of Adding DuraCrete

This section discusses the effect of adding different percentages of DuraCrete as a cement additive. As detailed in the methodology, four percentages of additives (10%, 20%, 25%, and 30%) were used; and for each percentage of additives, four DuraCrete to cement ratios were investigated (0%, 2%, 3%, and 4%).

To facilitate a clear comparison of results based on DuraCrete content, samples containing the same additive content are presented in one figure. In the same words, each figure comprises four groups representing the four DuraCrete to cement ratios, as shown in Figures 7–10.

The results reveal an improvement in compressive strength values with the use of the cement modifier (DuraCrete) across nearly all tested specimens with the exception of one mix group, 10A-2D, as illustrated in Figure 7. Notably, the strength of this group slightly dropped compared to the control group (10A-0D), resulting in unexpected strength that is not consistent with their counterparts in the other groups.

This can be attributed to the experimental execution procedure, spanning from mixing to compacting and final finishing. Group 10A-2D was the first group to be prepared at the beginning of the experimental work; consequently, the performance of preparation was not as experienced as that of the other groups. When scan checked, the samples of this group contained bubbles, and the color was not homogenous along their heights, indicating that the samples of this group were not precisely performed, and their results do not give an accurate impression of behavior.

Moreover, the samples were not manually extruded from the PVC molds due to sticking issues necessitating a hydraulic procedure. This deviation from the standard procedure could have caused preliminary damage to the samples leading to undesired compressive strength results, as shown in Figure 11.

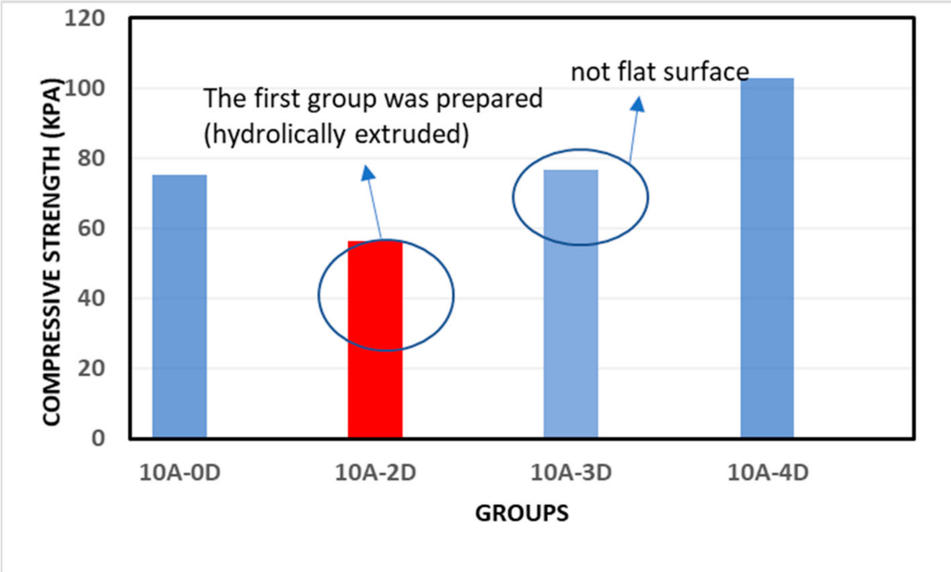


Figure 7. The compressive strength results of the specimens of 10% additives.

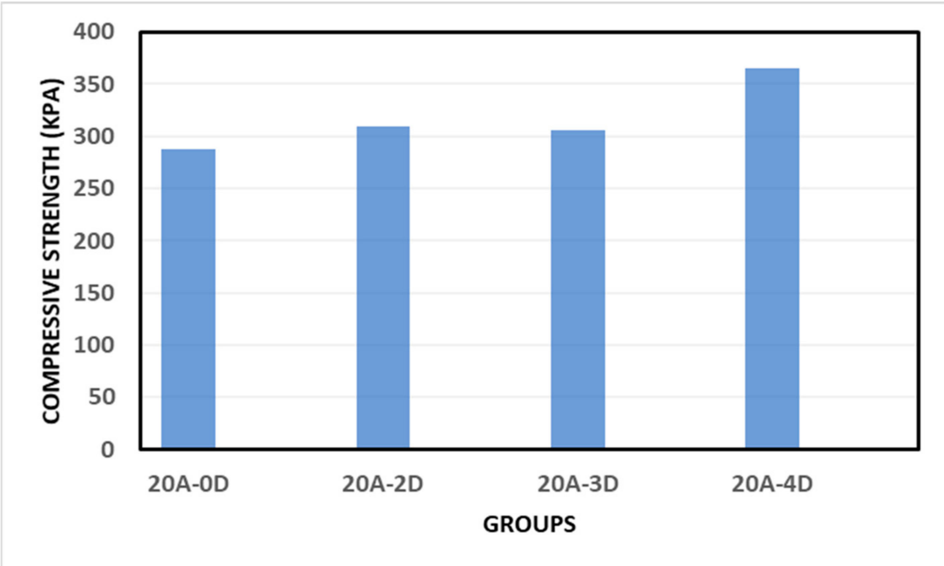


Figure 8. The compressive strength results of the specimens of 20% additives.

With the exception of the mentioned mix, the results indicate a noticeable increase in unconfined strength as DuraCrete was added to the mixtures. The average increase in the strength for group 10A-4D was found to be 36.4% compared to that of its control group (10A-0D). However, the average increase in the strength of group 10A-3D was found to be around 2%; this can be attributed to the unleveled surface of the samples, which could have caused uneven load distribution and led to an unexpected premature failure.

Referring to Figure 8 for mixes with 20% additives, the results reveal increases in unconfined strengths within the range of 7% to 27% compared to that of the control group (20A-0D), as DuraCrete content increased from 2% to 4% of the total additives. This demonstrates the capacity of DuraCrete to modify cement hydration bonding characteristics, thereby enhancing the stabilization and load-carrying capacity in the treated soil. Taking into consideration that with the content of DuraCrete comprising 4% of the total additives, which is a very small amount, the strength jumped about 27%. This could indicate the efficiency of the material to provide the desired geotechnical characteristics to soft soil.

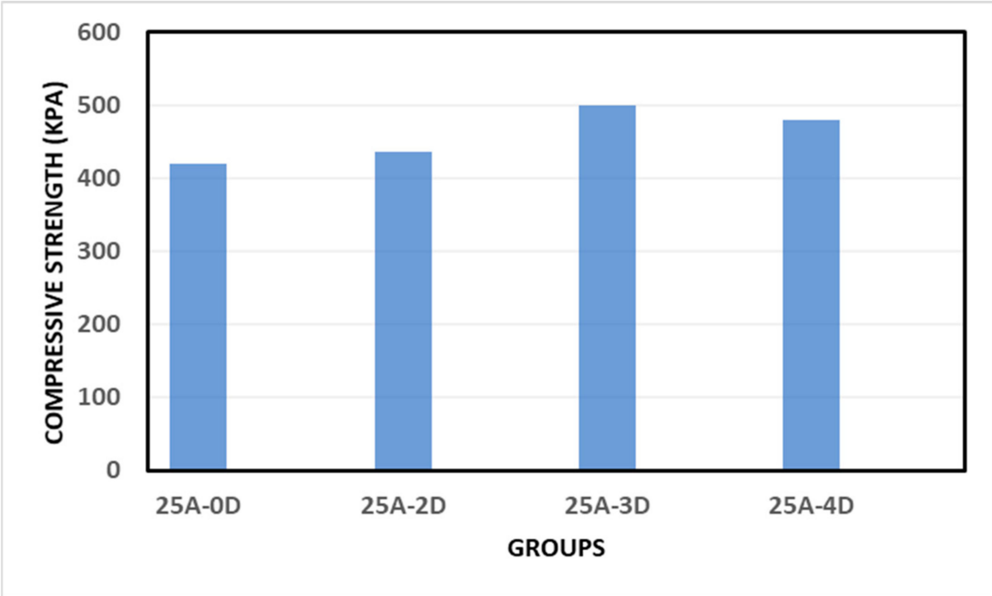


Figure 9. The compressive strength results of the specimens of 25% additives.

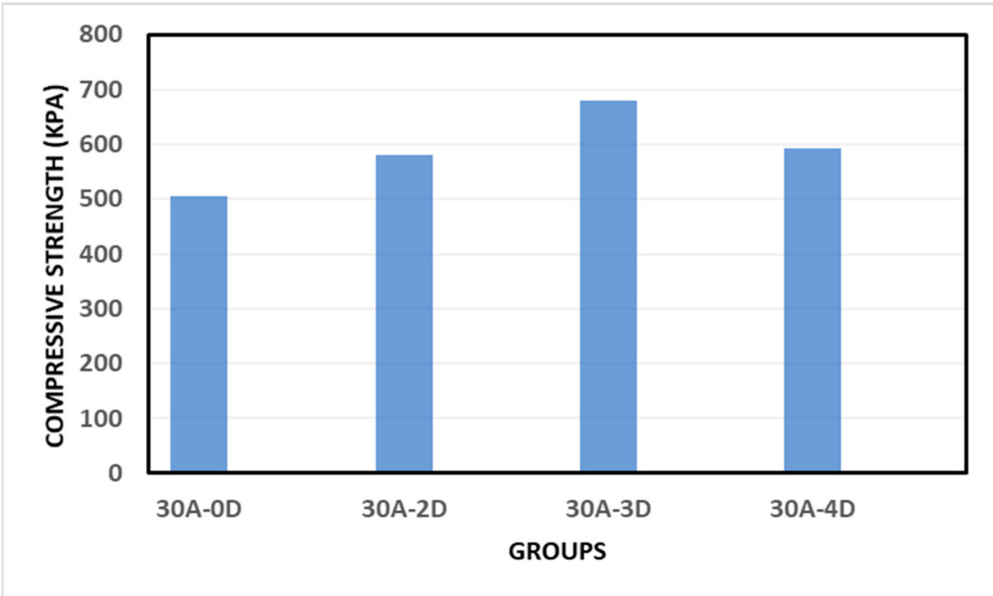


Figure 10. The compressive strength results of the specimens of 30% additives.

In the case of the other two groups with 25% and 30% additives, noticeable development of the unconfined strength values was observed as the DuraCrete content increased. Regarding the mixes with 25% additives, increases of about 4%, 19%, and 14% of the unconfined compressive strength were observed for the mixes with DuraCrete content of 2%, 3%, and 4%, respectively, as shown in Figure 9. This highlights the potential of the cement modifier in developing soil stabilization, particularly with contents of 3% and 4%.

Similarly, there were increases of about 15%, 34%, and 17% of the unconfined compressive strength with the content of DuraCrete of 2%, 3%, and 4%, respectively, for the specimens with the 30% content of additives. The significant 34% improvement in the strength of the treated soil can further demonstrate the ability of the material to recognizably develop the bonding properties of the cementitious materials and consequently the cement-treated soil.

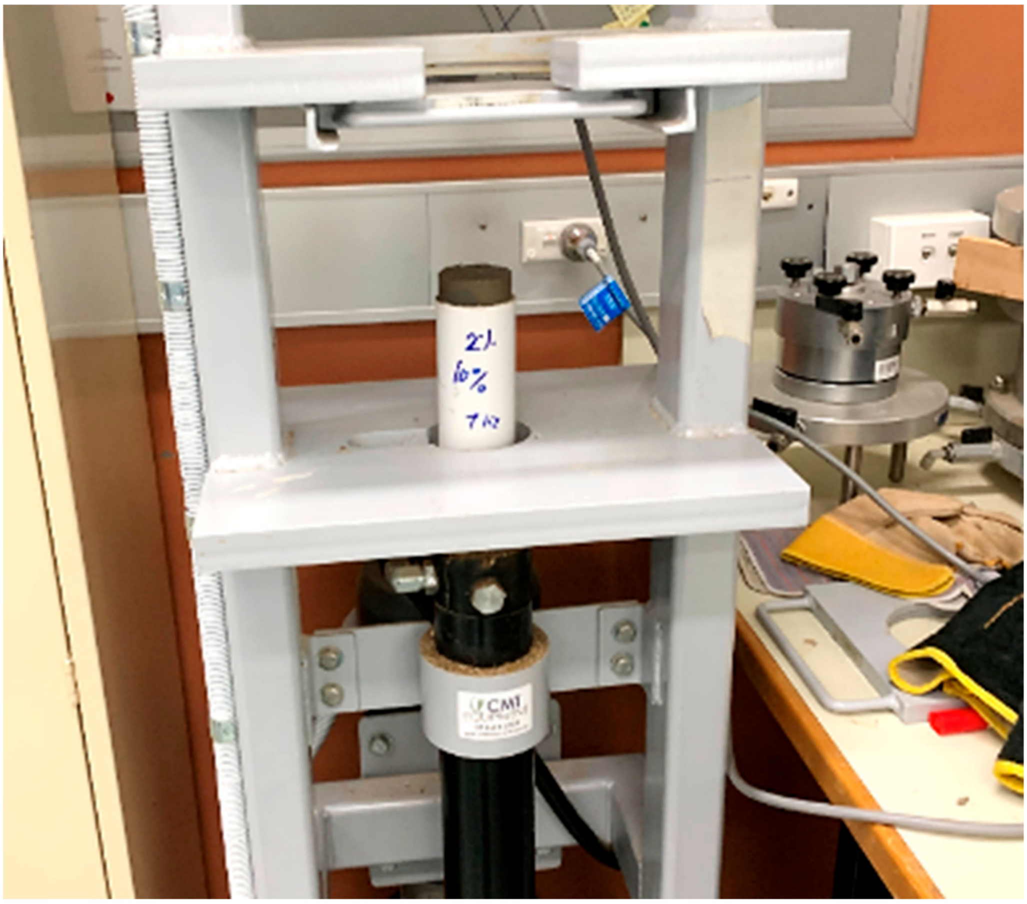


Figure 11. Extrusion of sample using hydraulic jack.

3.2.2. Optimizing the content of DuraCrete

In this section, the optimum ratios of DuraCrete to the total additives based on the obtained results of the experimental work of this study are discussed. As explained earlier, three ratios of DuraCrete to total additives were employed to identify the content that can impart the most desired geotechnical properties to the soft treated soil. The results presented in Table 7 are further discussed and analyzed in Figure 12 where compressive strength is depicted as a function of DuraCrete content. Four relationships were derived; each represents a percentage of the content of the additives. The results indicated that the compressive strength is linearly proportional to the modifier content when DuraCrete content increased from 2% to 3%, and this relationship is relative for each of the drawn curves. When DuraCrete content increased from 3% to 4%, the mixes of 10% and 20% of the total additives showed further increases in the compressive strength. However, for the mixes of 25% and 30% content of additives, the strengths of the specimens with 4% DuraCrete were observed to be slightly lower than those with 3% DuraCrete. It was discovered that the interfacial characteristics and matrix toughness show a correlation with a critical volume percent of the DuraCrete. The interfacial zone performs slip hardening, chemical bonding, and frictional bonding. Micromechanics, which quantitatively accounts for the interactions between the interface, matrix, and additives, is the basis of the tailoring process. Cementitious particle absence may have an impact on this microstructure. This is more likely the main cause of such behavior. To further compare the results to optimize the content of DuraCrete within the range of the ratios used in this study, the categorical data are presented in a bar graph shown in Figure 13.

In contrast to the interlocking structure formed by cement–soil stabilization, DurCrete encourages the creation of hexagonal nanostructures in crystalline formations. Consequently, soils with strong compressive and tensile strength as well as established static and dynamic elasticity will eventually exhibit further interlocking connectivity. The manufacture of this material discussed the nanostructure of both cement–soil stabilization and cement–DuraCrete soil stabilization, highlighting variations in crystal interlocking connections, both low and high [9]. Comparisons between the three contents of DuraCrete of each ratio of additives are more straightforward in Figure 13. It can be seen that the development of the unconfined strength when using a cement modifier is more efficient for the samples with 4% DuraCrete than the other two contents, especially when considering the first two groups of data (soils treated with 10% and 20% content of additives). On the other hand, for specimens with 25% and 30% of additives content, those with 3% DuraCrete presented the most desired unconfined strength. From this observation, it can be concluded that a 4% content of cement modifier is optimum for achieving the desired stabilization for soft soils mixed with additives by about 10% and 20% of their weights. Nevertheless, to stabilize soils by mixing 25% and 30% weight of additives, the addition of approximately 3% of DuraCrete to the total weight of the additives can noticeably develop soil strength and stabilization. Mix 25A-3D showed an increase in the strength of about 14% compared to the strength presented by mix 25A-2D, and an increase in the unconfined strength of about 17% was detected for the mix 30A-3D compared to that of mix 30A-2D.

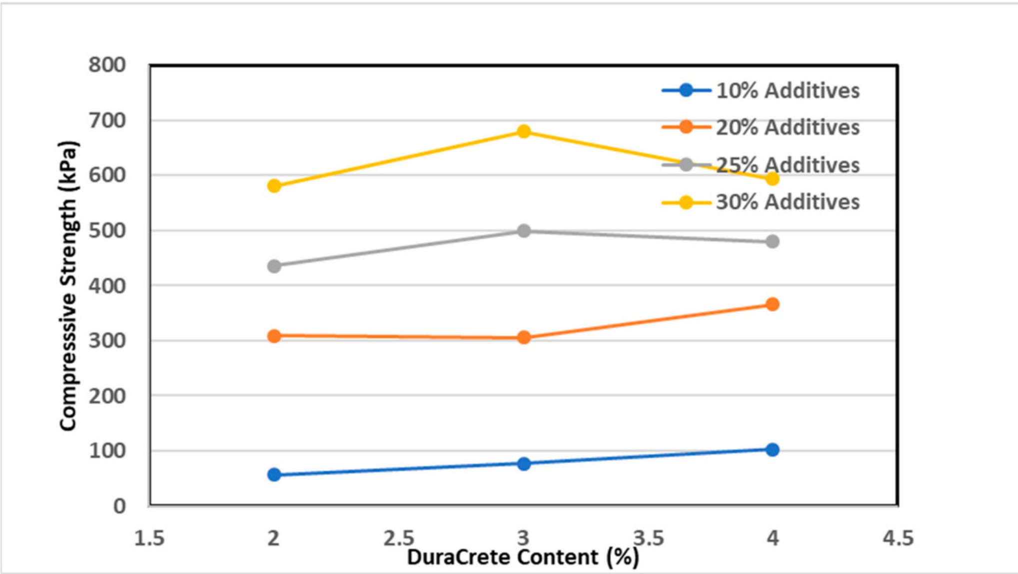


Figure 12. The development of the strength as a function of DuraCrete content.

3.2.3. The Effect of Additives Contents on Soil Stabilization

The effect of mixing four ratios of additives on the unconfined strength of additives mixed soft soils is presented in this section of the study. As mentioned earlier in the methodology of this study, percentages of 10%, 20%, 25%, and 30% were adopted, representing the proportions of soft soil weights substituted by equivalent weights of additives. The results of the tested specimens are presented in Figure 14. The findings indicate that the unconfined strength of the additive added soils is linearly proportional to the content of total additives with the range used in this study. Notably, the mixture with a 30% content of additives demonstrated a more significant gain in strength compared to those with other additive contents.

The figure illustrates similar strength development behavior as the total additives increase for the mixes with 0%, 2%, and 4% content of the cement modifier. However, specimens with a 3% content of the cement modifier exhibited particularly noteworthy behavior, especially for the mixes with 25% and 30% content of additives.

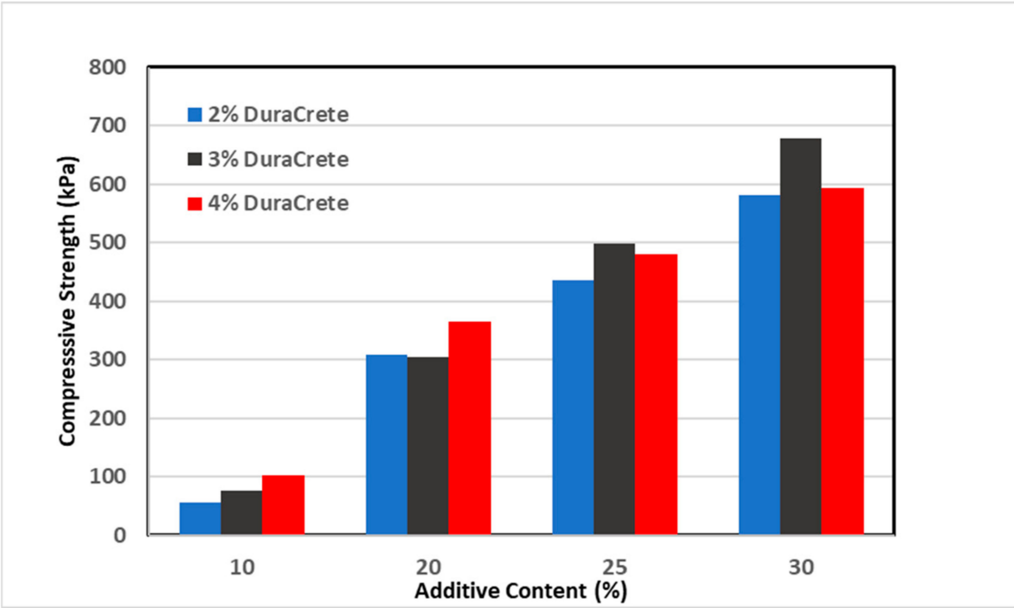


Figure 13. The optimum content of DuraCrete.

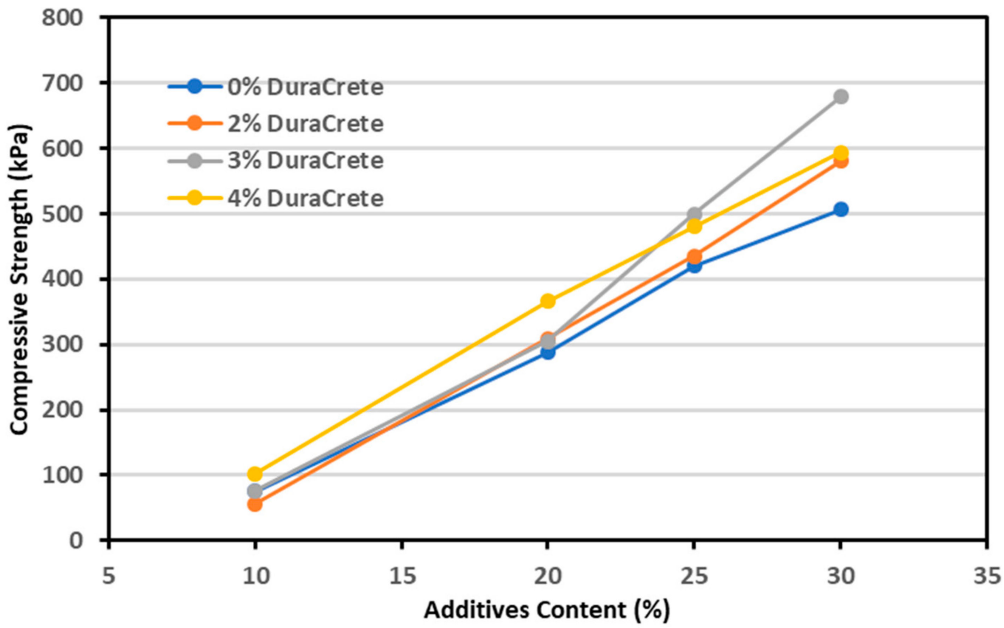


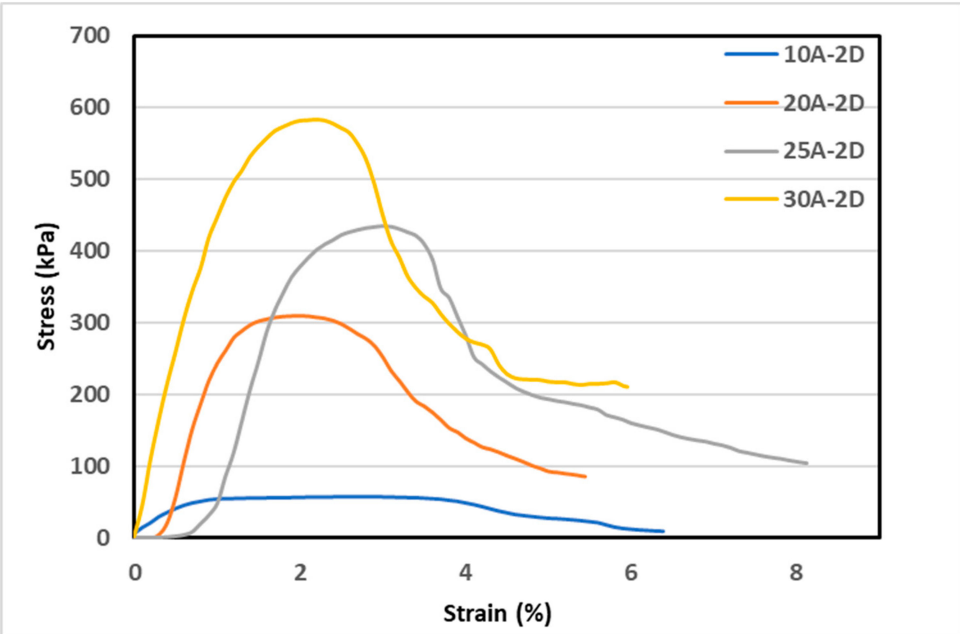
Figure 14. The effect of additives content on compressive strength.

3.2.4. Stress–Strain Behavior

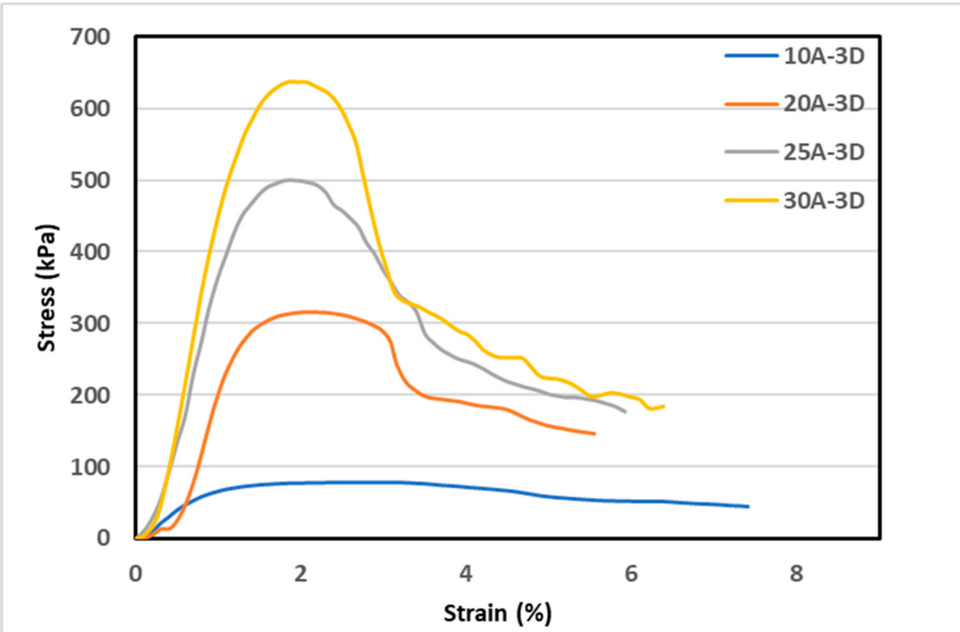
The behaviors of the additive-treated soil specimens are categorized based on the ratio of DuraCrete, as presented in Figure 15. Generally, the figures exhibit a linear ascending trend in each curve, indicating the elastic region followed by a nonlinear ascending trend. The ultimate stress is discernible in the stress–strain curves of each group, where the slope becomes zero. At the ultimate stress point, the first crack has already occurred. Subsequently, at this stage, each curve shows a nonlinear descending cord indicating the failure phase of the specimen. In this part of the curve, the initiated crack starts growing, and new cracks initiate, causing a progressing failure.

In the case of specimens with 0% of DuraCrete, the curves exhibit a sharp slope for the descending portions, indicating a brittle failure compared to those of the specimens contained a cement modifier. This highlights the ability of DuraCrete to improve the capability of the treated soil in sustaining applied loads after the ultimate load.

The shape of the curves clearly illustrates that the soft behavior of the untreated soils is characterized by high deformation at very low corresponding stress. In contrast, treated samples showed convex curves indicating active confinement resistance resulting in high stress with notability smaller deformation. Additionally, treated soil specimens presented curved with notable ascending trends holding the stress before reaching ultimate loads followed by descending chords, which is indicative of the characteristics commonly observed in construction soils.

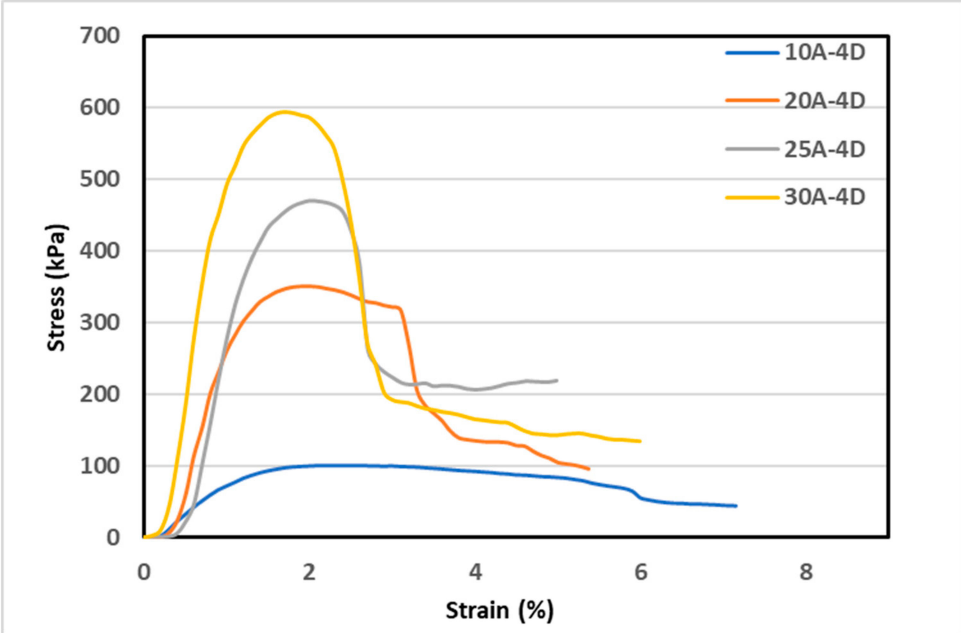


(**a**)

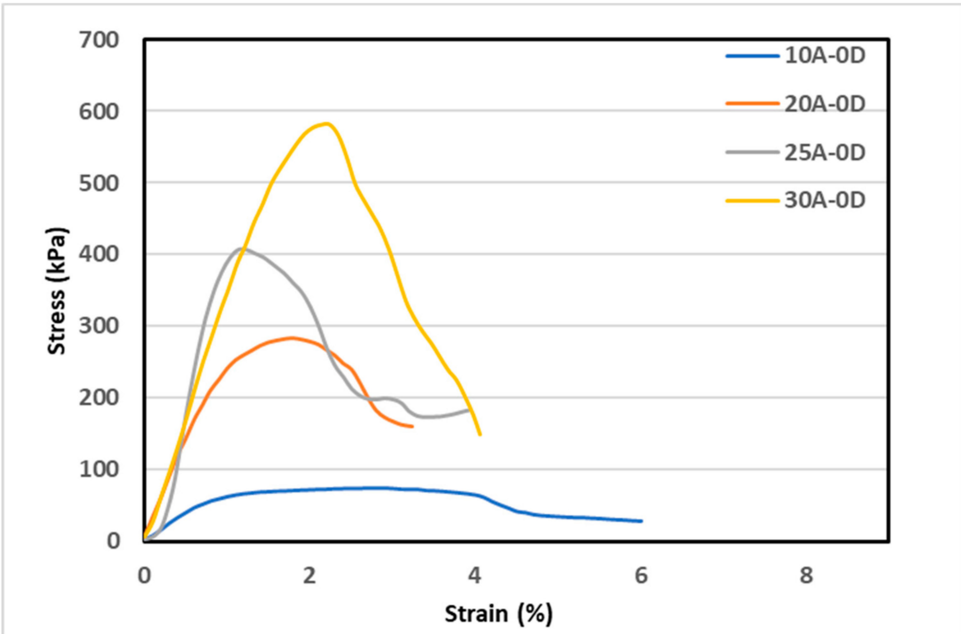


(**b**)

Figure 15. *Cont.*



(**c**)

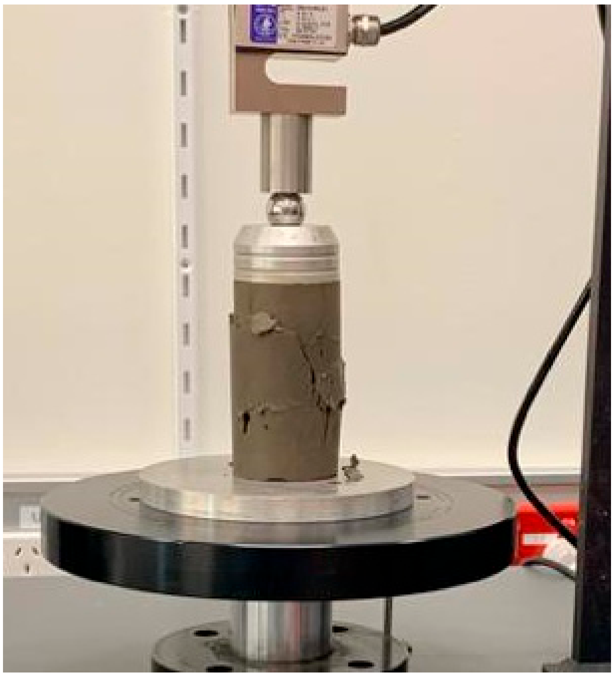


(**d**)

Figure 15. Stress–strain behavior of tested specimens with DuraCrete content of: (**a**) 2%; (**b**) 3%; (**c**) 4%; (**d**) 0%.

3.2.5. Failure Patterns

During the testing process, failure patterns of the treated soil samples were observed revealing two distinct failure modes. For specimens with 10% additives, soft failures were detected when multiple cracks initiated at the peak point and propagated in random directions as the load increased. This phenomenon resulted in the characteristic flat shape of the stress–strain curves, as presented in a previous section in this study; see Figure 15. As the load increased, the initiated cracks progressed, continuing until the test stopped at approximately 6% axial strain. This behavior is eminently similar to typical soil behavior, which is attributed to the low content of additives. As the content of additives increases, the failure modes of the specimens become more localized, with the cracks decreasing but exhibiting notable growths in crack width. Generally, the failure of the samples with a high content of additives commenced when loads reached peak values. At this stage, cracks initiated and progressed in the center of the specimens. With increasing loads, the cracks propagated toward the two ends in more noticeably diagonal directions, indicating shear failure along with the development of new cracks in different directions. Such behavior of treated soils is detected in previous studies such as [18]. Some tested samples are presented in Figure 16.



(**a**)

(**b**)

Figure 16. *Cont*.

(**c**)

Figure 16. Failure modes of tested samples: (**a**) mix with 10% additives; (**b**) mix with 30% additives; (**c**) different mixes.

4. Conclusions and Recommendations

In this experimental investigation, the southeast Queensland clay collected from the Port of Brisbane region, categorized as a soft clay, underwent treatment by adding a combination of cement and DuraCrete to enhance its geotechnical properties. Initial tests and soil preparation were conducted to determine the soil properties. To assess the performance of the additives treated soil, unconfined compressive strength test was carried out. Four additives contents were studied (10%, 20%, 25%, and 30% of soil dry weight); and three DuraCrete to cement ratios were employed (2%, 3%, 4%) alongside control samples with zero DuraCrete content. This led to a total of 32 cylindrical samples, each with a dimension of 50 mm in diameter and 100 mm in height. These samples were prepared, cured and treated under identical conditions at the geotechnical laboratory of Griffith University, Gold Coast campus. After a 28-day curing period, the specimens underwent unconfined compression conditions. The primary conclusions and recommendations of this study are derived as follows:

- Increases in unconfined strength were observed with the addition of DuraCrete to the mixtures. For example, increases of about 15%, 34%, and 17% were detected for samples with 30% of total additives and 2%, 3%, and 4% of DuraCrete contents, respectively.
- For samples with 10% and 20% of added stabilizer, the unconfined strength development of those treated with additives contained 4% DuraCrete overcome those of 2% and 3% DuraCrete mixed additives.
- The addition of 3% DuraCrete to total additives content was found to provide significant stabilization compared to the 2% and 4%, for 25% and 30% additives treated soils.
- The stress–strain behavior of the soils containing DuraCrete indicates capabilities of the samples to sustain applied loads after the ultimate load, resulting in a soft descending trend that indicates soft failure rather than the unwanted brittle failure.
- DuraCrete can be regarded as a promising material when added to cement for the stabilization of soft soil. This can be applied on southeast Queensland soft soils to acquire needed supports and capacities to carry the loads of constructions.
- Because of the small contents of DuraCrete compared to the total content of additives, it is recommended to use dry mixing to the additives to reach homogeneity and consequently the required activity of the additives.

- Further research is needed to explore the effectiveness of using DuraCrete when added with materials such as lime, fly ash, etc. to develop soft soils. Additionally, research could be extended to cover more geotechnical paraments such as California bearing ratio (CBR), triaxial shear test, etc.

Author Contributions: Conceptualization, N.A.-H. and D.E.L.O.; Writing—original draft preparation, A.N.A.-G. and N.A.-H.; Writing—review and editing, A.N.A.-G. and N.A.-H.; Supervision, D.E.L.O.; Validation, D.E.L.O., A.N.A.-G. and Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data will be available upon publication.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Peltier, L.C. The geographic cycle in periglacial regions as it is related to climatic geomorphology. *Ann. Assoc. Am. Geogr.* **1950**, *40*, 214–236. [CrossRef]
2. Granger, K.; Leiba, M. The south-east queensland setting. In *Natural Hazards and the Risks They Pose to South-East Queensland*; Australian Geological Survey Organisation and Bureau of Meteorology: Canberra, Australia, 2000.
3. Liu, Z.; Liu, Y.; Bolton, M.; Ong, D.E.; Oh, E. Effect of cement and bentonite mixture on the consolidation behavior of soft estuarine soils. *Int. J. GEOMATE* **2020**, *18*, 49–54. [CrossRef]
4. Priddle, J.; Lacey, D.; Look, B.; Gallage, C. Residual Soil Properties of South East Queensland. *Aust. Geomech. J.* **2013**, *48*, 67–76.
5. Willmott, W.F.; Stevens, N.C. *Rocks and Landscapes of Brisbane and Ipswich: Geology and Excursions in the Brisbane, Ipswich, and Pine Rivers Districts*; Geological Society of Australia Incorporated, Queensland Division: Brisbane, Australia, 1992.
6. Oh, E. Geotechnical and Ground Improvement Aspects of Motorway Embankments in Soft Clay, Southeast Queensland. Ph.D. Thesis, Griffith School of Engineering, Griffith University, Nathan, Australia, 2006.
7. Transport Technology. *Geotechnical Investigation: Brisbane Port Road—Stage 2 Investigation*; Report No. R3197; Queensland Department of Main Roads: Brisbane, Australia, 2000.
8. Vickers, N.J. Animal communication: When i'm calling you, will you answer too? *Curr. Biol.* **2017**, *27*, R713–R715. [CrossRef] [PubMed]
9. Shamrock. *EvoCrete-Soil Solidification and Concrete Modification*; Shamrock Geo Science Ltd.: Herne, Germany, 2017.
10. *AS-3972*; Portland and Blended Cements. Australian Standards: Sydney, Australia, 1997.
11. *AS-5101.4*; Methods for Preparation and Testing of Stabilized Materials—Unconfined Compressive Strength of Compacted Materials. Australian Standards: Sydney, Australia, 2008.
12. *AS-1289.1.1*; Sampling and Preperation of Soils-Preperation of Disturbed Siol Sampls for Testing. Australian Standards: Sydney, Australia, 2014.
13. *AS 1289.2.1.1-2005 (R2016)*; Methods of Testing Soils for Engineering Purposes—Soil Moisture Content Tests—Determination of the Moisture Content of a Soil—Oven Drying Method (Standard Method). Australian Standards: Sydney, Australia, 2005.
14. *AS-1289.3.1.1-2009 (R2017)*; Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Liquid Limit of a Soil—Four Point Casagrande Method. Australina Standards: Sydney, Australia, 2009.
15. *AS-1289.3.2.1*; Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Plastic Limit of a Soil—Standard Method. Australian Standards: Sydney, Australia, 2009.
16. *AS-1289.1.2.1-1998(R2013)*; Methods of Testing Soils for Engineering Purposes—Sampling and Preparation of Soils—Disturbed Samples—Standard Method. Australian Standards: Sydney, Australia, 1998.
17. *ASTM-D2166/D2166M-16*; Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM: West Conshohocken, PA, USA, 2016.
18. Gao, L.; Zhou, Q.; Yu, X.; Wu, K.; Mahfouz, A.H. Experimental study on the unconfined compressive strength of carbon fiber reinforced clay soil. *Mar. Georesources Geotechnol.* **2017**, *35*, 143–148. [CrossRef]