“Sustainable Solutions for Soil Stabilization: Evaluating the Impact of Duraflex On Strength and Porosity”

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Abstract
The possibility of improving the engineering properties of a silty clay from Calgary, Alberta was assessed. 144 samples of silty clay soil (S), silty clay-plus-cement (SC), and silty clay-plus-cement-plus-Duraflex Admixture (SCD) were tested for either unconfined compressive strength (qu (UCS)) or splitting tensile strength (STS). Two curing conditions were used (a curing room (100% RH) and the laboratory environment) for different curing durations (7, 14, 28 days, and 10 months). The results indicated that the Lab-cured 10-month samples with Duraflex admixture (DFI) were statistically stronger than the SC and S samples. Small but significant variations in S_T/q_u (STS/UCS) ratios ranging from 0.1-0.27 were observed for different curing durations and conditions. However, when the same type of samples were cured under identical conditions and duration, no statistically significant variation occurred. Brunauer–Emmett–Teller (BET N2) adsorption and desorption analysis resulted in a notable reduction in micro- and mesopores, pore surface area, and pore volume through the addition of DFI, suggesting more pores were filled with cementitious material with the addition of that admixture. Additionally, matric suction (U_a-U_w) analysis through the filter paper method also confirmed that SCD samples compacted at Optimum Moisture Content (OMC) gave 5% and 17% more suction (kPa) strength than samples of SC and S of the same OMC. As matric suction directly affects the soil's strength, DFI-stabilised soils achieved higher matric suction, resulting in statistically higher UCS and STS values.

1. Keywords
Soil stabilization, Duraflex Admixture (DFI), cementitious compounds, unconfined compression strength, splitting tensile strength, matric suction, porosity

Highlights
- The addition of Duraflex to soil stabilized with cement significantly improved unconfined compression strength, elastic modulus and splitting tensile strength.
- Across both curing conditions, SCD resulted in the highest strength performance.
- Samples cured in the lab had higher strength than those cured in the curing room.
- The changes observed through matric suction and BET N_2 analysis indicate less porosity in the SCD samples, aligning with their increased strength.

Abbreviations [1]

[1] DFI- Duraflex Admixture; S-soil; SC-soil plus cement; SCD-soil plus cement plus Duraflex Admixture; UCS or q_u-unconfined compression strength; STS or S_T-splitting tensile strength; GU-general use.

2. Introduction

The construction of structures on sites where the soil exhibits poor engineering properties requires stabilization of the soil. Numerous techniques have been used to stabilize weak soils such as the cut-and-fill method, vertical drainage systems, treatment with biological enzymes and treatment with chemicals [1][2][3][4][5]. Such procedures allow for adequate material properties to be developed in the soil to support foundation loads. Heavy civil infrastructure thus benefits from these advancements. Indeed, stabilizing agents can enhance poor-quality materials affordably to the point where they can be used efficiently in structures such as pavement subgrades [6][7]. Stabilizing agents also improve medium and high-quality natural materials and have effectively stabilized everything from well-graded crushed stones to extremely plastic clays [8][9][10].

The earliest known soil stabilization occurred roughly four thousand years ago through the use of natural materials and methods such as adding vegetation or other organic substances, compaction, layering of stone and gravel etc. A more technological approach to soil stabilization began about eight decades ago [11]. Chemical stabilization is the most common method for mitigating undesirable soil engineering properties. This technique involves mixing weak soil with binders such as cement, lime, fly ash etc. that react chemically in the presence of moisture to adhere/bond particles of soil to one another, leading to a more robust soil structure [12][13,14]. Soil stabilization has been investigated widely, with lime or cement being the most common chemical stabilizers due to their potential to improve the physical and geotechnical characteristics of the treated soil [15,16]. Such stabilized soils can be used in many applications for civil infrastructure including highway pavements or haul roads, parking lots and oil well pads.

Global demand for Ordinary Portland Cement (OPC) is expected to rise at a 5% yearly rate [17]. However, producing 1 tonne of OPC emits around 0.9 tonnes of carbon dioxide (CO_2), requires about 5.6 Gigajoules (GJ) of energy, and uses approximately 1.5 tonnes of virgin quarried materials [18]. OPC, which has traditionally served as the principal binder in building materials, accounts for around 5% to 7% of worldwide CO_2 emissions [19]. This has led to a tremendous amount of interest in substituting a more ecologically friendly binder for cement to lessen the environmental impact of cement-stabilized soils and enhance concrete modification while improving engineering properties. Duraflex Admixture (DFI) is a proprietary 4th generation soil stabilization cement admixture. With cement, DFI can turn all types of ordinary soil into valuable construction material, potentially eliminating the need for expensive aggregate sub-surface materials to be mined, transported, and placed.

Strength, permeability, consistency, and environmental benefits from stabilizing soil with cement and DFI were therefore examined in the laboratory. Unconfined compression (UCS) and splitting tensile (STS) tests were conducted on samples of soil (100% soil), soil (90%) plus cement (10% by total dry weight of sample) (SC) and soil (90%) plus cement (10% of total dry sample) plus Duraflex Admixture (2% by dry weight of cement) (SCD). Two different curing conditions were examined: curing in the fog room (100% RH, 20°C) and the laboratory environment. Samples were tested after 7, 14, 28 days, and 10 months of curing. In addition to UCS, and STS, the S_T/q_u ratio was also derived to measure the variation between test duration and curing condition. Lastly, on all three types of samples, Brunauer-Emmett-Teller (BET N_2) analysis was conducted resulting in an in-depth analysis of pore volume, and pore surface area in addition to assessing the matric suction (U_a-U_w) which provided information on the pore air, and pore water pressure.

3. Materials and Methods

3.1. Materials

3.1.1. Soil

The soil used in this research was collected from North Dufferin Industrial Park in Southeast Calgary, Alberta, Canada. A pit 3 meters in depth was excavated and the soil was collected. The soil was classified as a well-graded silty clay (group classification A-4), according to the American Association of State Highways and Transportation Officials (AASHTO) classification system [20]. The physical properties of the soil are presented in Table 1. Quantitative X-ray diffraction analysis (Q-XRD) (performed at Activation Laboratories Ontario Canada (Actlabs Ontario), and the Department of Chemistry, University of Calgary) indicated that quartz, feldspar, and chlorite were the main components in the soil. The elements silica, calcium, aluminium, potassium, etc. mentioned in Table 2 were observed through scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) performed at the Department of Chemical and Petroleum Engineering, University of Calgary. The main mineralogical composition of the soil is quartz (SiO_2), plagioclase ($Na_{0.5}Ca_{0.5}Si_3O_8$), muscovite ($KAl_2Si_2AlO_{10}(OH)_2$), calcite ($CaCo_3$) and dolomite ($CaMg\ (CO_3)_2$) as shown in Figure 1.

Table 1. Physical and chemical properties of silty clay soil

Property	Value
Soil type	Silty soil/clay (AASHTO group A-4)
In Situ moisture content of soil	17%
Grain size distribution (%)	4.99 % Sand, 40.21% Silt, 54.8% Clay
Liquid Limit, wL (percent)	28 %
Plastic Limit wP (percent)	21.89 %
Plasticity Index, pI	6.01 %
Specific Gravity of soil (G_s)	2.6
pH	7.95
Organic content/ Loss on Ignition test (LOI)	4.57%

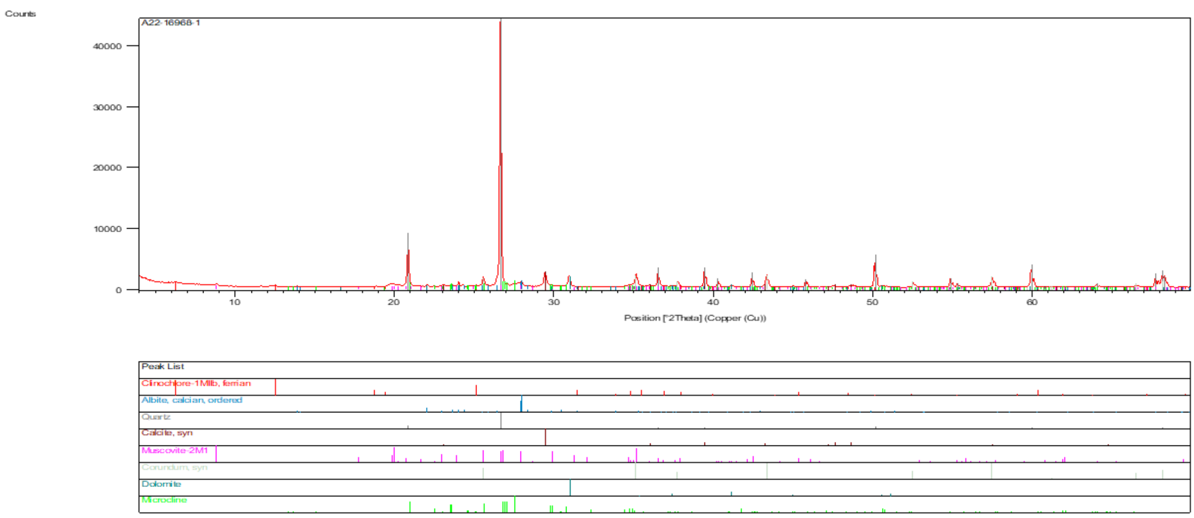


Figure 1. Quantitative XRD analysis on the silty clay soil sample (Act Labs Ontario)

Table 2. Elements and Oxides in silty clay soil as per SEM/EDS analysis

Element (symbol)	Characteristics (weight concentration)	Oxides	Characteristics (%)
Oxygen (O)	34.22	Silicon oxide (SiO_2)	35.92
Silicon (Si)	15.55	Calcium oxide (CaO)	32.11
Carbon (C)	21.25	Potassium oxide (K_2O)	3.99
Iron (Fe)	19.72	Magnesium oxide (MgO)	3.14
Aluminium (Al)	6.19	Others/unidentified	---
Potassium (K)	3.07		

3.1.2. Cement

General use type (GU) OPC, meeting the specifications and standards of ASTM C 150 [21], was used as a binder material for the stabilisation of the soil. Cement can hydrate and react with a soil's minerals in the presence of water improving engineering properties of the soil such as strength, durability etc. The main mineralogical composition of the OPC used was hatrurite (Ca_3SiO_5 (C_3S)), brownmillerite ($Ca_4Al_2Fe_2O_{10}$ (C_4AF)), gypsum ($CaSO_4.2H_2O$), calcite ($CaCO_3$), portlandite (Ca $(OH)_2$), periclase, larnite (β-Ca_2SiO_4 (C_2S)), dolomite (CaMg $(CO_3)_2$) as shown in Figure 2.

Table 3. Cement composition

Stabilising agent	Composition	Source/supplier
Cement	Ordinary Portland Cement (OPC) Types GU	QUIKRETE

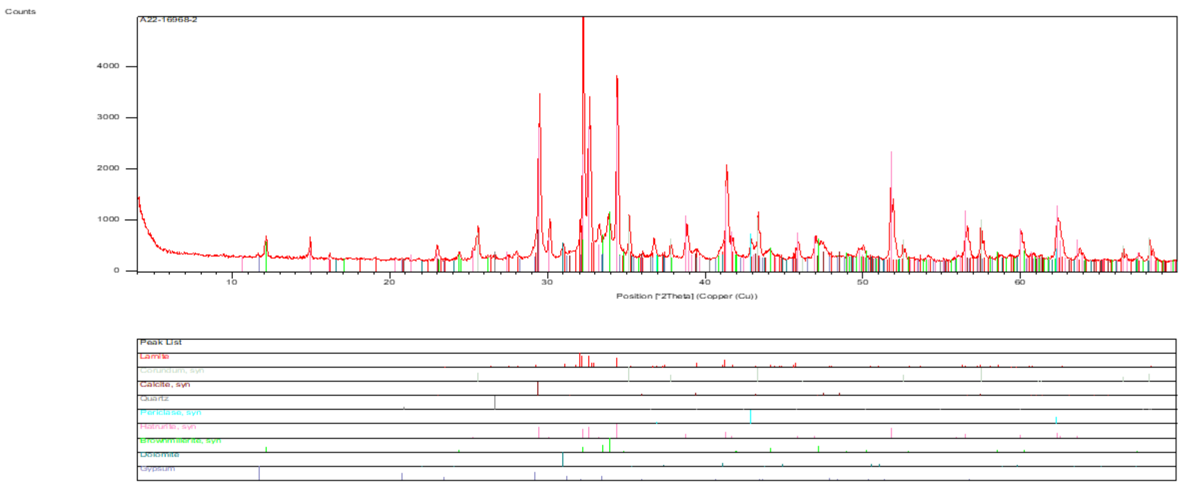


Figure 2. Quantitative XRD analysis on the Portland cement type GU (Act Labs Ontario)

3.1.3. Duraflex Admixture (DFI)

Duraflex Solution Limited provided the proprietary DFI for this study.

3.1.4. Water

Distilled water was used throughout the experimental program. The main reason for using distilled water was for consistency in outcomes.

4. Methodology

4.1. Preparation for test materials

The soil received from the site contained moisture and debris. To ensure consistency and reliability in the testing, the soil needed to be prepared. First, the soil was oven-dried for 24 hours according to ASTM D2216-19 at 110 ± 5 °C to remove field moisture [22]. Debris and boulders were removed from the dried soil after cooling. A Bico crusher and Bico pulverizer were used to crush the soil chunks into the desired size. After pulverizing, the soil was sieved through a No. 40 sieve (4.75 mm) according to ASTM D698-21 and used in the preparation of the specimens [23]. The cement and DFI needed no preparation and were kept in airtight containers after the bags had been opened to prevent contact with moisture and dampness in the environment.

4.2. Mix design

The UCS and STS samples were prepared from the soil and passed the No.4 sieve (4.75 mm) to follow the ASTM standards and maintain uniformity: any materials retained were discarded. The soil, cement (10% of the total sample dry weight), and Duraflex Admixture (2% of cement by dry weight) were weighed separately before dry mixing in a mechanical mixer for 10 minutes followed by hand mixing with spatulas and small trowels. Standard proctor compaction tests were conducted on the three resulting materials to derive the optimum moisture content (OMC) for their maximum dry densities (MDD). The OMC obtained from this method was then used as a standard for preparing samples of each type.

4.3. Preparation of specimens

To determine the OMC, four samples of each material (S, SC, and SCD) were prepared according to the standard proctor method described in ASTM D698-21 [23]. Once the OMC was determined for each material, that optimum amount of distilled water (pH 7) was added to the mechanical and hand-mixed dry samples. Initially, the mixing was carried out in the mechanical mixer but due to the high cohesion of the clay and adhesion of the soil particles, the wet soil stuck to the mixing pot boundaries and blender blades. Hand mixing was therefore employed thereafter to ensure uniformity of the mix and that all lumps were broken down to less than 5 mm in size.

One hundred and forty-four (144) samples were prepared for the UCS and STS tests in standard proctor test moulds (diameter of 101.6 mm and height of 116.4 mm). Each mould was filled in 3 equal layers with each layer receiving 25 blows with a rammer. The upper surface of the first and second compacted layers was scratched to improve the grip/hold of the subsequent layers. The specimens were demoulded through a hydraulic jack after completion of compaction.

4.4. Curing conditions and duration

After removing the specimens, half (72) were placed in the curing room at 100% humidity, while the other 72 were left in the laboratory. The purpose of the latter was to utilize the laboratory more as a field condition as in practice the soil is typically stabilized and left to hydrate in the open environment. Three samples of each mix were tested for UCS and STS at 7, 14, and 28 days and 10 months.

4.5. Testing Procedure

4.5.1. Unconfined compression test

The UCS was conducted following ASTM D2166-24 for cohesive soils [24]. The samples were tested at an axial strain rate of 1 %/min. The UCS's highest value of stress was calculated from the maximum load reached or the stress value at 15% strain, whichever came first, and the test was stopped according to ASTM D2166-24 guidelines. Considering the measured UCS values, the engineering properties of the stabilized soil were evaluated using the guidelines provided by the ASTM D 4609 [25] which states that “stabilization can be regarded as successful if UCS strength results in a minimum increase of 345 kPa” and the consistency classification (Table 4) proposed by Terzaghi et al., [26].

Table 4. Fine-grained soil consistency classification (modified from (Terzaghi et al.)[26])

Consistency	Unconfined compression strength (UCS, kPa)
Very soft	UCS values less than 24
Soft	Values between 24-50
Medium	Values between 50-100
Stiff	Values between 100-200
Hard/ very stiff	Values between 200-400
Very hard	Values greater than 400

4.5.2. Splitting Tensile Strength Test

The STS samples were tested according to the method adopted by Thompson [27] and Ramanathan [28]. The splitting test is primarily used for the evaluation of the splitting properties of concrete as per ASTM C496. This test is easily adopted for stabilized highway materials which are brittle in nature and have low tensile strength. In the STS, the cylindrical samples were placed horizontally between the loading platens, loading strips were placed above and below the sample as shown in Figure 3 to distribute the load. Usually, specimens which are brittle and have low tensile strength fail along the loaded diameter. The samples were tested at a strain rate of 1 %/min.

Figure 3. Splitting tensile strength test

In adopting the STS for cohesive soils, it is important to know whether the soil is brittle. Here, the soils behaved as hard/ brittle materials, fulfilling ASTM D 4609 standards and the consistency classification by Terzaghi et al. [26].

The STS was determined from:

$$St = \frac{2\mathrm{P}}{\pi \mathrm{DL}}$$

Where:

St = Splitting tensile strength (MPa)
P = Failure load in Newtons (N)

D = Diameter of cylindrical specimen (mm)
L = Length of cylindrical specimen (mm)

4.6. Pore Structure Analysis

4.6.1. Brunauer–Emmett–Teller Analysis

Brunauer–Emmett–Teller Analysis (BET N2 analysis) was performed on S, SC, and SCD samples to evaluate the microporosity and surface area of the pores. The de-gassing process took place at 105 ℃ to ensure all gasses and/or adsorbed moisture were removed from the samples. The samples were then allowed to cool down in the desiccator and were subsequently tested for Nitrogen adsorption in a Beckman Coulter J26S-XP. Specific surface area information was calculated after adsorption of nitrogen at the isotherm in the pressure range (P/P_o) of 0.01 to 0.96 (P_o being the saturation pressure of nitrogen). In addition, microporosity was identified through the Barrett-Joyner-Halenda (BJH) method providing the pore size distribution of the samples. This evaluation of the porosity and surface area through BET N_2 was performed to determine if there was a change in the microporosity which could account for the improvements in mechanical strength, as demonstrated in the UCS and STS tests after the incorporation of DFI.

5.6.2 Matric suction

This test was used to determine the matric suction (U_a-U_w) characteristics of the compacted silty clay soil and how matric suction affects soil strength. In this study, an indirect method (the filter paper method) according to ASTM D5298-16 was used [29]. In this method, a filter paper was placed in direct contact with the specimen. After moisture is exchanged, usually taking from 8 to 14 days, an equilibrium state is achieved. Following the standard, Whatman No. 42 filter papers with diameters of 55 mm and 60 mm were used. A formaldehyde solution (2%) was prepared, in which the filter papers were soaked for 24 hours to prevent any mould formation. S, SC, and SCD samples were compacted at 4% and 3% below OMC, at OMC, and at 3% and 4% above OMC. The samples were compacted in a standard proctor mould and immediately after removing from the mould one filter paper having 55 mm diameter was sandwiched between 60 mm diameter filter papers and placed on the mould and similarly, two more 55 mm diameter sandwiched filter papers were placed equally distanced from each other around the circumference on the compacted sample as shown schematically in Figure 4. Each specimen was then sealed in a plastic bag with the help of an air suction machine and double-sealed airtightly. The sealed samples were placed in a curing room with a temperature of 21 °C ± 2°C for 10-12 days, allowing the samples to attain a moisture equilibration state.

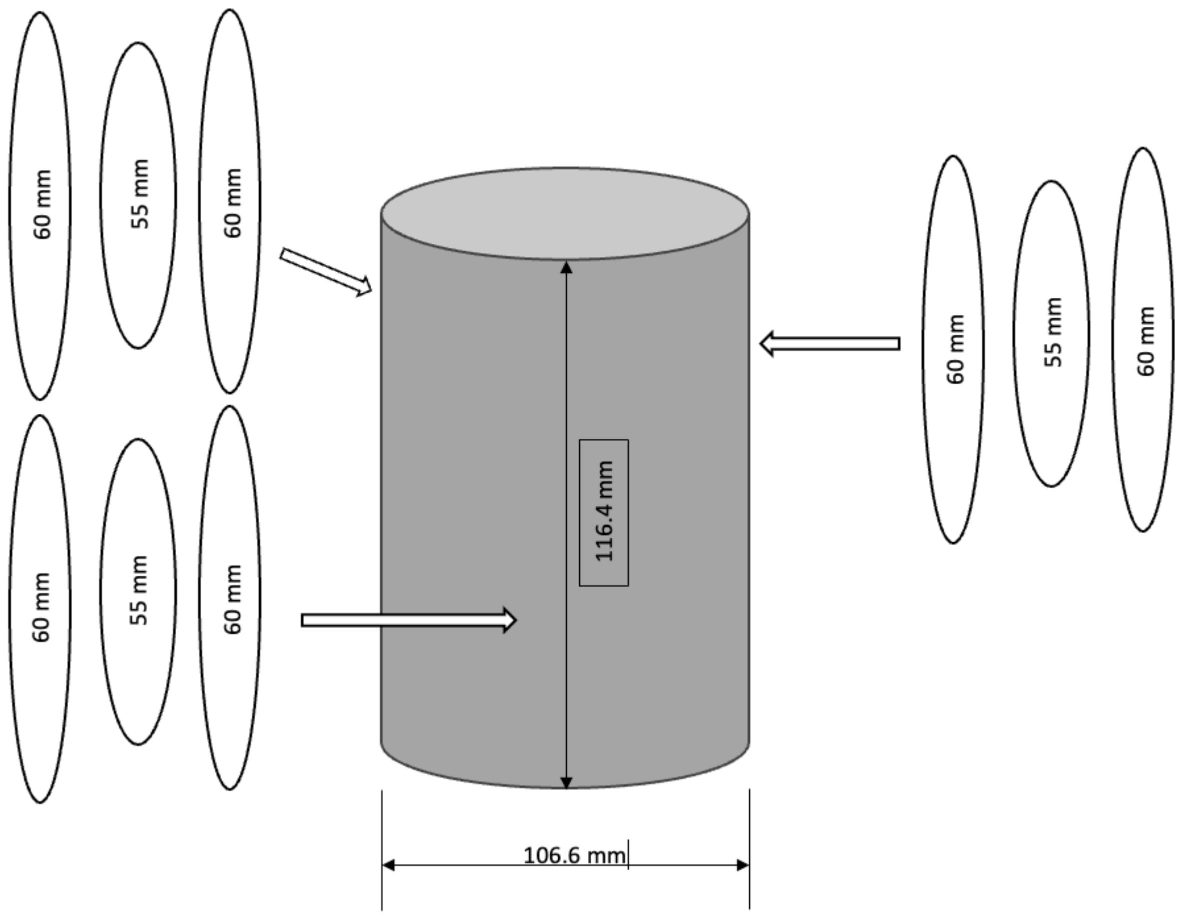


Figure 4. Schematic of Whatman No.42 filter paper placement on mould.

Upon equilibration, the moist 55mm diameter filter papers were removed carefully with two tweezers and weighed followed by oven-drying and re-weighing to obtain the water content percentage. The calibration curves were used to determine soil matric suction. [30] [31]

Log (matric suction in kPa) = 4.945 – 0.0673w (for water content, $w < 47\%$)

Log (matric suction in kPa) = 2.909 – 0.0229w (for water content, $w \geq 47\%$)

5. Results and discussion

5.1. Unconfined compression strength

The UCS values for S, SC, and SCD specimens at 7, 14, 28 days, and 10 months under both curing conditions (Lab and curing room) are presented in Table 5. The values are the average and standard deviation of three specimens. As may be seen in the table and Figure 5, the UCS increased from 7 days to 10 months for all types of samples. The addition of Duraflex (SCD) resulted in the highest strengths under both curing conditions, providing soil strengths statistically greater (t-test) than cement alone at all ages when cured in the laboratory except at 7-days.

The UCS values in Table 5 were also assessed against ASTM D 4609 [25] which states that if the minimum UCS value is 340 kPa or above for any type of soil modification/stabilisation then the stabilisation is effective. Additionally, the UCS values in the mentioned table were also assessed by the consistency classification of Terzaghi et al. [26]. According to these criteria, the modification to the silty clay soil using cement and Duraflex admixture stabilising agents worked well, resulting in greater strength than the lower limit of ASTM D 4609 and qualifying as "Hard" according to Terzaghi's consistency classification.

Table 5. UCS test results

Curing duration	Sample type	UCS samples (kPa) in Curing Room	Standard deviation, (kPa)	UCS samples (kPa) in Lab condition	Standard deviation, (kPa)	UCS increase (kPa) ASTM D4609	Consistency Classification (Terzaghi et al., 1996)
07 Days	S	366	98	1700	101	**>340**	Stiff
	SC	2186	165	3402	211	**>340**	Hard
	SCD	3110	1033	3900	328	**>340**	Hard
14 Days	S	971	171	1600	124	**>340**	Hard
	SC	2644	119	3160	229	**>340**	Hard
	SCD	3983	233	4970	216	**>340**	Hard
28 Days	S	2271	294	2488	223	**>340**	Hard
	SC	4427	180	4873	141	**>340**	Hard
	SCD	4661	168	5465	158	**>340**	Hard
10 months	S	2460	198	3352	193	**>340**	Hard
	SC	6143	138	6494	261	**>340**	Hard
	SCD	6428	156	7331	189	**>340**	Hard

Note: the values stated are the average of triplicate samples
The bold values indicate ASTM D 4609 (standard guide) standards satisfied

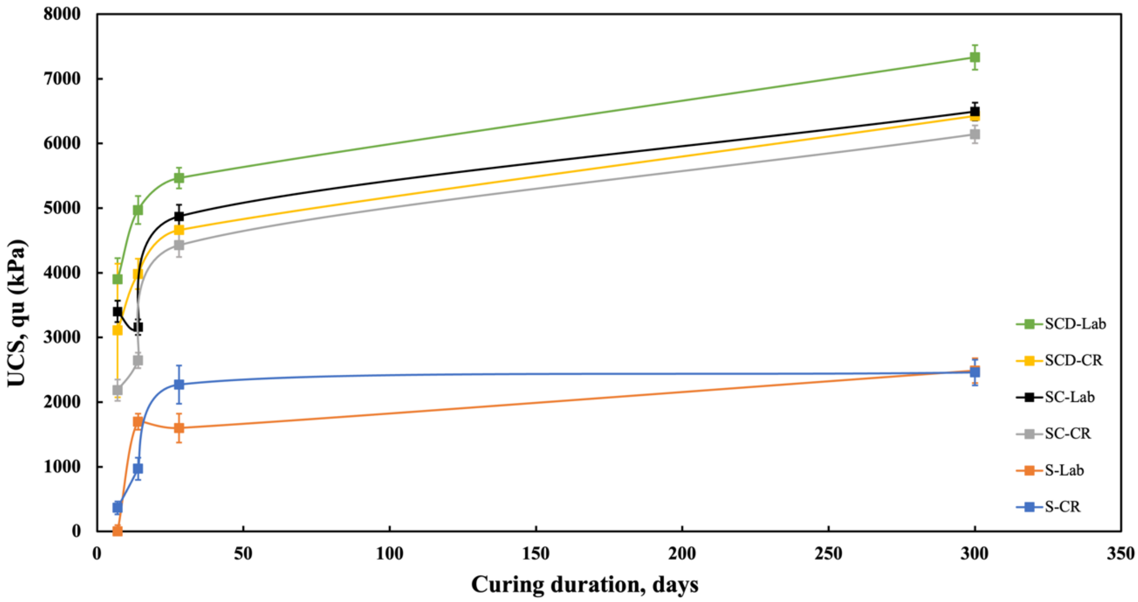


Figure 5. UCS (kPa) vs curing duration (days)

5.1.1. UCS stress-strain relationships

The stress-strain relationships of all specimens were obtained. The 28-day results/curves are presented in Figures 6-8. The displacement over the full height of the specimen was obtained with a linear variable differential transformer (LVDT) which was then converted to strain, % values. The addition of cement and cement plus DFI makes the mixes slightly more brittle in that there appears to be less of a descending branch post-peak.

The stress-strain behaviour of all samples whether S, SC, and/or SCD depended upon both curing duration and curing conditions. When cured in the lab, the average peak strain at 7 days of compacted S samples was 5.71%, reducing to an average of 3.26% at 10 months. Similarly, SC samples had an average peak strain of 5.7% at 7 days of curing, reducing to 2.64% at 10 months. Lastly, the average peak strain of SCD samples was 5.06% at 7 days while at 10 months the average peak strain reduced to 1.39%. Similarly, when cured in the curing room the average 7-day peak strain for compacted S samples was 7.05%, reducing to 4.51% at 10 months. For SC and SCD specimens the average peak strains reduced from 6.33% and 5.01 % at 7 days to 4.01% and 2.76% at 10 months respectively. This decrease in strain with curing time was due to the continuous cement and DFI hydration. The reaction products of the DFI in the SCD mixes resulted in a more dense structure and a reduction in pore volume over time, which in turn results in higher strength.

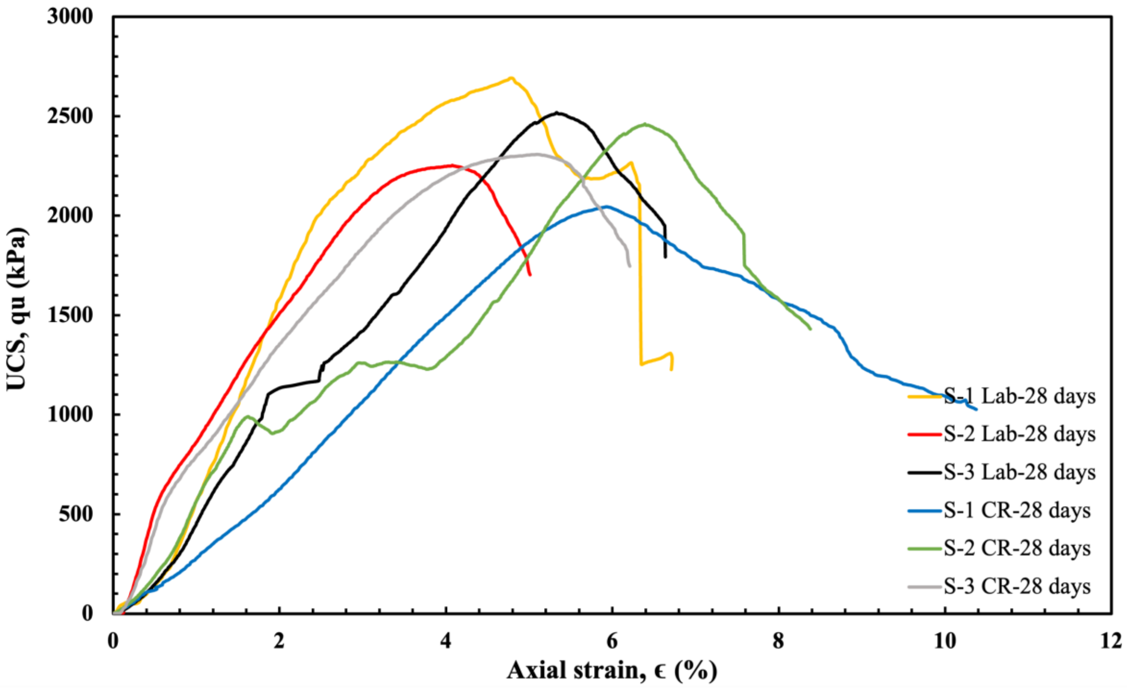


Figure 6. UCS 28-day stress-strain curves of S (Lab, and CR samples)

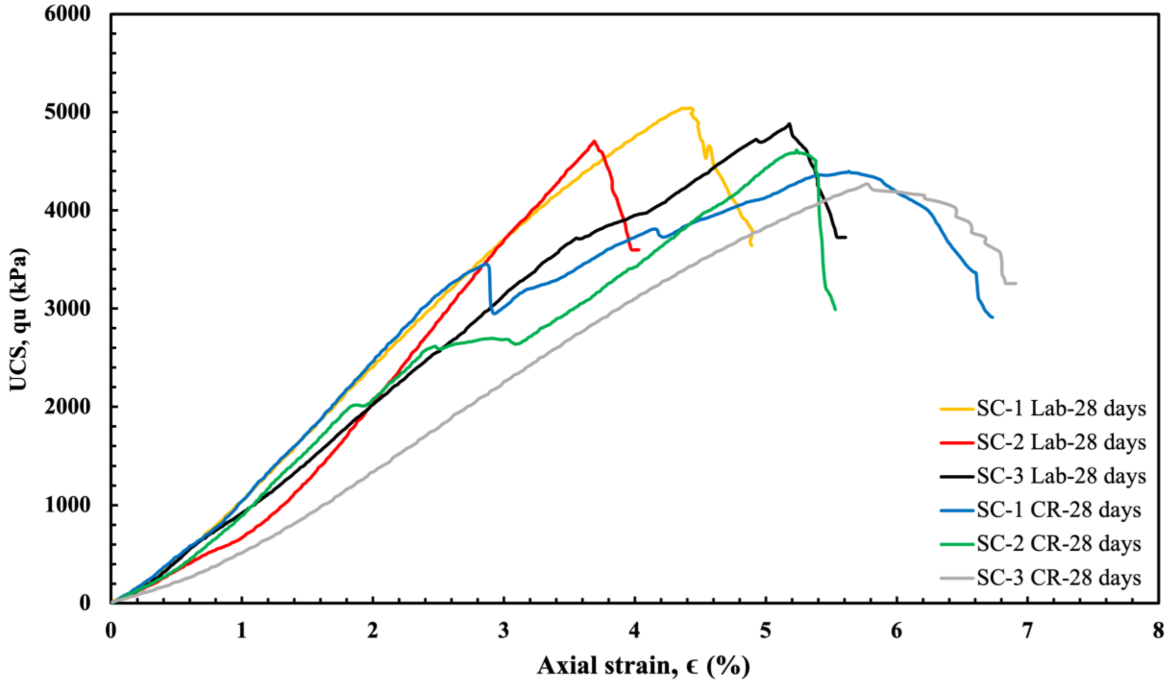


Figure 7. UCS 28-day stress-strain curves of SC (Lab, and CR samples)

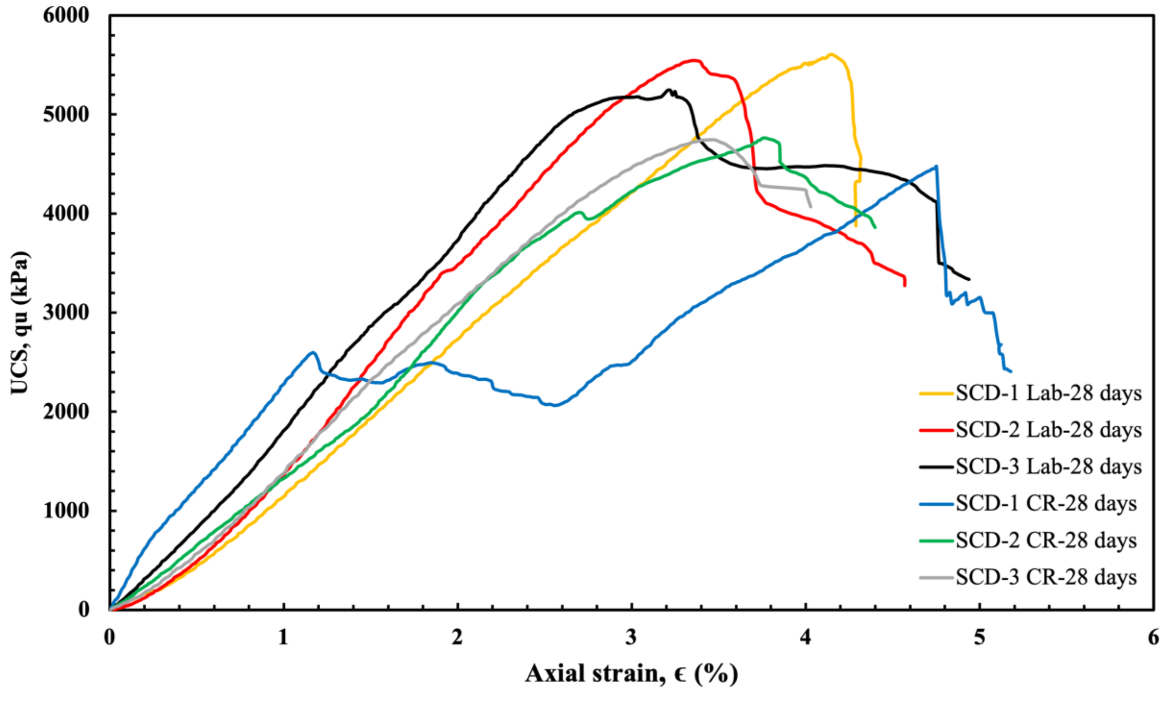


Figure 8.UCS 28-day stress-strain curves of SCD (Lab, and CR samples)

5.1.2. Elastic modulus analysis

The elastic modulus was calculated for all three types of samples as the slope from 5% to 30% of the peak stress and the elastic modulus values are tabulated in Table 6. As may be seen, the SCD specimens were consistently stiffer than the soil alone or the soil stabilized with just cement. The SCD sample results confirmed that when cement and DFI are used in soil stabilisation and weak soil improvement projects soil stiffness and long-term stability will be achieved. Additionally, this improved elastic modulus seconds the idea and research upon using Duraflex for long-term soil stabilisation projects especially where the durability of stabilised surface is important.

Table 6. Modulus of S, SC, and SCD samples between 5 and 30% of peak stress

Curing duration	Sample type	Curing room average Elastic Modulus (kPa)	Standard deviation (kPa)	Lab-Cured average Elastic Modulus (kPa)	Standard deviation (kPa)
07 Days	S	30910	38946	40060	600
	SC	55160	24114	77380	7504
	SCD	70930	35327	116540	26911
14 Days	S	29080	1973	65000	12309
	SC	61120	5430	85470	36313
	SCD	100910	39932	121140	23912
28 Days	S	69340	34242	88980	27859
	SC	111330	27707	120370	9212
	SCD	169970	30097	172170	4373
10 months	S	130640	51617	188000	45711
	SC	191190	36415	518000	586239
	SCD	386600	104183	829020	641827

Note: the values stated are the average of triplicate samples

5.2. Splitting Tensile Strength

The results of the splitting tensile tests are tabulated in Table 7. For soil-only samples, the STS strength increased from 100 kPa at 7 days to 250 kPa at 10 months in the curing room while in the lab-cured the increase was from 170 kPa to 400 kPa. SC samples increased from 500 kPa to 820 kPa in the curing room and from 630 kPa to 930 kPa in the laboratory. Samples including Duraflex (SCD) rose in strength from 7 days to 10 months from 610 kPa to 1000 kPa in the curing room and from 697 kPa to 1200 kPa in the laboratory. Similarly, after performing the t-test the SCD samples were statistically stronger than the SC samples with the difference increasing from day 7 to 10-months.

Table 7. Splitting tensile test results and ratio to unconfined compression strength (S_T/q_u)

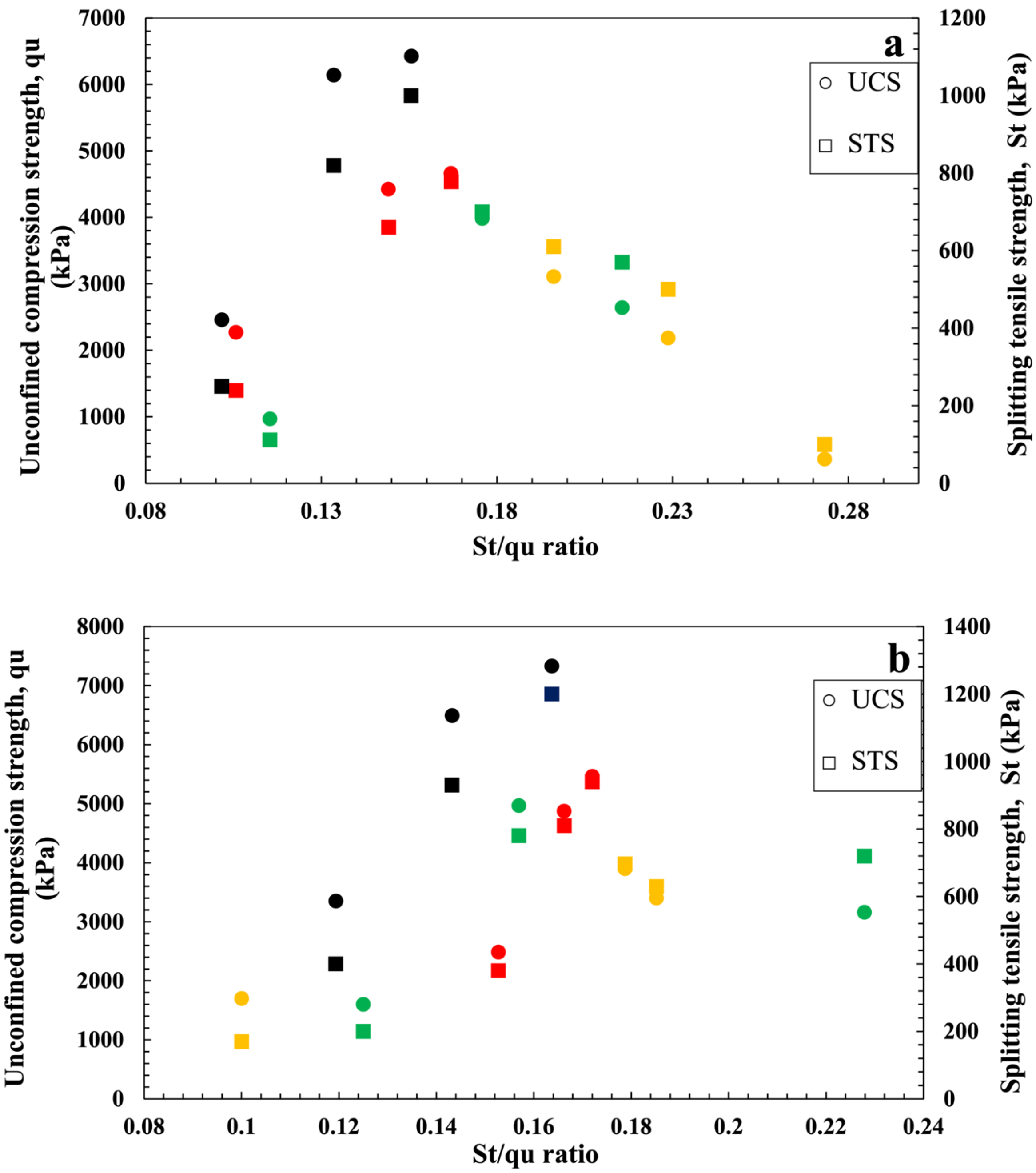
Curing duration	Sample	Split tensile test	Standard deviation, (kPa)	Ratio (S_T/q_u)	Split tensile test (kPa) Lab	Standard deviation, (kPa)	Ratio (S_T/q_u)

		(kPa) Curing room samples		Curing room samples	condition samples		Lab condition samples
7 days	S	100	62	0.27	170	53	0.10
	SC	500	87	0.23	630	96	0.19
	SCD	610	90	0.20	697	88	0.18
14 days	S	112	64	0.12	200	60	0.13
	SC	570	71	0.22	720	89	0.23
	SCD	700	86	0.18	780	63	0.16
28 days	S	240	60	0.11	380	63	0.15
	SC	660	77	0.15	810	70	0.17
	SCD	778	94	0.17	940	73	0.17
10 months	S	250	62	0.10	400	66	0.12
	SC	820	87	0.13	930	71	0.14
	SCD	1000	89	0.16	1200	85	0.16

Note: the values stated are the average of triplicate samples

5.2.1. Splitting Tensile Strength to Unconfined Compression Strength (S_T/q_u) ratio

The ratios of the splitting tensile strength to the compressive strength (the S_T/q_u ratio) for S, SC, and SCD samples are listed in Table 7. It may be seen that for the soil samples, the S_T/q_u ratio decreased from 0.27 at 7 days to 0.1 at 10 months in the curing room with most of the change occurring between 7 and 14 days. With laboratory curing the ratio stayed in the range of 0.10 to 0.15. For soil plus cement samples, the S_T/q_u ratio decreased from 0.23 to 0.13 in curing room samples and from 0.19 to 0.14 in the laboratory cured samples from day 7 to 10 months respectively. In the curing room, the reduction in the ratio was slower than for soil samples alone. For the laboratory-cured samples, the ratio was higher at 14 days than at 7, which may be a reflection of the variability of the ratio. Lastly, for the samples with Duraflex admixture, the S_T/q_u ratio decreased from 0.20 to 0.16 over the 10 months in samples from the curing room while staying in the range of 0.18 to 0.16 in the samples cured in the laboratory. The tensile strength being in the one-tenth to one-sixth range of the compressive strength is consistent with other cementitious materials. The trend of a reduction in the value of the ratio for some mixes in certain curing conditions suggests different rates of strength gain between compressive and tensile strength over the 10-month period. For example, for the soil plus cement samples cured in the curing room, the tensile strength rose from 500 to 820 kPa (a 64% increase) whereas the compressive strength rose from 2186 to 6143 kPa (a 180% increase). The mean values of the compressive and tensile strength of the various specimen groups are plotted against their S_T/q_u ratio in Figures 9 a, and b. The lower pair of each colour (curing age) is for S, the middle height for SC and the highest pair for SCD specimens. The variability of the S_T/q_u ratio can thus be seen for each curing age. Interestingly the ratio increases with material type (S to SC to SCD) at both 28 days and 10 months of curing in both curing conditions, but with different patterns for early-stage curing.



<u>Note:</u> Yellow represents 7-Day samples; Green, 14-days; Red, 28-Days; Black, 10-Months

Figure 3. Splitting tensile strength vs. unconfined compression strength ratio (S_T/q_u) (a) Curing room; (b) Lab curing

6. Pore Structure analysis

6.1. Brunauer–Emmett–Teller (BET N2) Analysis

The physisorption experiment was conducted 16 months after casting the samples to fully understand the long-term changes to the porosity and surface area of all three types of samples (S, SC, and SCD). The BET isotherms are shown in Figure 10, while the results derived from the measurements are provided in Table 8.

Table 8. The surface area and porosity of Sample S, SC, and SCD

Sample	Surface Area (m^2/g)	Micropore Surface area (m^2/g)	Pore volume (ml/g)	Micropore volume (ml/g)
S	16.8	5.3	0.065	0.003
SC	10.3	3.9	0.068	0.002
SCD	9.1	3.0	0.057	0.001

The surface areas and pore volumes of all three samples were rather small, confirming that the samples are bulk materials with limited porosities. However, it may be noted that mesopores (2-50 nm) are predominant in these materials as evidenced by the hysteresis loop. The micropore volumes contribute to the total volume by less than 5%, 3%, and 2% for S, SC and SCD samples, respectively. Additionally, the micropore surface area and pore volume decreased in the samples as listed in Table 8, with the SCD having the least micropores.

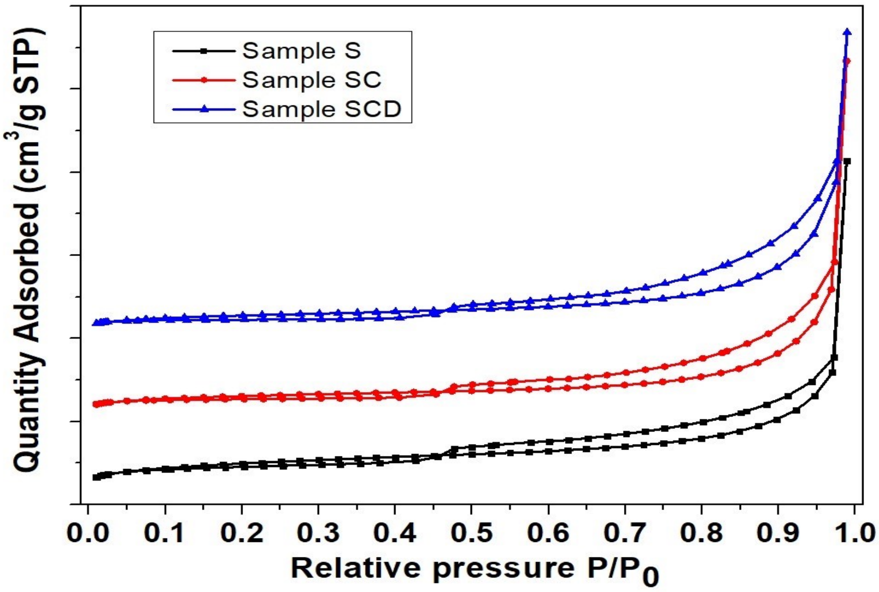


Figure 4. Nitrogen adsorption−desorption BET isotherm of sample S, SC, and SCD

6.2. Matric Suction (U_a-U_w) and soil strength

6.2.1. Soil Water Characteristic Curve (SWCC)

S, SC, and SCD samples were compacted at OMC and with water contents 3% and 4% above and below the OMC level. The matric suction data are plotted against the filter paper moisture content in Figure 11, representing the soil water characteristic curves of matric suction (kPa) of the compacted samples. The SCD samples compacted at 4%, and 3% below OMC and at OMC performed very well by achieving statistically higher matric suction strength in kPa than SC. It is a common phenomenon that when the matric suction forces increase, pore water pressure decreases, resulting in stronger inter-particle forces and therefore improved soil strength. Both these suction data and the BET data indicate that the porosity of the mix with the Duraflex admixture is lower than when cement alone is used to stabilize the soil. That is, the pores are being filled with reaction products from hydration. It is well established that lower porosity increases strength in materials, and this is reflected in both the UCS and STS results.

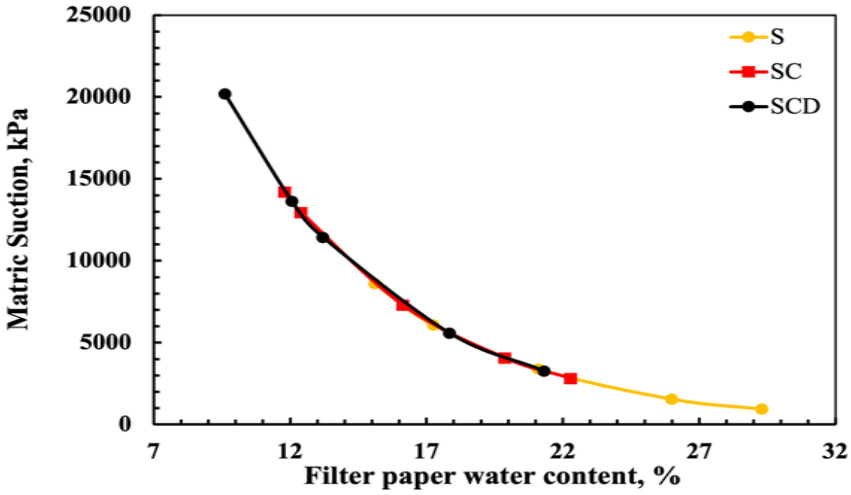


Figure 5. The soil-water characteristic curve of S, SC, and SCD compacted samples

7. Conclusions

The effect of Duraflex admixture usage on soil stabilisation in addition to cement was investigated. Different curing conditions (in the laboratory or the curing room (100% RH)) and different curing durations (7, 14, 28 days, and 10 months) were examined. Both compressive strength and tensile strength increase with time, no matter what the kind of sample and the curing duration, but the gain in compressive strength tends to be higher than the gain in tensile strength. The following conclusions can be drawn from the experimental results:

- The compressive and tensile strength of DFI-stabilised samples was higher than other types under both curing conditions.
- The stress-strain behaviour indicated that SCD Lab-cured were more brittle than similar samples cured in the curing room.
- Small but significant variations in the S_T/q_u ratio were observed ranging from 0.1 to 0.27 under different curing durations and conditions. However, when the same type of sample was cured under identical conditions and duration, no statistically significant variation occurred.
- The best S_T/q_u ratio calculated for DFI stabilised soils is an overall average of 0.16.
- The reduction in micropore surface area and pore volume of DFI stabilised soil examined through BET N_2 analysis confirmed that more hydration products filled these pores which resulted in strength improvement.
- Based on this investigation, if DFI is mixed with soil and cement adding the respective OMC for mixing, hydration, and compaction, there will be no further need for curing. In this way, adding DFI is better for the stabilisation of dirt roads, haul roads, oil well pads (for the oil and gas industry), parking lots, subgrade stabilisation for asphaltic roads, etc.

8. Recommendations for Future Work

- A detailed microstructure-level study needs to be conducted to explain more clearly the behaviour of stabilised soils with the addition of DFI as well as the chemical reactions which occur due to this modification. The formation of particle bonding, together with the evaluation of the formation of new compounds as a function of time would be informative.
- An in-depth evaluation of DFI behaviour under Freeze-thaw, and wetting-drying tests according to ASTM standards needs to be performed to evaluate DFI behaviour under these environmental conditions. These two tests are of great importance for northern climatic and environmental conditions. Additionally, a long-term Freeze-thaw test

should be conducted to evaluate actual field behaviour under prolonged frozen conditions.

9. Acknowledgements

The authors gratefully acknowledge contributions to the project from colleagues at the University and Duraflex Global.

10. Author contributions

Naveed Khan performed the experiments and wrote drafts of the paper under the guidance of Nigel Shrive, who acquired the funds and set out the parameters for the study, and edited the manuscript.

11. Funding sources

The authors acknowledge the financial support of Duraflex Global and Mitacs for funding this study. The University of Calgary also helped support the project.

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