

**EFFECTS OF ENVIRONMENTAL EXPOSURE
CONDITIONS ON ENGINEERING PROPERTIES
OF VARIOUS SAND DEPOSITS**

BY

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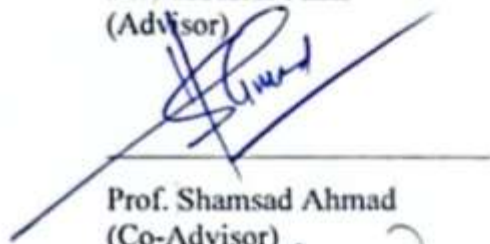


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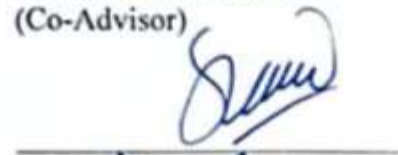
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2023

|Dedicated to

My cherished mother [**Madinah Ibona**], my family, family members, and my friends |

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LIST OF ABBREVIATIONS

ASTM	:	American Society for Testing Materials
BS	:	Beach Sand
DS	:	Dune Sand
FT	:	Freezing-thawing
HC	:	Heating-cooling
LVDT	:	Linear Variable Transducer
MC	:	Moisture Content
OMC	:	Optimum Moisture Content
QD	:	Quarry Dust
SEM	:	Scanning Electron Microscope
UCS	:	Unconfined Compressive Strength
WD	:	Wetting-drying
XRD	:	X-Ray Diffraction
XRF	:	X-Ray Fluorescent

ABSTRACT

Full Name : [HASSAN TUMWIINE]

Thesis Title : [Effects of Environmental Exposure Conditions on Engineering Properties of Various Sand Deposits]

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Countries across the world experience cyclic weather conditions which directly affect the soil properties and the performance of infrastructure. Sand is commonly used in construction projects and understanding the variation of sand properties due to cyclic climatic conditions is a must. In this study, three sand samples of various origins which includes beach sand (BS), dune sand (DS), and quarry dust (QD) were subjected to 20 freezing-thawing (FT), wetting-drying (WD), and heating-cooling (HC) cycles. The shear strength, microstructure, mineralogy, and chemical composition were evaluated at various cycles. The results indicated that the reduction in original mineralogy was about 1-70% and chemical composition reduction was in the range of 1-72%. Changes in surface texture were noticed in several experiments. The shear strength of BS initially reduced and later increased with progressive cycles. DS experienced continuous shear strength reduction in both HC and WD. In the FT experiment, the strength of DS reduced in the early stages of experimentation and thereafter increased. QD experienced a progressive strength decrease in FT and a slight strength increase in both HC and WD experiments. The friction angle for BS progressively increased with the cycles. It continuously reduced the DS. In QD, it initially increased and later reduced for the FT and WD. This was the opposite in HC for QD.

ملخص الرسالة

الاسم الكامل: حسن تومويني

عنوان الرسالة: تأثير التغيرات المناخية المختلفة على الخصائص الهندسة لأنواع مختلفة من التربة

التخصص: الهندسة المدنية

تاريخ الدرجة العلمية: ابريل 2023

تعاني البلدان في جميع أنحاء العالم من ظروف مناخية متغيرة دوريا تؤثر بشكل مباشر على خصائص التربة وأداء البنية التحتية. يستخدم الرمل بشكل كبير في مشاريع البناء وفهم تباين خصائص الرمال بسبب الظروف المناخية المتغيرة أمر لا بد منه. في هذه الدراسة ، تم إخضاع ثلاث عينات من الرمل من أصول مختلفة والتي ، (FT) إلى 20 دورة اذابة وتجميد (QD) ، وغبار المحجر (DS) ، رمال الكثبان (BS) تشمل رمال الشاطئ ، تم تقييم قوة القص ، والبنية الدقيقة ، ومينورولوجية التربة . (HC) ، وتسخين وتبريد (WD) وترطيب وتجفيف ، وتركيبها الكيميائي في دورات مختلفة. أشارت النتائج إلى أن الانخفاض في المينورولوجية الأصلية كان حوالي 1-70٪ والتدهور في التركيب الكيميائي كان في حدود 1-72٪. لوحظت تغييرات في نسيج السطح في العديد من في البداية وزادتها لاحقاً مع الدورات المتغيرة تدريجياً. شهدت تربة BS التجارب. قللت التجربة قوة القص لـ ، انخفضت قوة FT في تجربة الـ WD والـ HC انخفاضاً مستمراً في قوة القص في كل من دورات الـ DS الـ انخفاضاً تدريجياً في القوة في تجربة QD في المراحل الأولى من التجريب وزادت بعد ذلك. شهدت الـ DS الـ BS تزايدت زاوية الاحتكاك الخاصة بـ WD والـ HC وزيادة طفيفة في القوة في كل من تجارب الـ FT الـ ، زاد في البداية ثم انخفض لاحقاً بالنسبة إلى QD في الـ DS تدريجياً مع الدورات. خفضت باستمرار الـ QD لـ HC كان هذا عكس ذلك في الـ WD والـ FT دورات الـ

CHAPTER 1

INTRODUCTION

1.1 Background

Sand is the type of soil commonly used in most construction projects. The properties of sand are subjected to aging depending on the construction application (filters, embankments) and deposition environment (winter, summer, and spring). The aging of soil refers to the periodic alteration of soil properties. The variations in the soil properties are related to stiffness, chemical composition, mineralogy, strength, shape, and texture. Factors that lead to aging are time-dependent chemical, mechanical, and geomicrobiological processes [1–3].

The mechanical process of aging involves changing the stress state acting on the soil sample resulting in particle breakage (negative aging) or rearrangement of particles to a denser state (positive aging). The rearrangement of soil particles occurs in less dense soil whose void ratio is high leading to the instability of particles as the force is progressively transmitted from one particle to another [4]. The chemical process leads to either diagenesis or a reduction in the fraction of the original chemical constituents which directly affects the mineralogy of the soil. This process is attributed to the potential of solubility and precipitation for certain minerals. The solubility and precipitation of minerals in a particular deposition environment depend on the intensity of rainfall, duration, amount of rainfall, temperature, and soil permeability [1].

In granular soils, the chemical process for strength enhancement is attributed to the formation of carbonate minerals. This happens by infiltration of fluid containing carbon dioxide that lowers the potential of hydrogen in the soil hence increasing carbonate precipitation. CaCO_3 precipitation often results in the cementation of pore space between particles as the moisture evaporates, hence, increasing the bonding strength of granular soils [5–7].

The biological process can occur naturally or artificially induced in terms of microbes, and nutrients (proteins, fats, carbohydrates) [8]. The presence of nutrients like cellulose is a potential for low strength, especially in highly organic soils. However, bacteria like *Bacillus cereus* exist naturally in the soil or can be artificially induced. The bacteria derive energy from urea and produce highly active urease during the metabolism process. The bacteria hydrolyses urea to produce CO_3^{2-} and NH_4^+ which are responsible for the generation of CaCO_3 that crystalizes in the pore space of uncemented soils like clean sands [9]. The factors of aging usually act concurrently on a given soil deposit and their effects differ with the soil deposition environment [1]

1.2 Need for this research

The variation in properties of soil can be attributed to the changes in climatic conditions like winter, spring, and summer which alter the groundwater table. Countries like Saudi Arabia, Iran, Singapore, Brazil, and Nigeria, have an annual average temperature above 24 °C. However, in some areas of Iran, the daily temperature is higher than 63 °C [10] whereas in Saudi Arabia highest daily temperature is about 49.3 °C [11]. Russia, Canada, Denmark, and Iceland have annual average temperatures of less than 0 °C. In winter, some provinces in Russia

experience a daily temperature of less than $-30\text{ }^{\circ}\text{C}$ [12]. Several countries across the world (India, Thailand, Netherlands, and USA, among others) experience seasonal floods that submerge and damage the foundations of various infrastructures [13–16]. Therefore, understanding the effects of such weather conditions on soil properties is of great importance.

1.3 Objective of study

The main objective of this study was to experimentally evaluate the effects of freezing-thawing (FT), wetting-drying (WD), and heating-cooling (HC) cycles on the engineering properties of various sand deposits (fresh and aged deposits). The following are the specific objectives.

1. Evaluate the effects of WD, HC, and FT cycles on the mineralogy and chemical composition of beach sand (BS), dune sand (DS), and quarry dust (QD).
2. Assess the deviations in microstructure for BS, DS, and QD before and after environmental exposure cycles.
3. Explore the variations in shear strength properties of BS, DS, and QD at various environmental cycles.

1.4 Thesis layout

This thesis is organized into six chapters. The content in every chapter has been elucidated as follows.

Chapter 1: It includes an overview of the study, its relevancy, and objectives of the study.

Chapter 2: This provides an insight into the recent research trend about this topic.

Chapter 3: This Chapter includes the material characterization and the detailed methodology adopted for the research.

Chapter 4: This chapter reports the results and discussions obtained from this study.

Chapter 5: This Chapter highlights the conclusions and recommendations.

Chapter 6: The chapter indicates the publications obtained from this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Freezing-thawing effects on engineering behavior of soils

Two types of freezing phenomena exist in soil across the globe, which include permafrost and freezing-thawing (FT). Permafrost happens when a given portion of soil keeps permanently below 0 °C throughout the year. Permafrost phenomena happens when the depth of ice penetration in winter is greater than that in summer. FT conditions happen in soils because of seasonal changes in temperatures above and below 0 °C. In this case, saturated soils can form a column of ice lens (freezing) when the temperature is below 0 °C, the ice melts (thawing) when the temperature progressively increases above 0 °C [17].

Frozen land covers about 24% of continental crust. Countries like Mongolia, Alaska, Canada, and Russia have over 50% of their land mass covered by ice [18]. However, many countries experience frost action during the winter which thaws in summer. During freezing, the volume of water within the pore space expands by 9% and exerts pressure on the walls of the soil [19–21]. Thawing happens due to temperature differences between the heat-generating source and the frozen soil. Due to temperature differences, melting starts from the top to the bottom. In most cases, the drainage at the bottom is restricted by the frozen soil, the melted water is usually absorbed by the soil grains and the excess water soaks the soil particles [18, 22]. The recurring FT cycles change the soil fabric and structure hence affecting the overall properties of the soil [23]. It is a necessity to comprehend the FT effects and how

buildings, embankments, subgrades, and other related constructions respond to FT cycles [24–28].

Numerous factors affect the FT process which include, evaporation time [29], soil saturation level [30], and freezing environment (closed or open system) in which the FT can occur [31]. An open system is one where the sample is free to interact with the environment in form of heat exchange, water supply, and humidity among others, whereas a closed system does not interact with the environment [32]. Previously, studies have been performed to elucidate the FT effects on soil properties.

Liu et al. [33] compacted fine-grained silt sand soil and exposed it to 12 FT cycles using a closed system environment. Freezing temperatures of -5 °C, -10 °C and -15 °C and a thawing temperature of 20 °C were adopted. The freezing lasted for 12 hours as well as thawing and a total of 24 hours was adopted to complete one cycle. The samples were later tested for shear strength using the unconsolidated undrained triaxial test and the following observations were noted.

- (i) The freezing temperature had insignificant effects on soil strength.
- (ii) The strength at failure reduced up to the 7th cycle and thereafter increased, as shown in Figure 1. The same phenomenon was experienced in the changes of the friction angle at failure. This was attributed to the effect of strain softening up to the 7th cycle and strain hardening from the 8th to the 12th cycle.

Xie et al. [34] remolded soil the sample, froze it at - 40 °C, and thawed it at 20 °C. A total of 15 cycles were applied, each having a duration of 12 hours. The strength results indicated strength reduction which later became constant with increasing FT cycles of the siltstone sample. The strength reduction was because of an increase in

volumetric deformation that led to increased interparticle spacing, hence, the reduction in the shearing resistance.

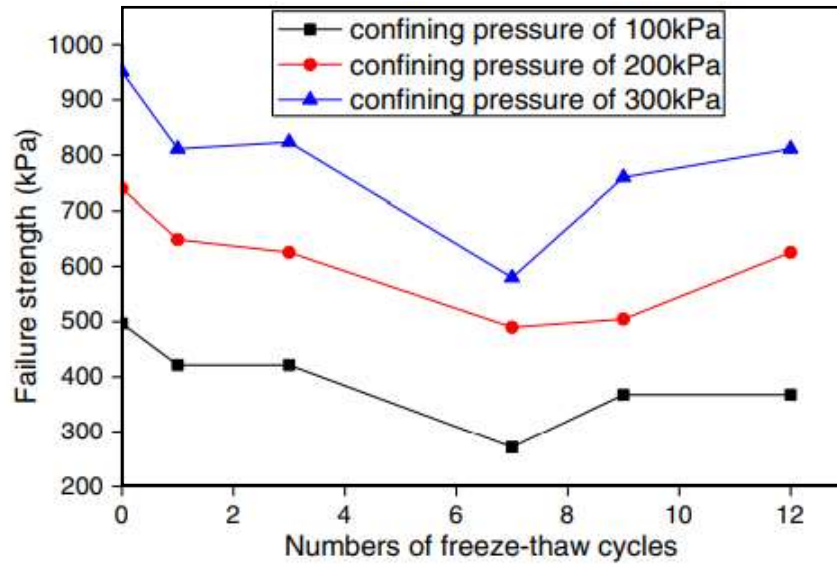


Figure 1. FT effects on failure strength of soil at -15 °C [33]

In another study, Wang et al. [35] remolded clay soil. The soil was frozen at -7 °C for 18 hours and thawed at 14 °C for 4 hours adopting a total of 21 closed system FT cycles. The samples were later evaluated using a triaxial machine with a cell pressure of 200, 400, 600, and 800 kPa. The results indicated that the failure strength reduced between the 3 to 7th cycle, and later became constant for confining pressure of 600 and 800 kPa. Inconsistent strength for the pressure of 200 and 400 kPa was noted as demonstrated in Figure 2. This was because high confining pressure closes the pore space (cracks) making the sample more intact and hence the consistency of results.

Sharma et al. [36] biologically stabilized sand samples using the microbial-induced calcite precipitation technique. The 40% relative density was adopted for all samples and the required dosage containing bacteria was injected. The treatment process lasted for 16 days, and strength gain was due to the hydration of urease by the bacteria during their metabolic process that leads to calcite precipitation. Bio-stabilized

samples were then fully saturated with water and then frozen at -14 °C and thawed at 25 °C each process taking 12 hours. A total of 20 FT cycles were adopted and the unconfined compression strength test (UCS) was evaluated at 0, 5, 10, 15, and 20th cycles. The results indicated a continuous reduction in UCS as the cycles. The strength reduction was due to the pore pressure exerted on the soil walls during freezing and pressure relaxation during thawing which resulted in progressive cracking and precipitation of calcite. The continued activity led to softening of the soil grain as well as loss of interparticle cementation hence, an overall strength reduction with cycles.

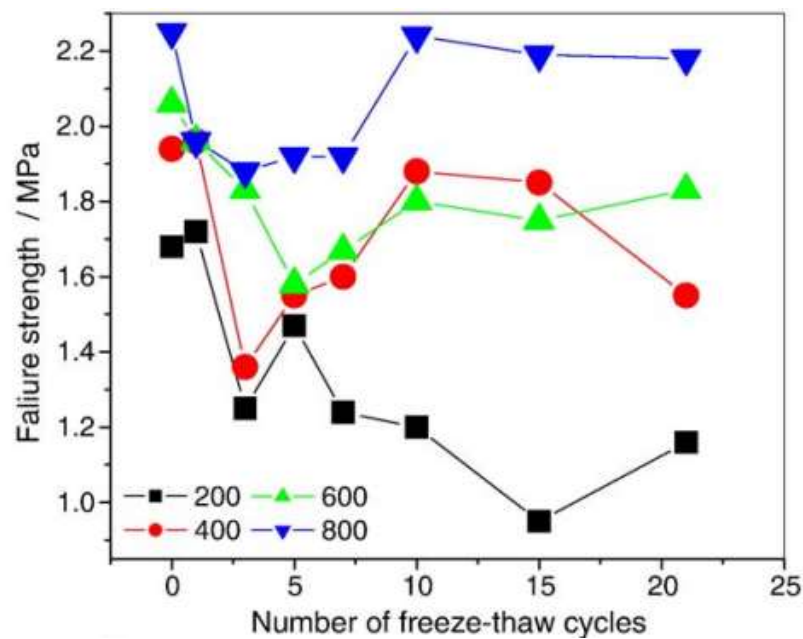


Figure 2. Effects of FT cycles on soil strength [35]

In a related study, Cheng et al. [37] biologically treated sand soil of different gradations. Samples were densified and treated using a solution containing bacillus bacteria. After the samples had obtained considerable strength, they were fully saturated with water, frozen at -14 °C, and thawed at 25 °C. Freezing lasted for 12 hours as well as thawing, hence adopting 24 hours to complete one experimental

cycle. A total of 10 cycles were performed and UCS evaluation was performed at 0, 4, and 10th cycle. The results demonstrated progressive strength reduction with increasing FT cycles. The strength reduction was attributed to the development of minute crack induced by irrecoverable tensile strain during the FT action. The strength of fine-grained sand was less affected by FT cycles as opposed to coarse-grained sands. This was because of the increased coordination number. Fine-grained particles have a high number of particles to particle contact points [38] which reduces the pore space within the soil and hence reduces the damaging effects of FT cycles on the binding agent.

Güllü & Khudir [20] stabilized fine-grained soil with fibers and lime. The samples were allowed to obtain considerable strength and then frozen at -18 °C for 24 hours and thawing was done at 18 °C for 24 hours as well. A temperature of the same magnitude was adopted to allow for complete frost penetration. A total of three cycles were adopted and the UCS test was performed at all the cycles. The results indicated a progressive strength reduction as the cycles advanced, as presented in Figure 3.

Lu et al. [39] remolded silt, clayey, and sandy soil at various moisture content (MC). Freezing temperatures were -5, -10, and -20 °C each lasting for 12 hours and the same thawing duration was employed at 25 °C. A total of 12 FT cycles were adopted and UCS evaluation was performed at 1, 2, 3, 5, 7, 9, and 12th cycles. The results indicated a general strength reduction with increasing FT cycles. This was attributed to the tensile strains due to FT action that leads to soil cracking and reorientation of the soil structure. Severe effects on strength were noticed in samples frozen at -10 °C as compared to other freezing temperatures. Samples with higher remolding moisture content presented less strength as opposed to those with low water content. There was

also a progressive reduction in bulky density which was attributed to the altering of the soil porosity by FT cycles.

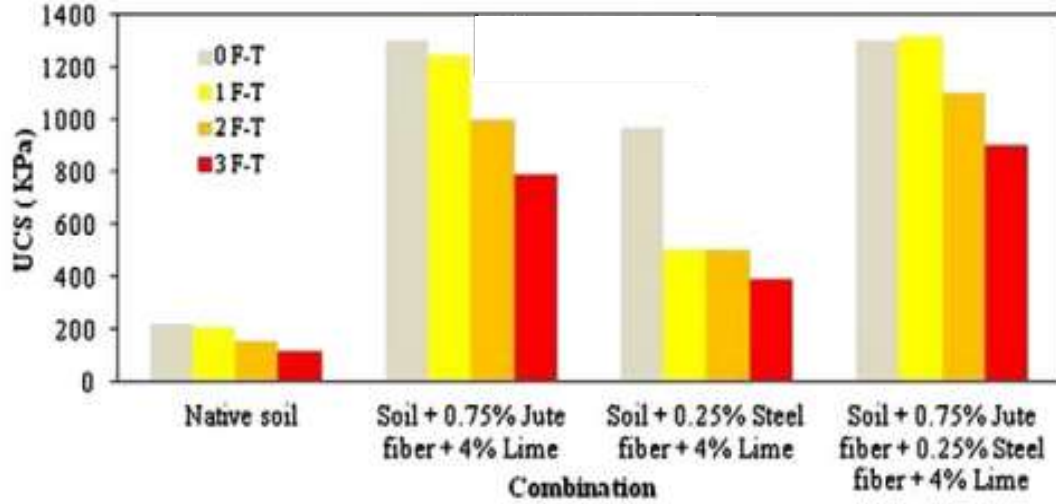


Figure 3. Effects of FT cycles on stabilized soil [20]

Wang et al. [40] obtained coarse-grained soil, froze it at $-20\text{ }^{\circ}\text{C}$, and thawing was done at $20\text{ }^{\circ}\text{C}$ each lasting for 24 hours. The shear strength evaluation was done at 0, 2, 5, 10, and 20th cycles. The results presented an initial strength increase and later a reduction. The friction angle progressively increased with the subsequent cycles. In another study, Kong et al. [41] remolded loess soil at various moisture content and subjected it to 15 FT cycles. Freezing was done at $-14\text{ }^{\circ}\text{C}$ for 12 hours and thawing was performed at $14\text{ }^{\circ}\text{C}$ adopting the same duration. Strength evaluation was performed at 0, 1, 3, 6, 10, and 15th cycles. A progressive strength reduction and a slight increase in friction angle with the increasing cycles were reported. Samples evaluated at higher moisture content portrayed less strength at all cycles as opposed to that remolded at lower moisture content. Previous studies on microstructure have been performed on naturally or artificially cemented soils [41–46]. These findings are regarding FT effects on the pore structure other than the individual soil grains, hence less related to this study.

2.2 Wetting-drying effects on the engineering properties of soil

Wetting-drying (WD) refers to the cyclic variations in the soil moisture content. High temperatures increase the rate of moisture evaporation hence reduction in the soil moisture content. This phenomenon greatly affects the groundwater table, continued activity results in several natural cycles of WD [47]. At shallow depths, WD cycles significantly affect the soil properties due to the changes in climatic regime (seasonal floods due to rainfall, rise and fall of sea level, and surface temperature changes) [48]. WD can also be artificially induced by the irrigation of plants along highways, urban streets, and around buildings.

At the early stages of WD action, the individual soil grains expand and contract which leads to a change in soil strength, and bulky density, among other properties [49]. This affects the arrangement and orientation of soil grains [50] by changing the pore pressure [51, 52] which diminishes the soil's effective stress. Hence, affects the general performance of embankments, foundations, and pavements [53, 54]. The WD cycles have been previously studied by immersing samples in water that is at atmospheric pressure, by using vacuum-controlled pressure [55] and by examining changes in the remolding moisture content [56]. The vacuum-controlled method has been previously used in studies that focus on the real-time changes in soil properties during the drying and wetting paths of the samples [50, 57–59, 59–67]. Generally, these studies have reported progressive strength reduction and swelling of soil samples as wetting and drying samples intensify. However, this study has been limited to understanding the soil properties after being subjected to the complete WD cycles.

Xu et al. [56] obtained undisturbed residual soil samples and monitored the in-situ moisture content. The maximum observed field moisture content was 32% and the minimum was 10%. The observed moisture content was used in the laboratory simulation of WD cycles. The initial moisture content of the undisturbed samples was reduced to 10% and later increased to 32%. The samples were later exposed to room temperature to allow for loss of moisture up to 10%. The samples were later sealed in a moisture-controlled container for 24 hours to complete one cycle. The procedure was repeated for 9 cycles and strength was evaluated using a direct shear test. The results shown in Figure 4 indicated a reduction in shear strength as WD cycles were increased. This was due to the strain softening of the sample.

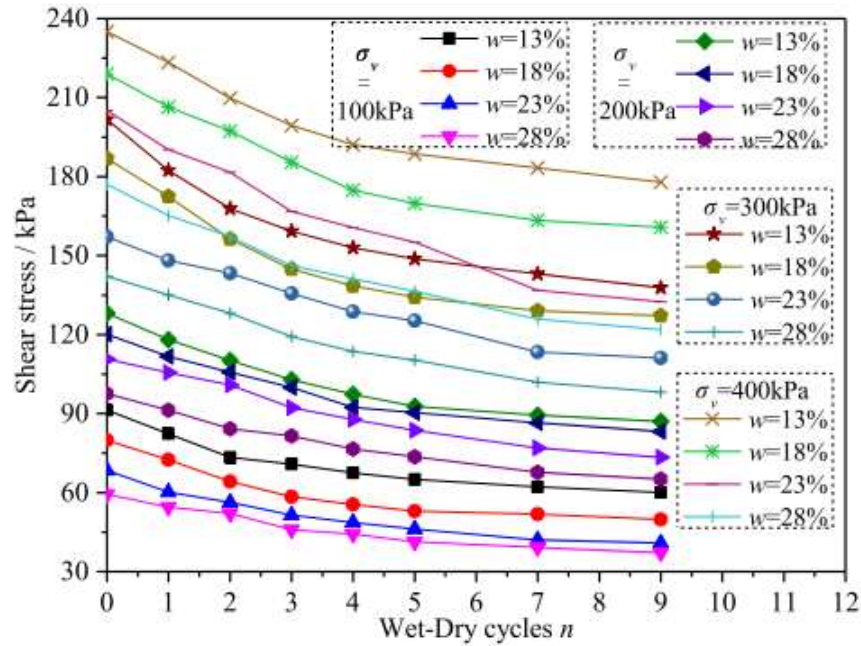


Figure 4. Effects of WD cycles on shear strength [56]

Wang et al. [68] studied the effects of WD cycles on shear strength parameters by remolding a mixture of sandstone and mudstone. Wetting done by soaking samples for 24 hours and drying them at 110 °C for 8 hours. At the end of every cycle, the water content was re-adjusted to suit the OMC for the next cycle. A total of 30 cycles

were performed and shear strength evaluation was done at 1, 3, 10, and 30th cycle. The direct shear test was conducted at the normal stresses of 100, 200, 300, and 400 kPa. The following observations were noted. The results indicated a continuous shear strength reduction with an increasing cycle. This was attributed to the strain softening as the number of cycles increases.

In a related study, Qin et al. [69] collected a loess soil sample and subjected it to 3 WD cycles. The moisture content (MC) of the sample was adjusted to 20% and air-dried up to 5%. The target MC for the shear strength test was 20, 15, 10, and 5%. At every target moisture content, samples would first be placed in a water bath for 24 hours to achieve a constant MC before shearing. Shear strength evaluation was done at 0, 1, and 3rd cycle and the results indicated a progressive reduction in shear strength parameters. Yan et al. [70] studied the effects of WD cycles on fiber-stabilized and unsterilized loess soil. Wetting of samples was done by remolding samples at MC of 22% and drying it to 9%. Each cycle lasted for 24 hours and a total of 10 cycles were adopted. A direct shear test was used to evaluate the samples with a normal load of 50, 100, 150, and 200 kPa. The results presented in Figure 5 indicated a continuous reduction in shear strength parameters as the number of WD cycles advanced. The soil permeability progressively increased, and this was attributed to the cracking of the soil sample.

He et al. [71] conducted a study on undisturbed muddy soil by wetting it in a humidity chamber for 24 hours and drying it at 40 °C in an oven for 4.5 hours. A total of 6 cycles were adopted and shear strength evaluation was performed at a normal load of 100, 200, 300, and 400 kPa. Crack development was also monitored at all cycles using a photographic camera and further analysis was conducted. The results indicated a continuous shear strength reduction with increasing WD cycles as shown

in Figure 6. The strength reduction was attributed to the progressive increase in the length and number of cracks which reduced the cohesion of the soil sample.

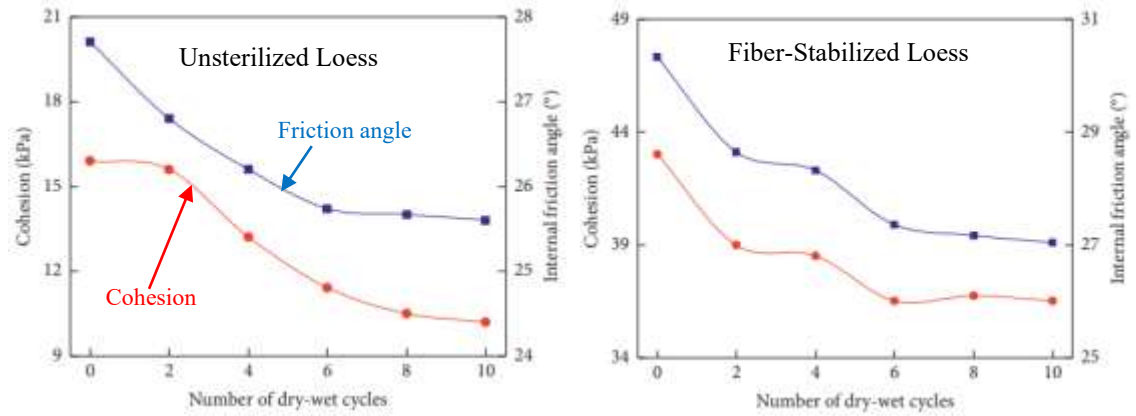


Figure 5. Effects of WD cycles on the shear strength parameters [70]

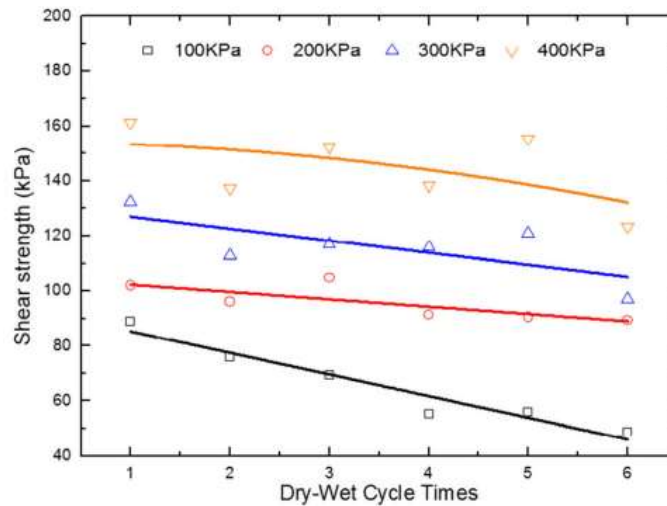


Figure 6. Variation of shear strength with WD cycles [71]

In another study, Li et al. [72] submerged intact rock samples in water for 42 hours and oven-dried them at 50 °C for 12 hours and, thereafter dried them at room temperature for another 42 hours. A total of 96 hours were adopted to complete one experimental cycle. 30 cycles were adopted, shear strength and water absorption were evaluated at various cycles. The results indicated a progressive reduction in shear strength and an increase in water absorption with increasing WD cycles as

demonstrated in Figure 7. The reduction in shear strength was attributed to strain-softening and cracking of the sample.

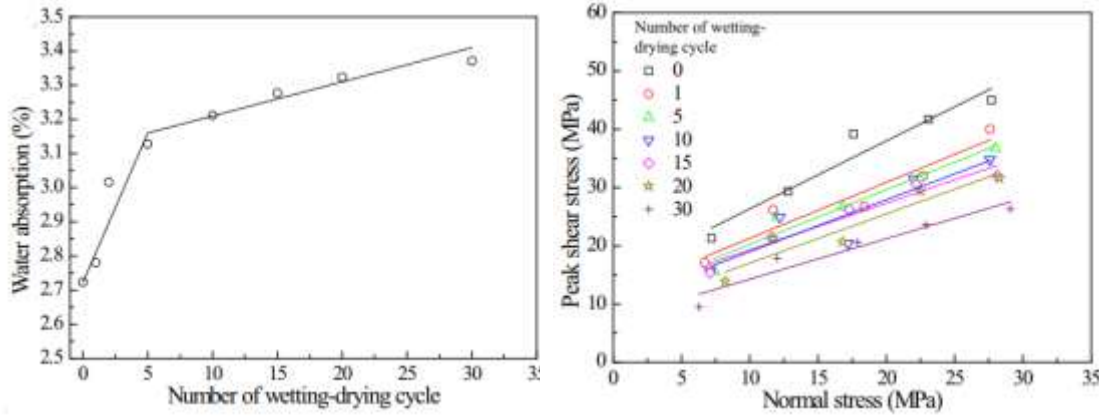


Figure 7. Effects cycles on water absorption and shear stress [72]

2.3 Effects of heating-cooling on soil properties

It is of great importance to understand the thermo-mechanical behavior of soils because it is very critical in thermally active embankments [73], high voltage underground electric cable, thermally active retaining walls [74], geotechnical tunnel liners [75], and structures built in regions with large temperature variations [76]. Several researchers have investigated the effects of heating-cooling (HC) cycles on the engineering properties of soil. Sittidumrong et al. [76] collected sand samples and subjected them to 100 HC cycles. Heating and cooling were done at 50 and 28°C, respectively and a duration of one hour was used to complete one HC cycle. The results indicated that the vertical strain increased exponentially for the first 20 cycles and thereafter the increase was minimal.

In another study, Abuel-Naga et al. [77] heated clayey soil at 70 and 90 °C and cooled them at 25 °C. The HC cycle resulted in strain-softening and an increase in strength for both drained and undrained conditions. In a related study, Li et al. [78] subjected two HC cycles to a clayey sample. The cycles were formulated from a combination of

2 and 15 °C, 15 and 38 °C. Each temperature was maintained for two hours, and shearing was done at the final temperature of the cycle. Cycles that ended with a higher temperature demonstrated a higher shear strength as opposed to that at a lower temperature.

Weng et al.[79] obtained rock samples and subjected them to 15 HC cycles. Heating was done by applying a temperature of 350 °C for six hours and cooling was done by submerging samples in water. The high temperature was chosen in consideration of the rock material used in the confinement of geothermal energy. The results indicated that the axial stress was reduced with subsequent cycles as shown in Figure 8. This was attributed to the progressive cracking of the samples due to increasing cycles. Peng et al.[80, 81] explains that the surface cracking of the sample is due to variations in the response of various minerals to the changes in temperature.

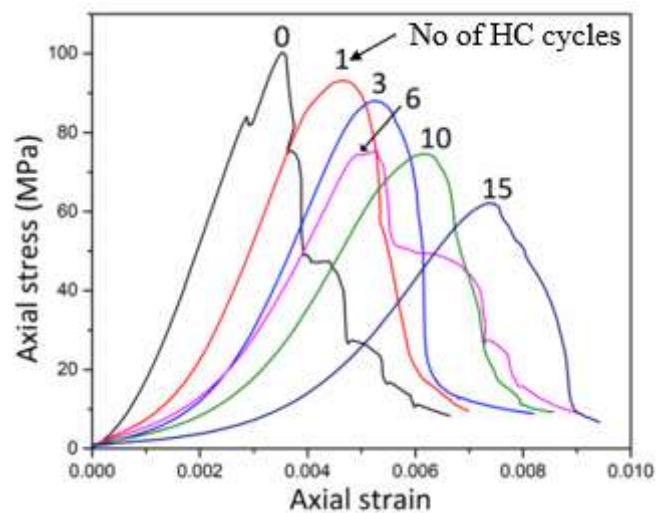


Figure 8. Effects of HC cycles on stress-strain [79]

In a related study conducted by Brotóns et al. [82] on intact rock samples heated at various temperatures between 105 to 600 °C. The samples were cooled at room temperature (free air) and in water. The study revealed that samples cooled in the water had much strength reduction as opposed to those cooled in the air. Xiao-li et al.

[83] obtained granite rock samples and heated them at a selected temperature in a range of 25 to 1300 °C. All samples were subjected to one cycle of selected temperature and cooled at room temperature. The axial stress reduced with an increase in the temperature and the failure strain continuously reduced with progressive temperature increase. It should be acknowledged that there are limited studies on the effects of HC cycles on soil properties, however, several studies have focused on the effects of testing temperature on soil properties other than the HC cycles [75, 84–94]. Generally, these studies have indicated an increase in soil strength and compressibility with a gradual increase in temperature.

Previously, several studies have focused on the FT, WD, and HC effects on cemented (naturally or artificially) soils. Very limited attention has been given to such environmental effects on soil mineralogical, chemical, and microstructural (of individual grains) properties yet they greatly influence the soil strength. In most cases, the HC has been performed using a smaller number of cycles with a maximum heating duration being six hours. It has been observed that in all exposure conditions, a particular soil type is studied for one experiment. It, therefore, remains unclear if another soil subjected to the same experimental conditions or if a particular soil type subjected to numerous exposure conditions would still behave the same or not.

Climatic conditions are dynamic throughout the year and in most cases, soil deposition is heterogeneous in nature. Therefore, great efforts should be taken to understand how various soil depositions are affected by several environmental exposure conditions. It should be noted that uncemented soils (clean sand and crushed rock) are highly recommended in most construction projects (embankments, filters, among others). Therefore, understanding how uncemented soils respond to various environmental conditions is a must. The main objective of this study was to establish

how sand samples of various origins respond to FT, WD, and HC cycles. The main emphasis was on changes in shear strength, mineralogy, chemical, and microstructure of the clean sand samples.

CHAPTER 3

MATERIAL AND METHODS

3.1 Samples collection for the study

Three sand types of different origins have been used in this study which includes beach sand (BS) that was collected from KFUPM beach ($26^{\circ} 06' 06''$ N $50^{\circ} 06' 29''$ E), approximately 29 km from Dhahran in the Eastern Province of Saudi Arabia. Dune sand (DS) was collected from Abqaiq ($25^{\circ} 59' 42''$ N $49^{\circ} 43' 26''$ E) located 82 km from Dhahran, and the quarry dust (QD) of limestone origin was collected along Dammam-Riyadh highway ($25^{\circ} 14' 33''$ N $47^{\circ} 04' 13''$ E) approximately 350 km from Dammam city. Sand samples used in this study are shown in Figure 9 and their respective locations are shown in Figure 10. The main objective of collecting sand samples of different origins was to establish how various soil deposition is affected by several environmental effects of aging.



Figure 9. Sand samples before environmental exposure conditions

QD is formed as a fresh sand deposit because it was collected from a quarry plant in form of well-graded stone dust with a controlled maximum size of less than 4.75 mm. It was postulated that the QD grains have not been exposed to any chemical and/or biological effects of aging. BS had lenses of fine-grained gravel whereas DS had a

maximum particle size of 0.85mm. BS and DS were regarded as aged deposits since they were collected from natural deposits reportedly exposed to the mechanical, chemical, and biological effects of aging.



Figure 10. Respective locations of sand samples

3.2 Determination of index properties of the sand samples

Grain sizes of BS, DS, and QD samples were determined using the wet and dry sieving method as per ASTM D6913. This was done to establish whether the samples contained soluble materials or not. The grain size distribution curves presented in Figure 11 indicate the same trend for a given sand type. This implies that the samples did not contain soluble compounds and it can therefore be confined that they were clean sands. Soil classification was done according to ASTM D2487 (USCS). Specific gravity was established using the water pycnometer method (ASTM D854) and de-airing was done by vacuum method. The index densities and void ratios were determined as per ASTM D4254 and ASTM D4253, the details of the results are

given in Table 1. The $e_{\max}$ and $e_{\min}$ were used to evaluate the relative density at which sand samples were tested for shear strength.

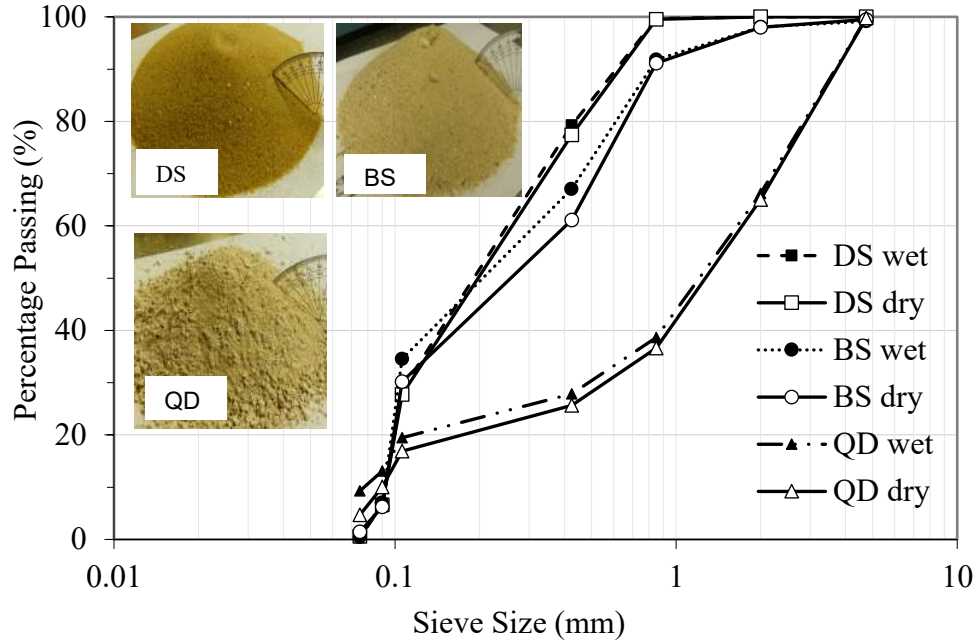


Figure 11. Grain size distribution curves for the sand samples

Table 1. Index properties of samples in the natural state

Property	Sand Type			Testing Standard
	BS	DS	QD	
Soil classification	SP	SP	SW	ASTM D2487
Maximum particle size	4.75	0.85	4.75	
C_u	3.5	2.7	21.3	
C_c	0.4	0.4	1.8	
Percentage finer (wet sieving)	0.4	0.3	9.2	ASTM D6913
Percentage finer (dry sieving)	1.4	0.6	5	ASTM D6913
Specific gravity	2.68	2.67	2.68	ASTM D854
Minimum dry unit weight (kN/m^3)	14.8	15.2	14.1	ASTM D4254
Maximum dry unit weight (kN/m^3)	19.5	18.1	18	ASTM D4253
$e_{\max}$	0.77	0.72	0.86	ASTM D4254
$e_{\min}$	0.35	0.45	0.45	ASTM D4253

3.3 Mineralogical and chemical composition of the sand samples

Sand samples were quartered thoroughly using a riffle box to get the true representative sample. Samples for mineralogical and chemical composition were sieved through a $75\ \mu\text{m}$ sieve as per the specification of the laboratory testing

equipment. The X-ray diffraction (XRD) machine which was used in studying the mineralogy of the sand samples is shown in Figure 12. A detailed mineralogical composition is portrayed in Table 2. BS was mainly composed of 15% calcite, 31.5% dolomite, and 45% feldspar. Initially, DS was composed of 18.7% calcite and 70.5% feldspar. QD was mainly composed of 90% calcite hence, achieving the objective of studying the environmental effects of aging on sands of various origins (aged and fresh deposits). The phase relationship diagrams are also shown in Figure 13-15.

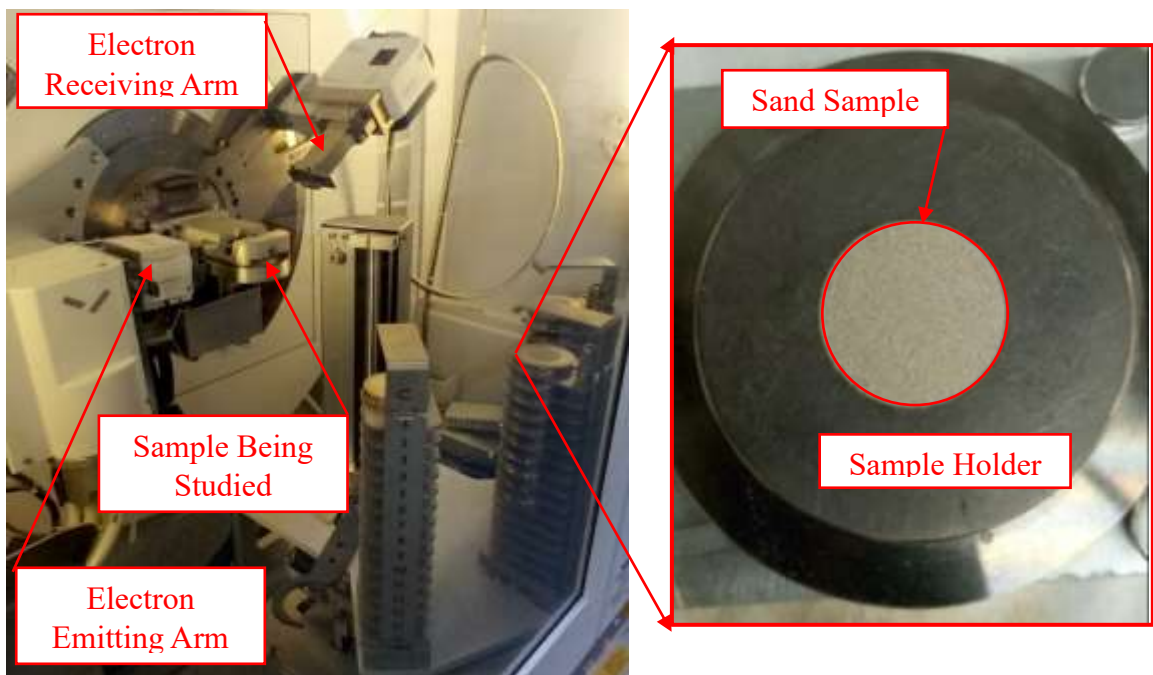


Figure 12. Setup of the X-ray diffraction system

Table 2. Mineralogical composition of sands before exposure to environmental cycles

Mineral	Chemical Formula	Constituents' Weight (%)		
		Beach Sand	Dune Sand	Quarry Dust
Dolomite	$\text{CaMg}(\text{CO}_3)_2$	31.5	9.6	0.2
Quartz	SiO_2	1.7	0.6	N/A
Albite	$\text{NaAlSi}_3\text{O}_8$	0.4	0.3	N/A
Feldspar	KAlSi_3O_8 , $\text{NaAlSi}_3\text{O}_8$, $\text{CaAl}_2\text{Si}_2\text{O}_8$	45	70.5	9.8
Calcite	CaCO_3	15	18.7	90
Halite	$\text{NaCl} \cdot 2\text{H}_2\text{O}$	6.3	0.3	N/A

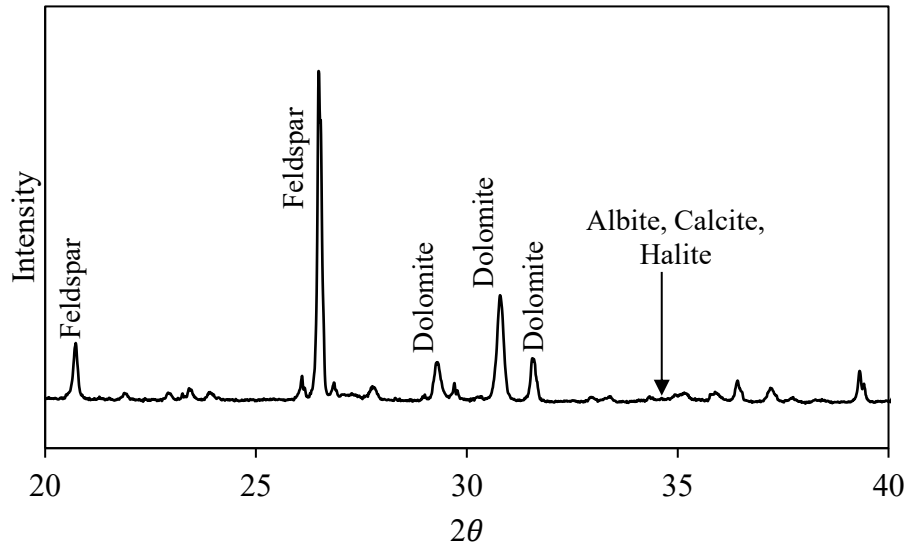


Figure 13. Mineralogical phase relationship diagram for beach sand

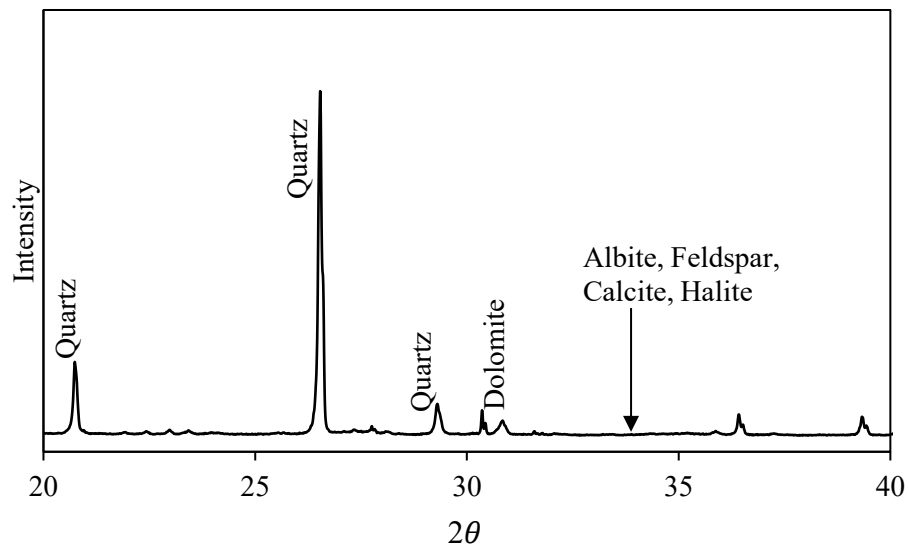


Figure 14. Mineralogical phase relationship diagram for dune sand

The chemical composition analysis was performed using an X-ray fluorescent (XRF) machine. The chemical composition results for all the sand samples are indicated in Table 3 and they strongly agree with the mineralogical composition. Beach sand (BS) had equal amounts of SiO_2 and CaO which was about 33.9%. However, because of its deposition environment (seawater), it contained a few concentrations of Na_2O and Cl . Dune sand (DS) was mainly composed of 60.1% SiO_2 and 17.8% CaO . Quarry dust (QD) being of limestone origin, it was mainly dominated by 84.3% CaO .

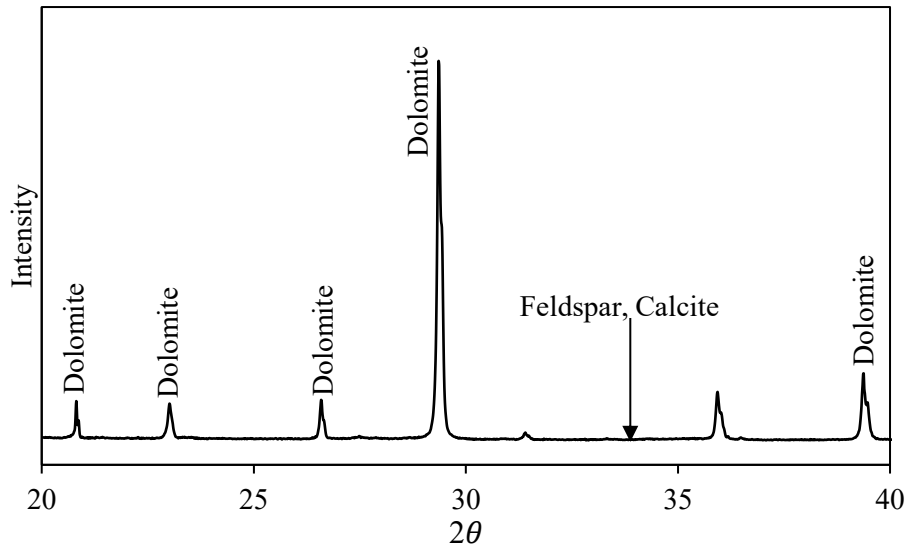


Figure 15. Mineralogical phase relationship diagram for quarry dust

Table 3. Chemical composition of sands in original state

Chemical Formula	Constituents' Weight (%)		
	Beach sand	Dune sand	Quarry dust
Na ₂ O	3.6	0.1	0.0
MgO	10.6	6.7	1.5
Al ₂ O ₃	3.5	5.7	2.7
SiO ₂	33.9	60.1	9.3
CaO	33.9	17.8	84.3
Cl	7.2	1.1	0.0

3.4 Microstructure analysis of sand samples

To ascertain a greater depth of understanding, the microstructure study for both particle shape and texture was done using a scanning electron microscope (SEM). SEM was selected for microstructure analysis because of its simplicity in sample preparation [95]. The sample was thoroughly dried, and quartering was done to get a truly representative sample. To improve electrical conductivity, the sample was placed on a double-sided tape and coated with a 20 nm layer of copper. This approach has been successively used by several scholars [96–98]. The samples were later

placed in the SEM machine and studied for both particle morphology (large scale) and surface texture (small scale).

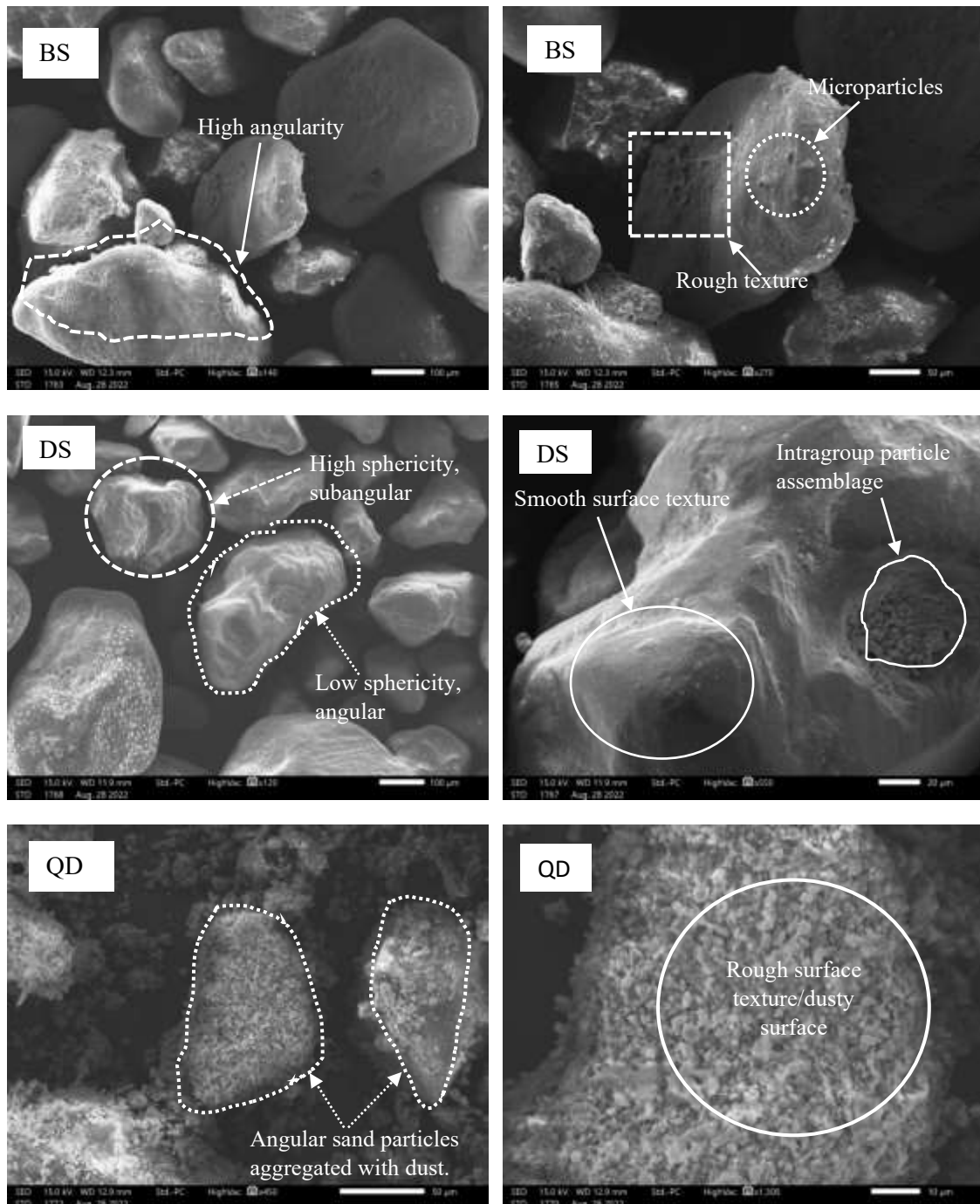


Figure 16. SEM image of sand samples for the particle shape (left) and texture (right)

Microstructure images for both the shape and texture of the sand samples are presented in Figure 16. BS was composed of angular soil particles, a partially rough

texture, and microparticles attached to the sand particles. DS was composed of spherical, subangular, and angular soil particles, having smooth surface texture and assemblage of intragroup particles on the surface. Similar findings of an individual particle having intragroup particle assemblage were reported by Collins & McGown [99]. QD had a rough surface texture and angular particles aggregated with other small particles/dust.

3.5 Experimental testing program

Three independent environmental exposure conditions which include freezing-thawing (FT), wetting-drying (WD), and heating-cooling (HC) were subjected to the sand samples. The FT experiment was done by placing sand samples on trays, fully saturated/submerged in water, and later frozen to -12°C for 24 hours as shown in Figure 17. Samples were then thawed at room temperature for 24 hours and a total time of 48 hours was adopted to complete one experimental cycle. After every cycle, water was filled up to the predetermined level. The FT conditions were selected after reviewing several kinds of literature where Wang et al. [27] suggest that temperatures close to 0°C should be avoided because it might result in incomplete freezing of the sample. Previous studies [20, 39, 40, 100] have used freezing temperatures in a range of -10 to -20°C and a thawing temperature of 18 to 25°C and significantly affected the soil properties. Temperatures used in previous studies were based on the climatic conditions of countries that experience FT cycles like China, and Russia, among others.

The WD experiment was performed by submerging samples in potable water for 48 hours at room temperature and later drying them at an ambient temperature of 35°C for 24 hours. The samples submerged in water during the WD experiment are

presented in Figure 18. This method has recently been employed by several researchers [72, 101–103] in the study of the WD effects of intact rock samples. It is important to mention that at the end of every cycle, the water used to soak samples was discarded and replaced with fresh water for the next cycle. This was done to simulate the field WD condition, especially in soils with high permeability (free draining).



Figure 17. A view of the frozen sand samples

The HC experiment was conducted by placing samples on trays and heating them in an oven at 70 °C for 48 hours as shown in Figure 19. Cooling was done at room temperature for 24 hours. A total of 72 hours was required to complete one cycle for both WD and HC experiments. The heating temperature was selected after reviewing various studies [76–78], where heating was done in a range of 38 to 90 °C and considerable changes in soil properties were reported. However, it is important to mention that the selection of heating temperature was also based on countries Iran and Saudi Arabia which experience daily temperatures of 49-63 °C in summer [10, 11].

It has been reported that the initial cycles have a significant impact on the mechanical properties of soil samples which minimizes when cycles are in the range of 5 to 15 [41, 44, 46, 104–106]. Therefore, a total of 20 FT, WD, and HC cycles were

performed. The soil shear strength was evaluated at 0, 1, 5, 10, 15, and 20th cycles by applying a normal load of 40, 80, and 120 kPa (ASTM D3080). At every strength testing cycle, a portion of the required sample for testing in the FT and WD experiment was thoroughly dried to a constant mass at an ambient temperature of 35 °C for 24 hours.

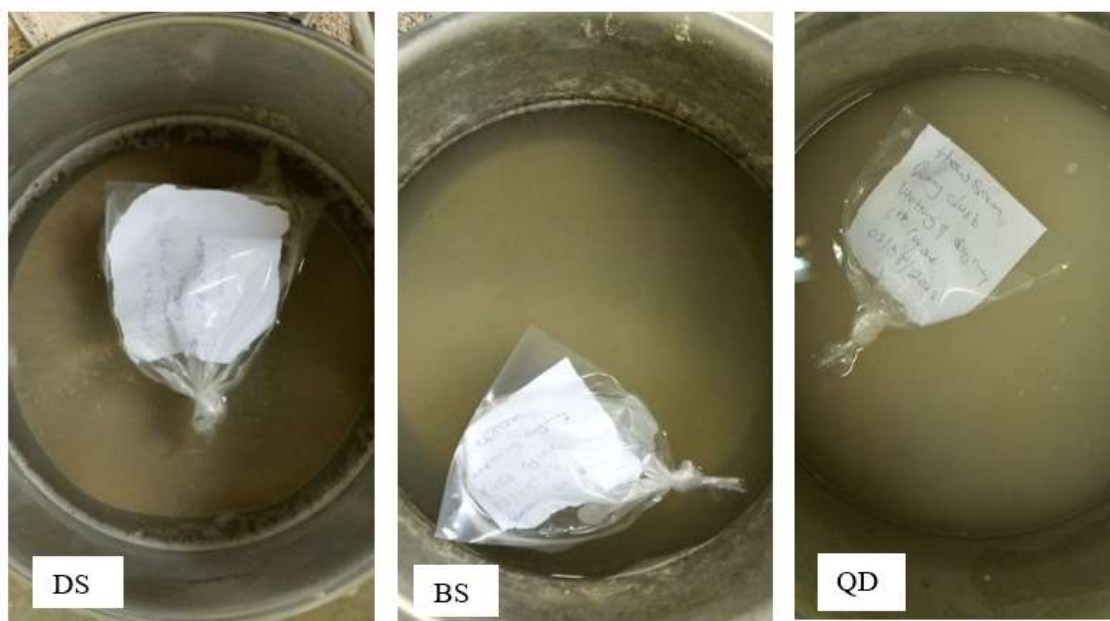


Figure 18. Submerging samples in water during the WD experiment



Figure 19. Sand samples in the oven during the HC experiment

To avoid particle size effects on the test results, all samples were sieved through a 2 mm sieve and prepared at a relative density of 75%. A total of three tests at each normal load was performed and an average value was reported. The sample was sheared at a strain rate of 1 mm/minute and a total of 432 tests were performed which

attributed to 144 stress-strain curves. The details of the shear box test machine used in this study are presented in Figure 20.

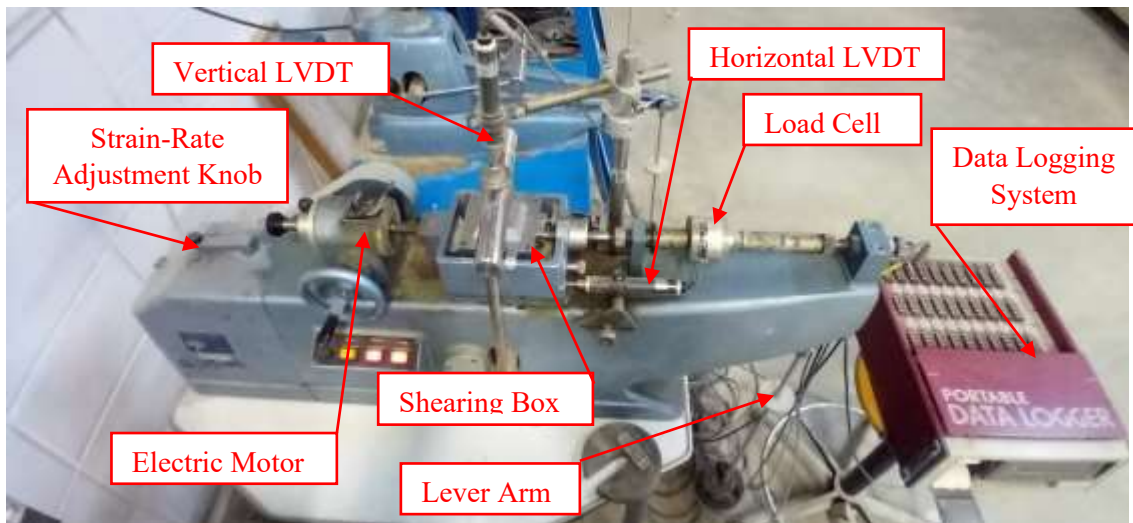


Figure 20. Setup of the direct shear box machine

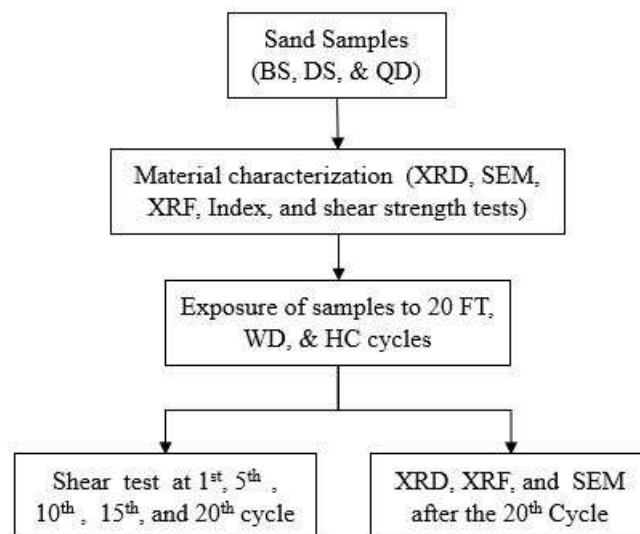


Figure 21. The layout of the experimental program

The changes in the microstructure, mineralogy, and chemical composition were evaluated at the 0 and 20th cycles. The studies after the 20th cycle were performed after thoroughly drying the sand samples. A total of twelve tests were evaluated on each test (SEM, XRD, and XRF). A summary of the experimental program is illustrated in Figure 21.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Effects of experimental cycles on the mineralogy of sand samples

The changes in the mineralogy of beach sand (BS) after the 20th FT, WD, and HC cycles are presented in Figure 22 and the phase relationship diagrams are shown in Figure 23. As regards results interpretation, the notation “OS” indicates the composition of the sand sample before exposure to environmental conditions. Originally, BS was composed of 45% feldspar and 31.5% dolomite. In the FT experiment, dolomite increased by 3.3% whereas feldspar reduced by 7.4%. The reduction in Feldspar was mainly compensated by a 7% increase in halite. Because halite is a weak mineral as opposed to feldspar, this accounts for the observed strength reduction in BS (see Section 4.4).

The WD cycles of BS led to a 12.6% increase in feldspar and a 9.7% reduction in dolomite. The increase in feldspar (a strong mineral) accounted for the increase in shear strength and friction angle of BS after the 20th cycle. In the HC experiment, dolomite was reduced by 19.9% and this was mainly replaced by 4.5, 11.9 and , 15% of feldspar, albite, and quartz, respectively. Since the percentage of quartz and felspar was greater than that of albite (weaker mineral), this accounted for the increased friction angle after the 20th HC cycle.

The effects of experimental cycles on the mineralogy of DS are demonstrated in Figure 24. The phase relationship diagrams are presented in Figure 25. Before the experimental cycles, DS was mainly composed of 70.5% feldspar, 18.7% calcite, and

9.6% calcite. The FT experiment resulted in a 69% reduction in feldspar, and this was compensated a 46.1, 10, and 7.6% of quartz, albite, and dolomite, respectively. Quartz and feldspar are all silicate (framework class of minerals) and they have relatively the same strength. The increase in weaker minerals like dolomite and albite accounted for the strength and friction reduction trend in the FT experiment.

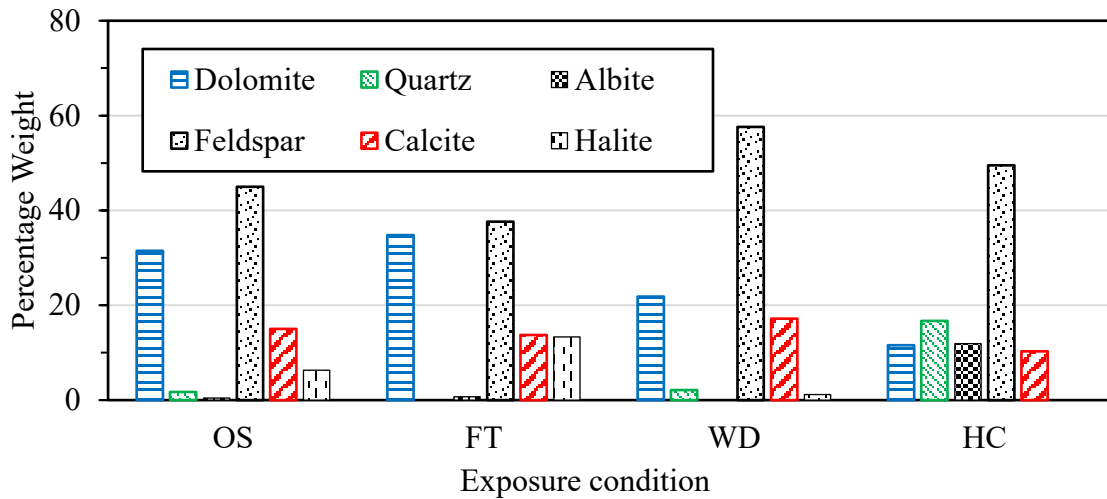


Figure 22. Changes in the mineralogical composition of BS after the 20th cycle

After the 20th WD cycle, feldspar was reduced by 59.5% and it was replaced by 27, 21.6, and 5.2% of quartz, dolomite, and calcite, respectively. The increase in carbonate minerals led to a reduction in shear strength and friction angle. The HC experiment led to a 48.9% reduction in feldspar, which was substituted with 34.6% quartz, 5.9% dolomite, and 4.4% albite. Since quartz and feldspar relatively have the same properties, the increase in dolomite and albite accounted for the shear strength and friction angle reduction in the HC experiment of DS after the 20th cycle.

Figure 26 presents the effects of experimental cycles on the mineralogical composition of QD. The phase relationship diagrams are shown in Figure 27. In the original state, QD was composed of 90% calcite and the changes in the original

mineralogy due to FT effects were insignificant. In the WD experiment, calcite was reduced by 35% and was replaced with 27.6% quartz and 14.4% dolomite.

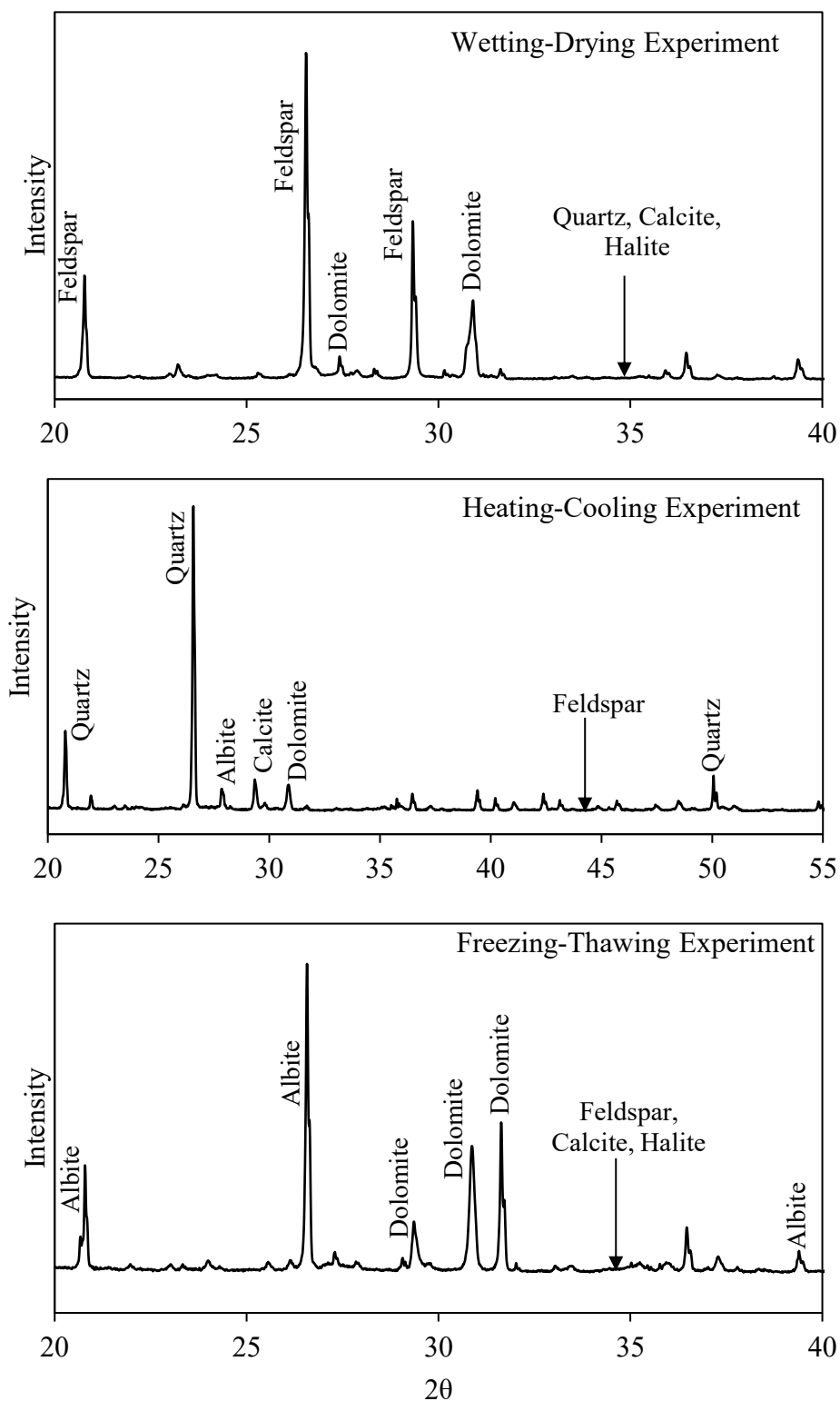


Figure 23. Phase relationship diagrams for BS after the 20th cycle

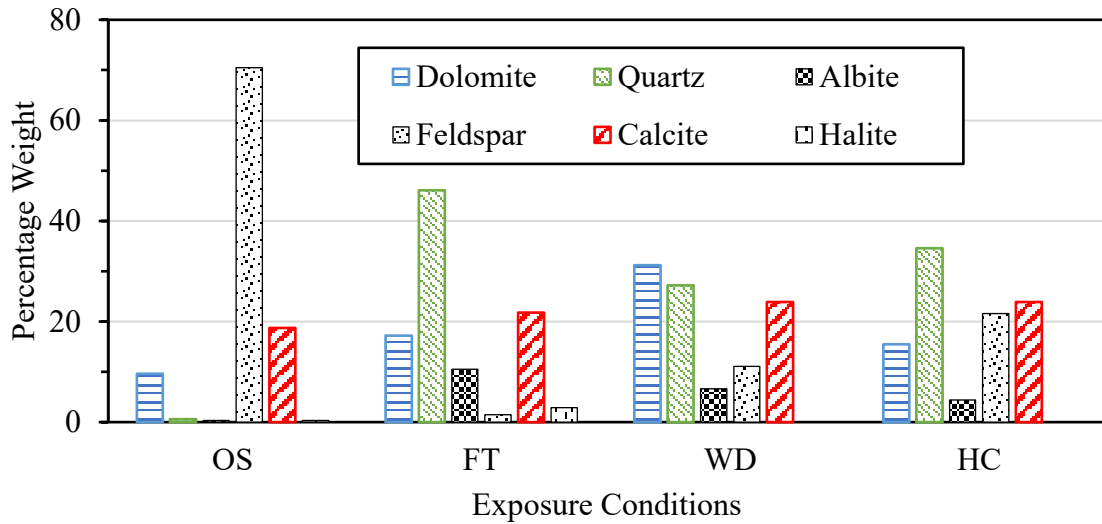


Figure 24. Effects of experimental cycles on the mineralogy of DS

At the end of the 20th HC cycle of QD (see Figure 26), there was a 14% reduction in calcite, and this was mainly substituted with 14% dolomite. The increase in weak minerals like dolomite was attributed to the reduction in the friction angle of QD after the 20th cycle.

Interestingly, the mineralogy of DS was strongly altered followed by BS and thereafter that of QD. This was the reverse of what is expected from a sample with feldspar (stable mineral) as the main constituent [1]. Considering individual experiments, significant variations in the original mineralogy of sand samples have been noticed in WD and FT as compared to the HC experiment. This is because the WD and FT experiment involved a leaching action. It should be noted that the water used in the WD experiment was discarded every after an experimental cycle and replaced with fresh water. The water in the FT experiment was always refilled to the predetermined level at the start of every cycle. This could have led to the dissolution of some minerals in water because at the point of mineralogy evaluation, all water was poured, and the sample was thoroughly dried at ambient temperature.

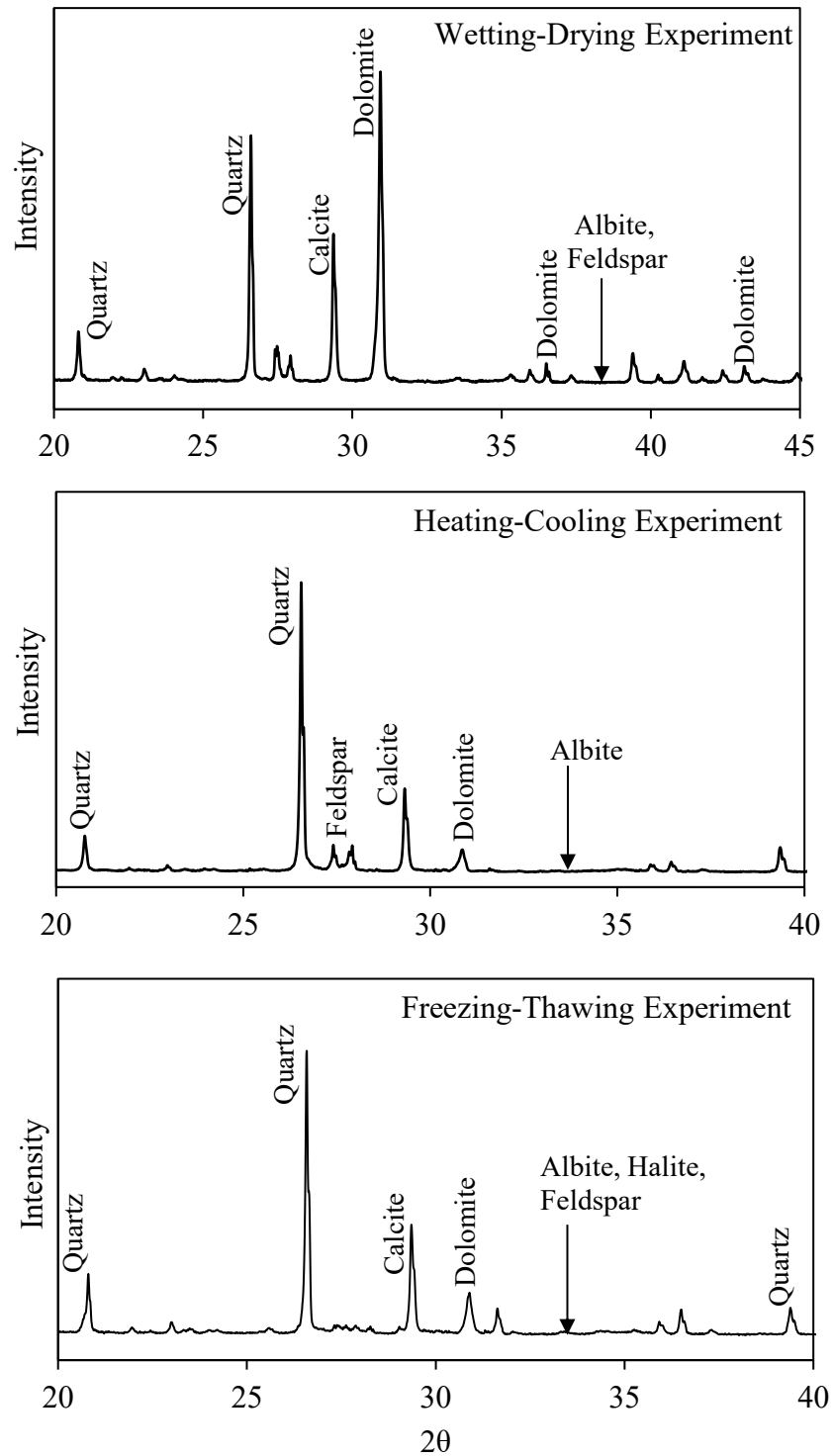


Figure 25. Phase relationship diagrams for DS at the 20th cycle

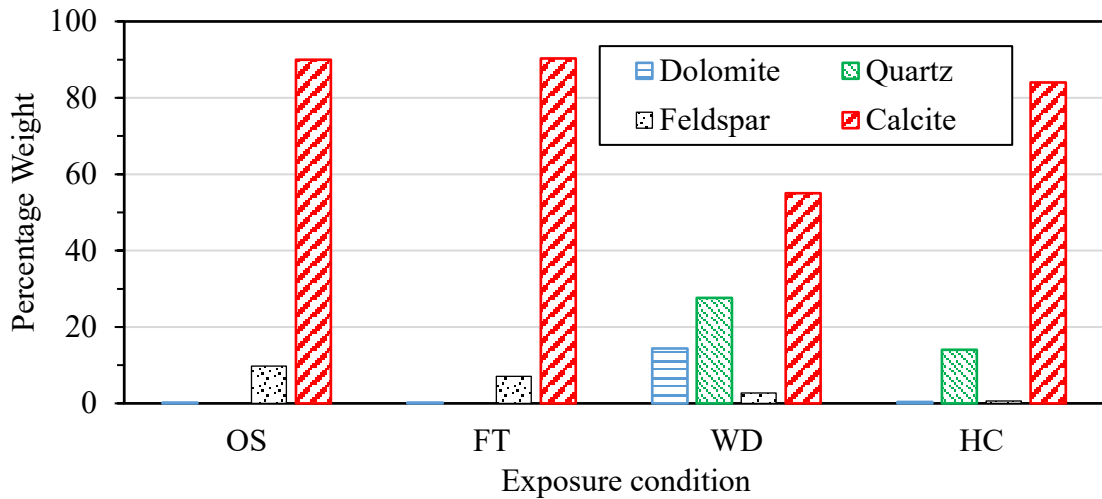


Figure 26. Changes in the mineralogical composition of QD after the 20th cycle

4.2 Experimental effects on the chemical composition of sands

The changes in the chemical composition of BS after the 20th cycle of FT, WD, and HC are demonstrated in Figure 28. Initially, BS was mainly composed of 10.6% of MgO (chemical element for dolomite), SiO₂ (chemical element for quartz or feldspar), and CaO (chemical element for calcite) each having 33.9%. Since the sample originated from a saline environment (seawater), it contained a few proportions of Na₂O (chemical element for albite) and Cl (chemical element for halite). After the 20th FT cycle, there was a reduction of 10.8 and 3.6% in SiO₂ and CaO respectively. This was mainly replaced by 6.2% of Cl. Since Cl is part of the chemical elements for halite, relating to the changes in the mineralogy of BS due to FT cycles, it was observed that there was a significant increase in halite (weak mineral) hence the overall strength reduction in BS after the 20th cycle.

In the WD experiment (Figure 28), there a was 21.1% increase in SiO₂ which was balanced a 25.8% reduction in CaO. However, there was also a 15.7% increase in Al₂O₃ (chemical element for calcite or feldspar). Comparing the mineralogy of BS in

the WD experiment with its chemical composition, there was a corresponding increase in feldspar.

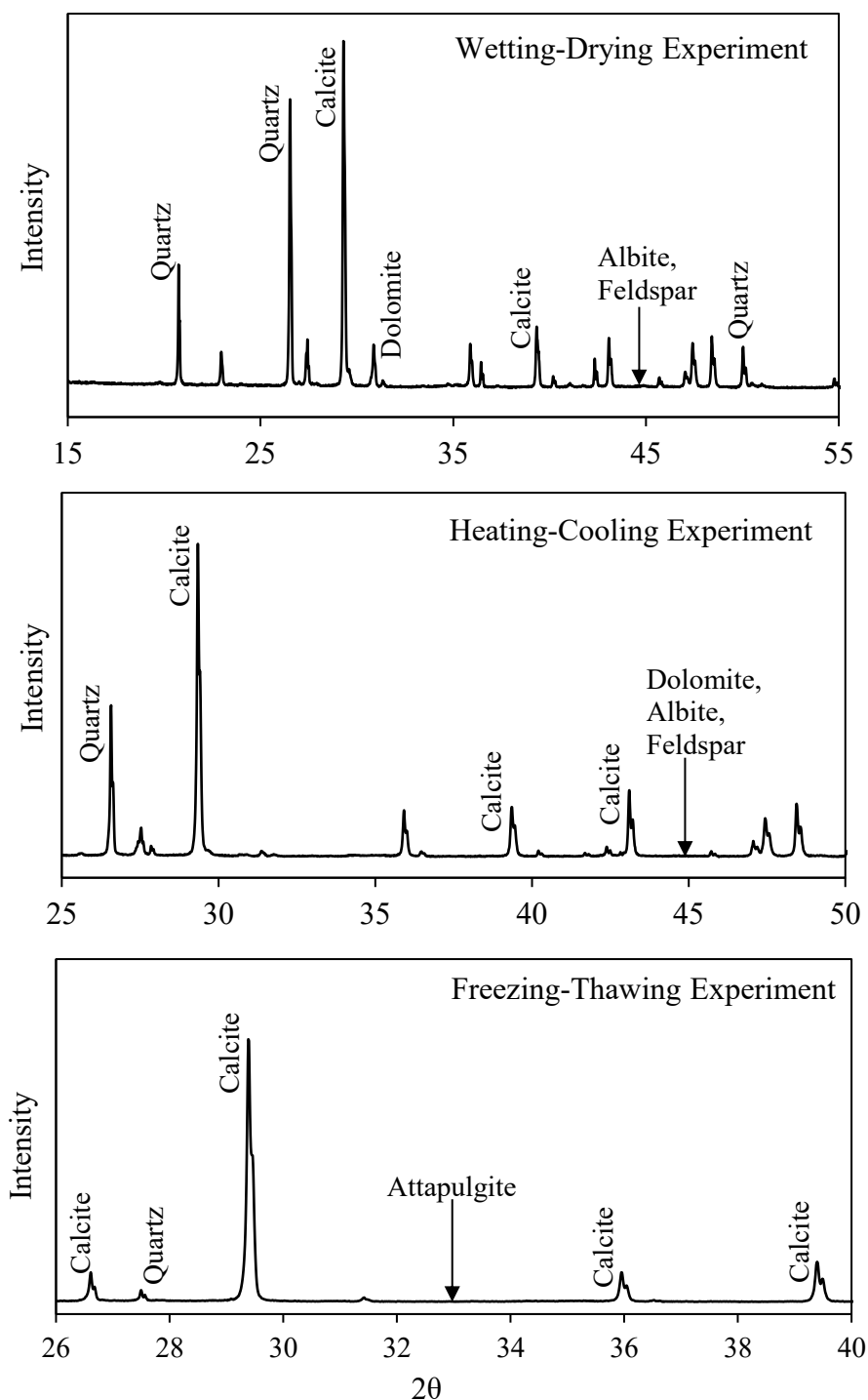


Figure 27. Phase relationship diagram for QD after the 20th cycle

This implies that an increase in Al_2O_3 contributed to the proportion of feldspar other than calcite hence, the observed increase in shear strength and friction angle after the 20th WD cycle. The HC experiment led to a 33.1% reduction in CaO, which was substituted with MgO (18%) and Na_2O (22.1%). The increase in Na_2O directly increased feldspar hence an increase in friction angle after the 20th HC cycle.

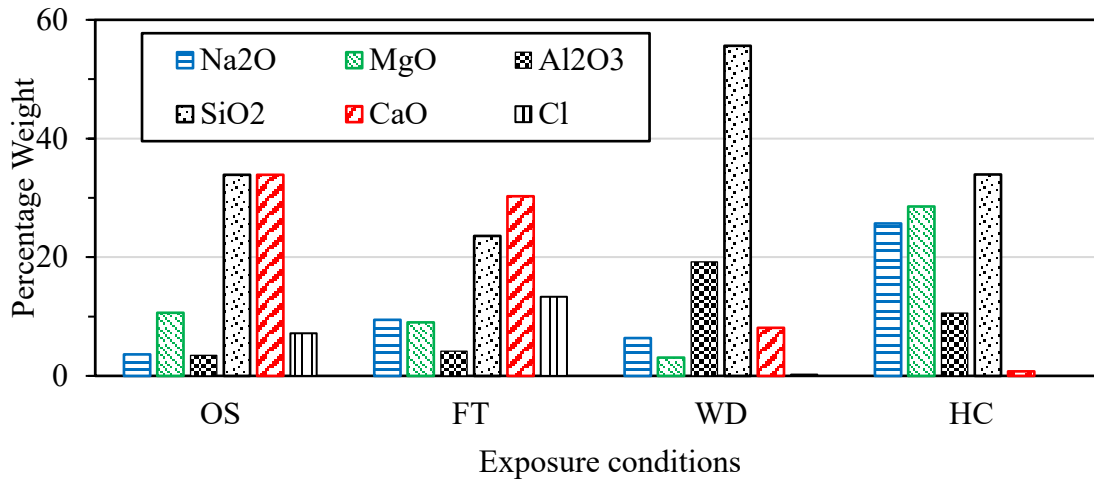


Figure 28. Effects of experimental cycles on the chemical composition of BS

The effects of experimental cycles on the chemical composition of dune sand (DS) are presented in Figure 29. Originally, DS was composed of 60.1% SiO_2 , and 17.8% CaO. The FT experiment resulted in a 44.8% reduction in SiO_2 as well as a 15% decrease in CaO. The decrease in the initial composition was compensated by 36.1 and 24.6% of Na_2O and MgO, respectively. The development of the chemical elements for albite and dolomite (weaker minerals) accounted for the shear strength and friction angle reduction in DS after the 20th FT cycle.

In the WD experiment (see Figure 29), there was a 22.3 and 14% reduction in SiO_2 and CaO, respectively. This was mostly replaced by 38.7% of MgO which corresponded to a 21.6% increase in dolomite. Therefore, the shear strength and friction angle reduction after the 20th WD cycle was due to the reduction in strong oxides which were replaced by weak oxides. The HC experiment resulted in a 13.5%

reduction in SiO₂ which was mainly compensated by 8.5% CaO. This was the reason for the strength reduction after the 20th HC cycle of DS.

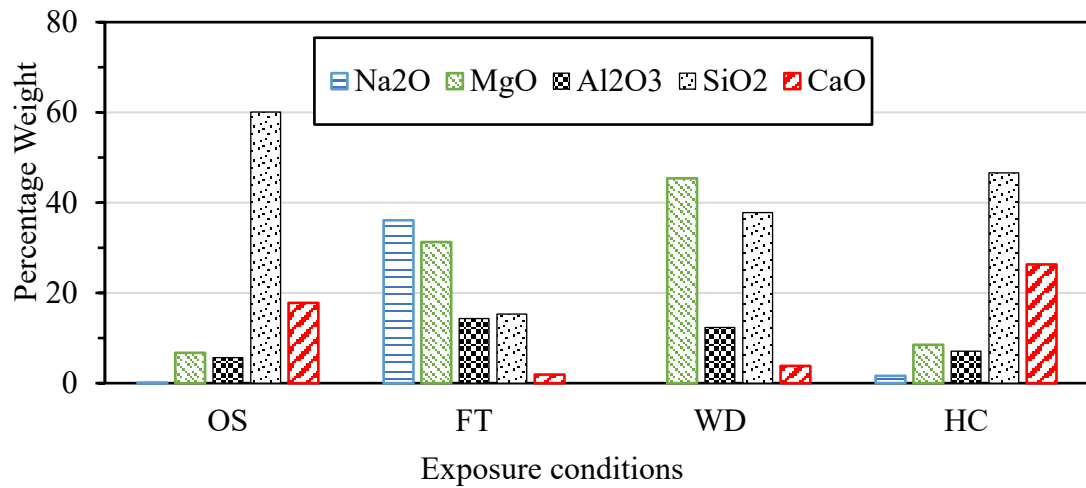


Figure 29. Effects of experimental cycles on the chemical composition of DS

The changes in the chemical composition of quarry dust (QD) due to experimental cycles are presented in Figure 30. The sample was composed of 79.2% CaO before exposure to experimental cycles. After the 20th FT cycle, CaO was reduced by 70.3% and was replaced by 35.3% MgO, 28.8% SiO₂, and 7.7% Al₂O₃. Even though there was an increase in SiO₂, this was less than the proportion of other weak oxides which accounted for the reduction in friction angle after the 20th cycle.

In the WD experiment (Figure 30), there was a 67.2% reduction in CaO which was mainly compensated by 37.9, 19.9, and 10.9% of MgO, SiO₂, and Al₂O₃, respectively. The HC experiment led to a 66.4% reduction in CaO which was replaced by 37.4% MgO, 20.6% SiO₂, and 9.8% Al₂O₃. In the WD and HC experiment, it is seen that MgO (dolomite) relatively balances with the oxides of stronger minerals like SiO₂ (quartz or feldspar) and Al₂O₃ (feldspar). This clearly explains the reason behind the slight change in the shear strength of QD after the 20th cycle of HC and WD experiments.

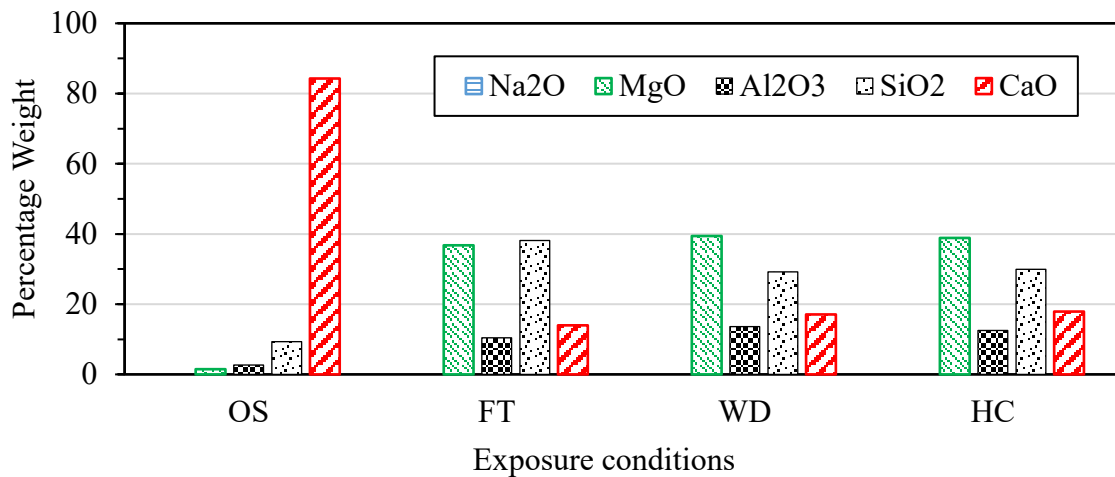


Figure 30. Effects of experimental cycles on the chemical composition of QD

4.3 Experimental effects on the microstructural properties of the sands

The changes in the particle shape would not be established in all the sands. This was attributed to the complexity of particle morphology measurement methods which were not employed. Since there were significant changes in the mineralogy and chemical composition in all the sand samples, it should be acknowledged that this was accompanied by changes in particle shape and texture.

Figure 31 presents the effects of experimental cycles on the microstructural properties of the BS samples. A rough surface texture was noticed in BS for the FT and WD experiment after the 20th cycle. This was due to the increase in weak minerals like halite, especially in the FT experiment which increased the water absorption capacity of individual sand grains, hence, increased surface degradation. After the 20th HC cycle, the changes in surface texture would not be established. This was attributed to the complexity of studying the microstructure of individual grains since the study of the same grain going through the experimental cycles was not considered. It is anticipated that the rough surface texture was responsible for the increase in friction angle due to increased resistance along the micro-plane of the two halves of the shear box machine.

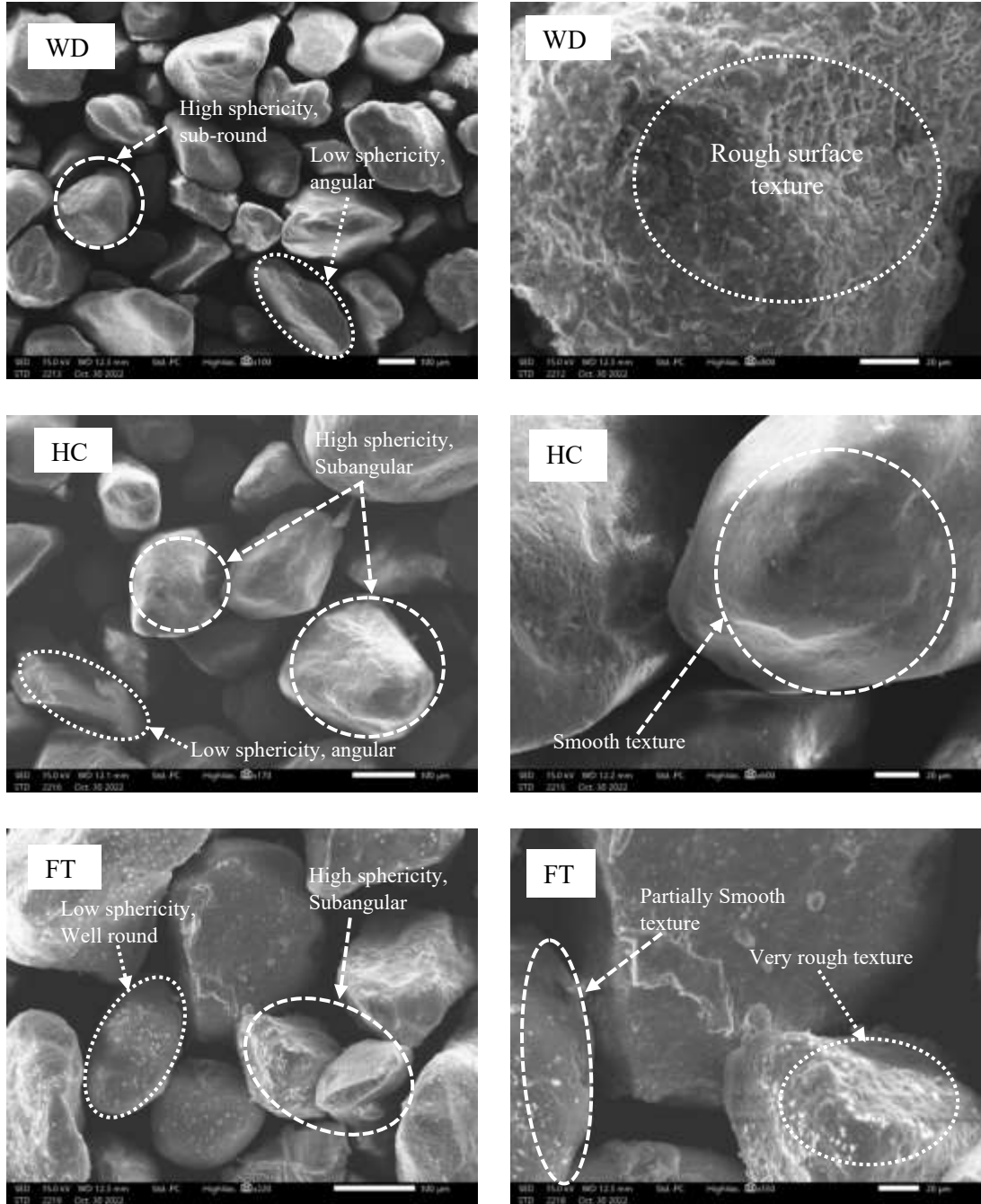


Figure 31. Particle shape (left) and texture (right) of BS after the 20th cycle

The effects of experimental cycles on the microstructural properties of dune sand (DS) are shown in Figure 32. After the 20th experimental cycle, the texture was smoother as opposed to that of the original state (see Figure 16). The smooth surface texture was the reason for the reduction in shear strength and friction angle after the 20th cycle.

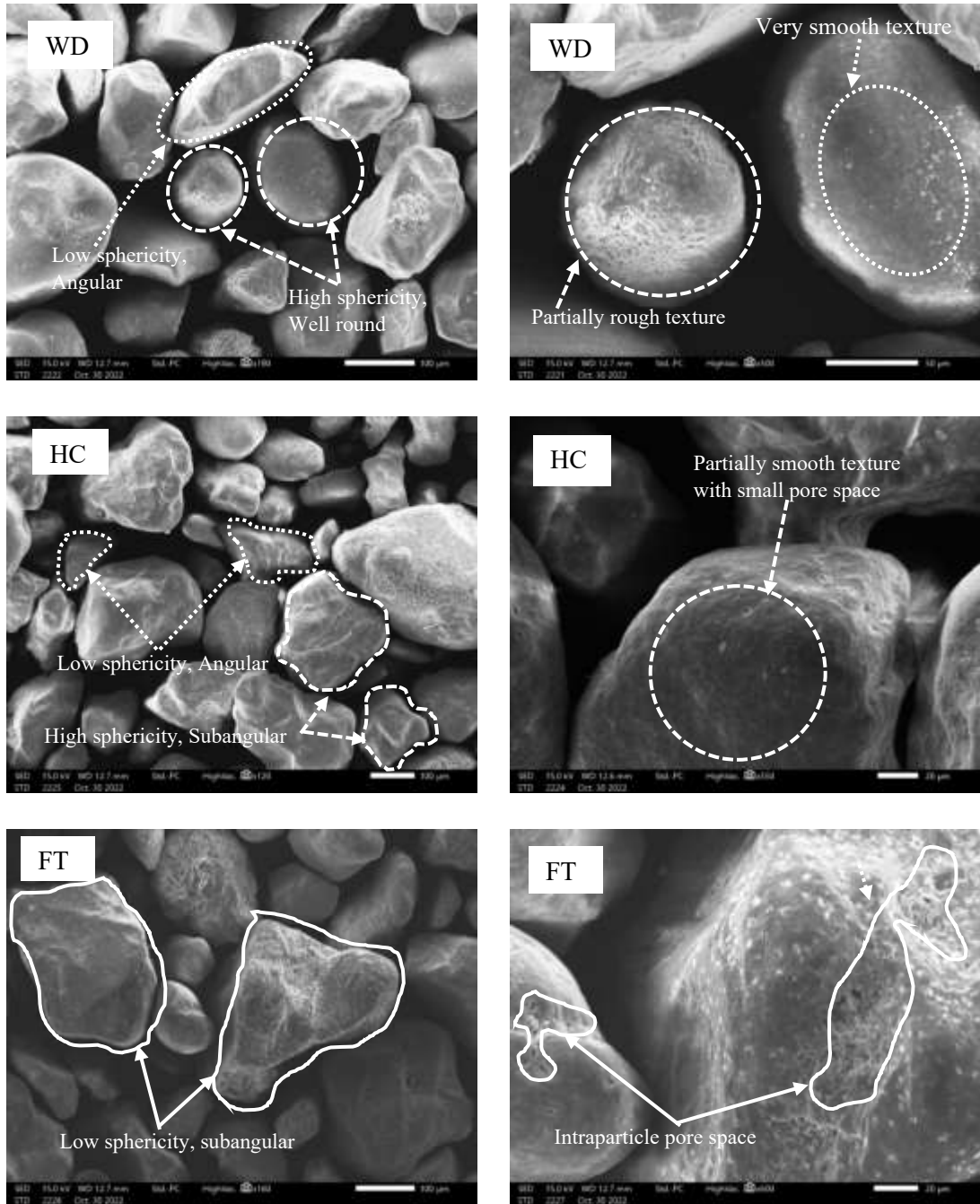


Figure 32. Particle shape (left) and texture (right) for the DS after the 20th cycles

The SEM images for both particle shape and texture of QD after the 20th cycle are presented in Figure 33. The surface of QD was originally coated with dusty sand particles (see Figure 16) and this made it difficult to observe the changes in the particle shape and surface texture. In both the natural state and after the FT cycles, white spots were observed on the sand samples for BS and DS which was expected to

be the precipitation of CaO. This has been confirmed by the chemical composition (see Figure 28-30) where CaO appears in all experiments. Similar findings have not been observed in SEM images of QD because the grain surface was partially clean/dusty.

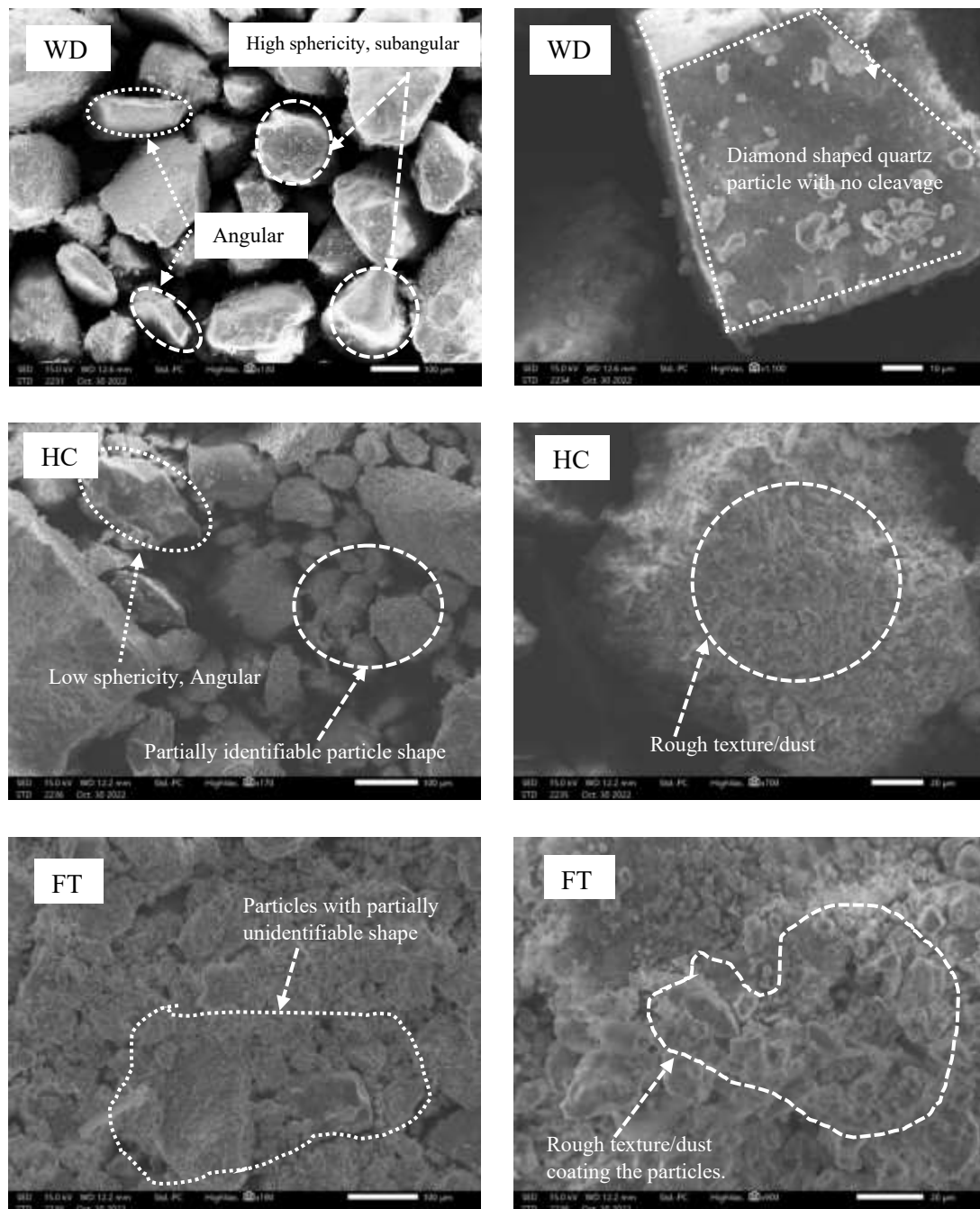


Figure 33. Particle shape (left) and texture (right) for the QD after the 20th cycles

4.4 Effects of experimental cycles on the shear strength of sand samples

The effects of FT cycles on the shear strength of sand samples are demonstrated in Figure 34. BS demonstrated a progressive strength reduction for the first 10 cycles and later gradually increased concerning the samples evaluated at a normal load of 40 and 80 kPa. Even though there was a progressive strength increase after the 10th cycle, the shear strength was 9.1 and 8.4% less than the original value for an evaluation done at 40 and 80 kPa normal load, respectively. The strength reduction trend was attributed to a 7.4% reduction in feldspar which was mainly compensated by halite and dolomite which are much weaker than feldspar. However, an increase in the strength after the 10th cycle was due to the strain hardening of the sand samples. Samples evaluated at 120 kPa demonstrated a 13.6% progressive strength increase with an increasing number of cycles and this was attributed to the strain hardening.

In the FT experiment, DS presented a progressive strength reduction trend up to the 10th cycle and later gradually increased. Considering individual data points, the shear strength after the 20th cycle was slightly equal to the original strength irrespective of the applied normal load. The strength reduction in DS was due to the 44.9% reduction in SiO₂ (chemical element for quartz) which was compensated by weaker oxides like 36.1% of Na₂O (part of chemical elements for albite or feldspar) and 24.6% of MgO (part of chemical elements for dolomite). However, the strength increase was attributed to the strain hardening of the sand samples. In the recent past, a similar trend of shear strength results was presented by Liu et al. [100]. Gradual strength reduction and later becoming constant have been reported by several scholars [107, 108].

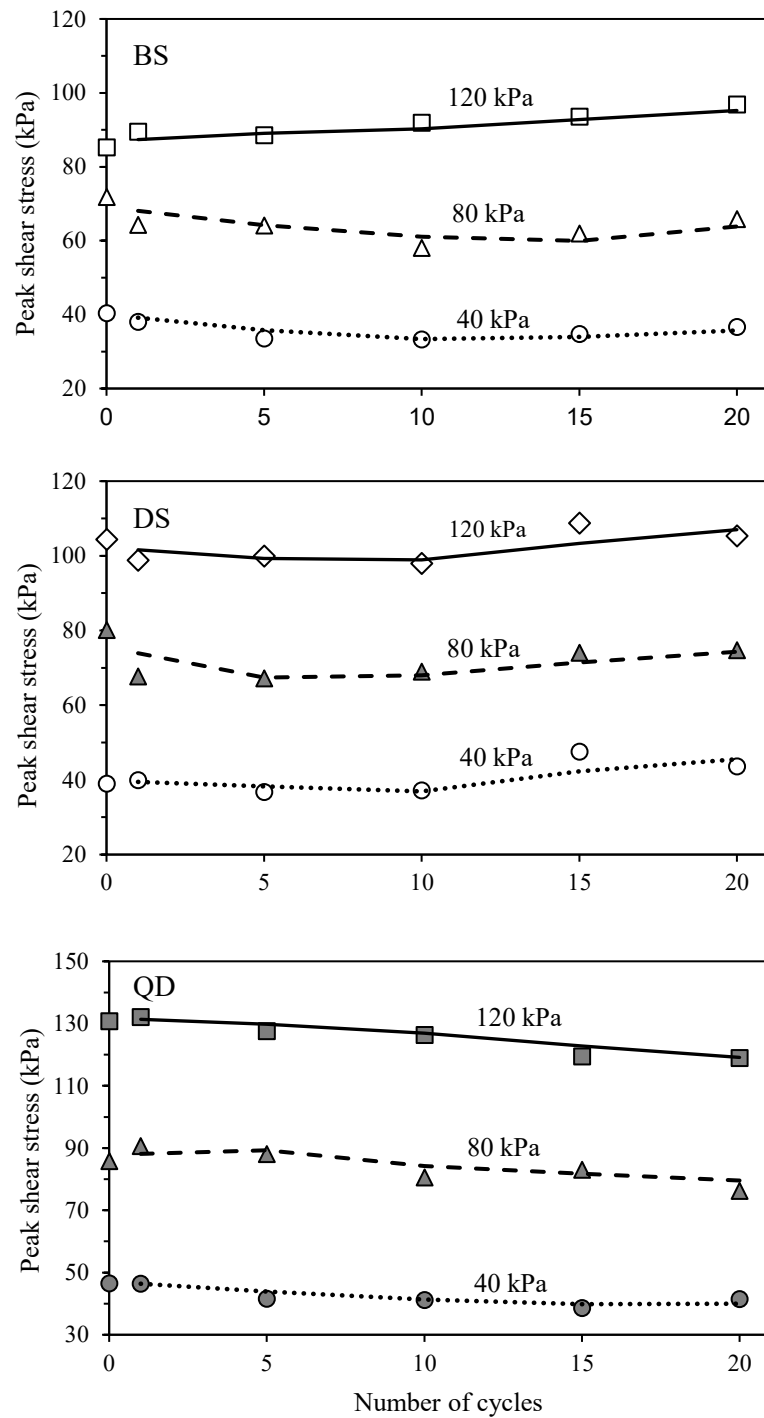


Figure 34. Effects of FT cycles on shear strength of sand samples

The QD sand samples evaluated in the FT experiment depicted a continuous strength reduction with an increasing cycle (see Figure 34). The strength reduction was attributed to a 70.3% reduction in CaO which is the main chemical element of calcite (a strong non-clay mineral). This was mainly compensated by 35.3% MgO, part of the main chemical element for dolomite (slightly weaker anhydrous mineral), and 7.7%

of Al_2O_3 the main chemical element of albite (weak clay mineral). Several authors [20, 36, 41, 109, 110] have reported progressive strength reduction with an increasing FT cycle.

The effects of WD cycles on the shear strength of sand samples at various normal loads are shown in Figure 35. BS presented a strength reduction trend for the first 5 cycles, then increased from the 5th to the 15th cycle and thereafter became constant. After the 20th cycle, the shear strength increased by 2, 1, and 19.1% at a normal load of 40, 80, and 120 kPa, respectively. The strength increase was attributed to (1) the 12% increase in feldspar. (2) The formation of a rough surface texture on the sand grain after the 20th cycle (see Figure 31). It is anticipated that the rough texture would create an interlocking plane along the two halves of the shear box which would increase resistance against shearing action.

QD experienced a slight strength increase as the WD cycles were increased. The strength increase was accredited to the 27.6% increase in quartz mineral. Similar findings of strength increase with progressive WD cycles have been reported by Allam & Sridharan [111], with a study done on red soils having 70% sand content. DS presented a trend of strength reduction with increasing WD cycles (see Figure 35). This was attributed to the 59.5% reduction in the feldspar content, which was compensated by weaker minerals like 21.6% dolomite and 5.2% calcite.

Previous studies have reported progressive strength reduction with increasing WD cycles for studies conducted on residual soils [56], loess soils [69, 70], a mixture of mudstone and sandstone [68], limestone [112], and sandstone [71, 72]. Concerning the individual data points, large strength variations have been noticed in the initial experimentation cycles in this case the 1st and the 5th cycle. Several studies have

reported similar observations [71, 113, 114]. However, this could be attributed to the initial response of soil structure and mineralogy of the sample which slightly stabilizes with time.

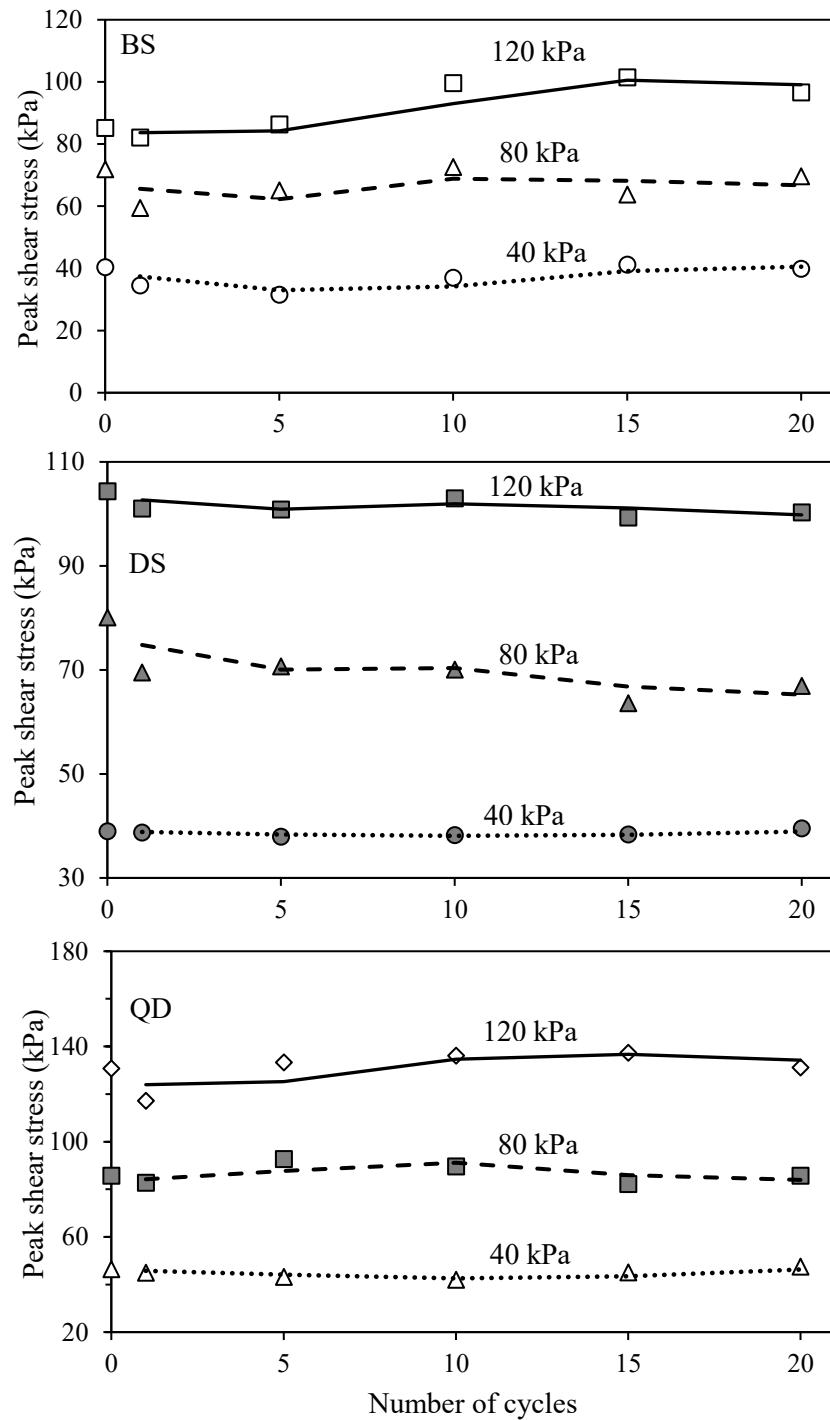


Figure 35. Effects of WD cycles on shear strength of BS, DS, and QD

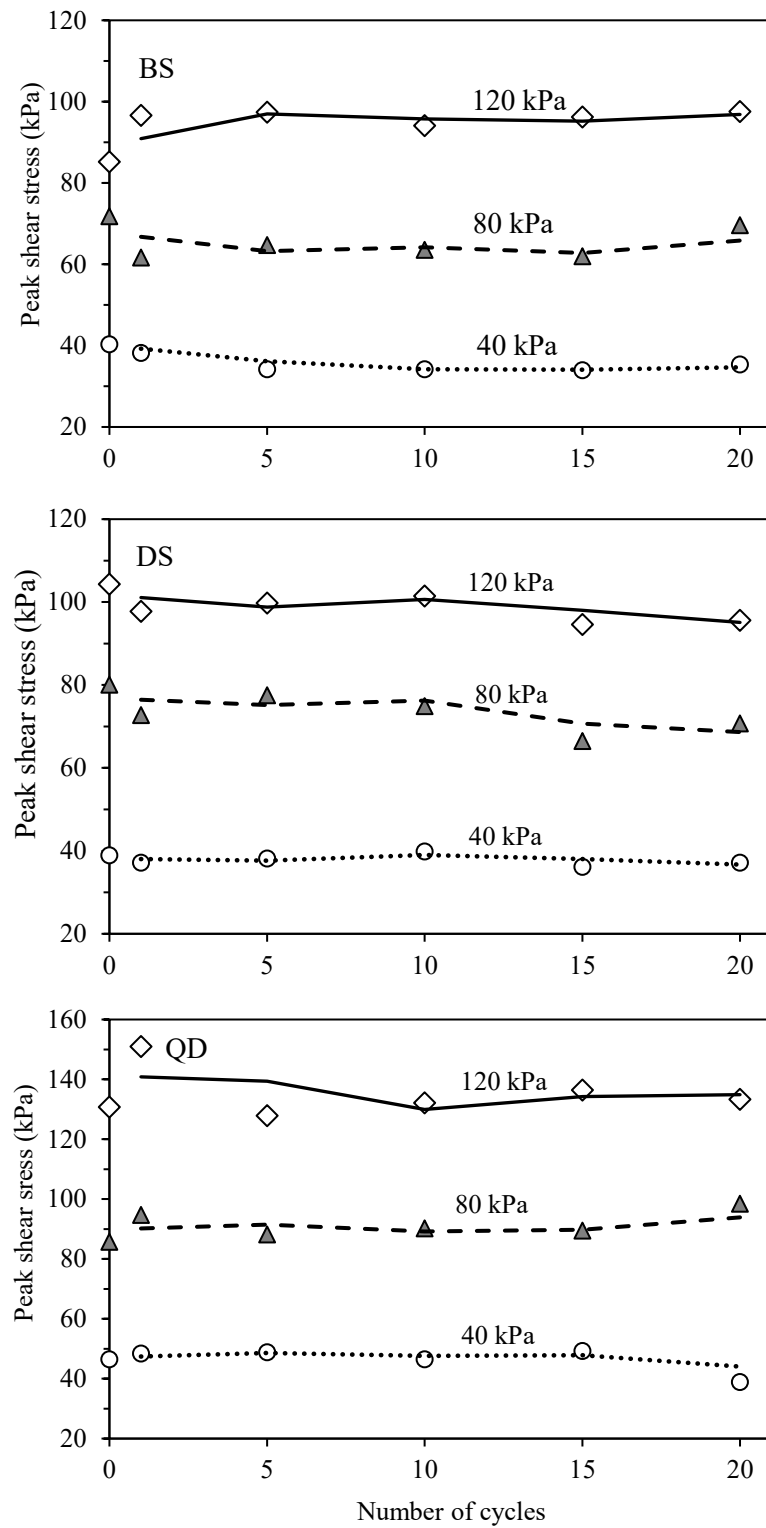


Figure 36. Effects of HC cycles on shear strength of sand samples

Figure 36 demonstrates the effects of HC cycles on the shear strength of sand samples. There was a reduction in the shear strength of BS for the first 10 cycles and thereafter increases. The strength reduction was attributed to the 33.1% reduction in

CaO which was compensated by 18% MgO and 22.5% Na₂O (see Figure 28). DS showed a progressive strength reduction trend with an increasing number of cycles.

The strength reduction was because of a 13.5% reduction in SiO₂ which was mainly replaced by 8.5% CaO (see Figure 29). QD demonstrated a slight strength reduction after the 20th cycle. This was attributed to a 14% reduction in calcite which was replaced by an equal amount of dolomite. Previously, strength increase with increasing HC cycles has been reported by various researchers [77, 82, 115].

4.5 Effects of experimental cycles on friction angle of sand samples

The effects of FT, WD, and HC cycles on the friction angle of sand samples are presented in Figure 37. BS had an initial friction angle of 29.2°, this progressively increased by 26.7% after the 20th FT cycle. The WD experiment resulted in a 30.1% increase in friction angle for the first 10 cycles and was later reduced to a value higher than the original angle. In the HC experiment, there was a 29.7% progressive increase in friction angle up to the 20th cycle. It has been reported that the peak friction angle of sand is a function of the resultant direction/inclination of shearing force on the micro-plane and the angle of dilation [116, 117]. Therefore, the increase in the friction angle of BS was due to the formation of a rough surface texture (see Figure 31) which increased the angle of dilation (negative dilation hence, expansion of samples) along the shearing plane.

Originally, DS had a friction angle of 39.3° which was gradually reduced by 2, 5.3, and 8.1% after the 20th FT, WD, and HC cycles, respectively. The reduction in friction angle was due to the formation of a smooth surface texture (see Figure 32) as well as the development of weak minerals in all the experiments. The formation of

weak minerals like dolomite, albite, and halite would increase the particle crushability.

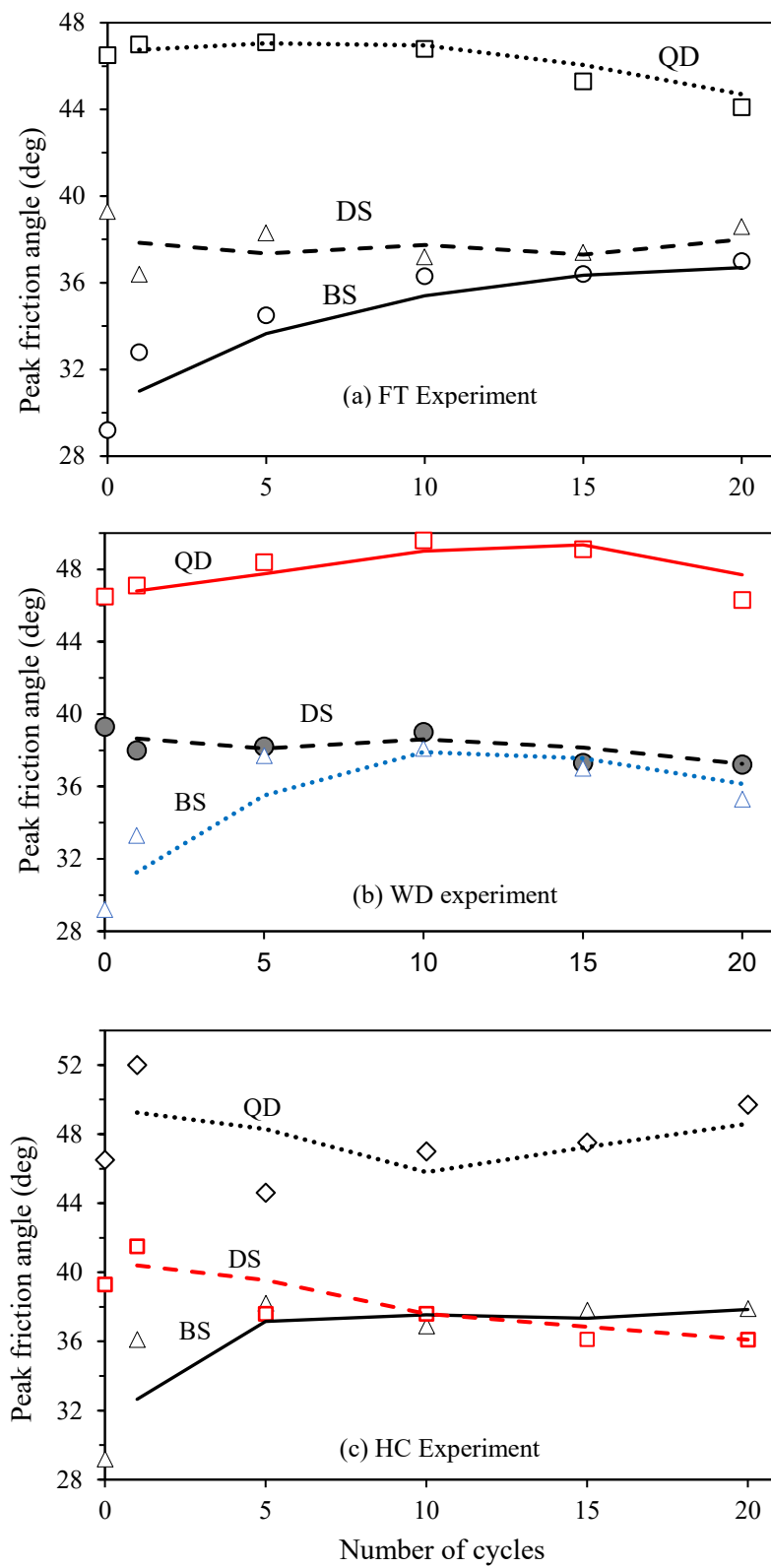


Figure 37. Effects of experimental cycles on the fiction angle of sands

QD had a friction angle of 46.5° before exposure to experimental cycles. The sample experienced an increase in friction angle for the first 10 cycles which was later reduced by 5% after the 20th cycle of the FT experiment. The reduction in friction angle was attributed to the 70.3% reduction in CaO which was mainly replaced by weaker oxides like MgO (35.3%) and Al₂O₃ (7.7%). The WD experiment led to an increase in friction angle for QD up to the 10th cycle and thereafter reduced to a value equal to the original friction angle. The friction at the 20th cycle was equal to the original value and this was attributed to a slight reduction in calcite which was replaced by equal amounts (14%) of dolomite.

In the HC experiment of QD, the friction angle initially reduced for the first 10 cycles and later increased by 6.8% after the 20th cycle. Previous studies on the effects of FT cycles on the friction angle of soil samples have indicated the following. Insignificant changes [107], a progressive increase [41, 118], a continuous reduction [39, 100, 106, 119], and an initial decrease in friction angle and later increases [120]. As regards the studies performed in the WD experiment, a reduction in friction angle with an increasing number of WD cycles has been previously reported by several authors [68–70].

4.6 Effects of exposure conditions shear strain of sands

The changes in the shear strain at failure for the sand samples in FT experimental cycles are presented in Figure 38. Generally, the shear strain at failure started by increasing for the first 10 cycles and gradually reduced. The maximum increase in the shear strain of BS at all normal loads was in a range of 40-50% and later reduced to a value above the initial strain. Considering individual data points, the difference in the initial strain was significant and became insignificant at the 20th cycle. DS had a 38-50% maximum range of shear strain increase at all the normal loads and the final

shear strains were higher than the original values. In the natural state, the shear strain at failure was nearly the same, but after the 20th cycle, the difference was visible. The range of maximum shear strain increase in QD was about 29-36% and the final shear strain was higher than the original value.

The increase in the shear strain at failure for all sands was attributed to the increase in minerals that are weaker than the original mineralogy for example an increase in halite for BS, albite and dolomite in DS, and dolomite in QD. It is anticipated that the increase in the weaker minerals would make the sand grains softer hence taking in large strains before the peak stress is reached. Previously, the continuous strain increase with the number of cycles, and later reduction has been reported [27, 100, 106].

The effects of WD cycles on the shear strain at failure for the sand samples are shown in Figure 39. The shear strain of BS started by increasing up to the 15th cycle and later reduces to a value higher than the original shear strain. The maximum observed shear strain increase was in the range of 25-48% irrespective of the applied normal load. DS demonstrated a 70% progressive increase in shear strain after the 20th cycle. The initial and final shear strains in DS were nearly the same at all normal loads. The increase in shear strain at failure was attributed to the increase in weak oxides like MgO (part of the chemical element for dolomite) in both DS and BS.

QD portrayed an initial shear strain increase with an increasing number of WD cycles (see Figure 39). The maximum value was attained at the 15th cycle which was later reduced to a value less than the original strain. The reduction in the shear strain after the 20th cycle was about 20-28% irrespective of the normal load. This was due to the increase in strong minerals like quartz (see Figure 26) which could lead to strain

hardening. The trend in the shear strain at 80 and 120 kPa was almost similar at all WD cycles. Previous studies on WD cycles have indicated a progressive increase in strain at failure [56, 68, 121, 122].

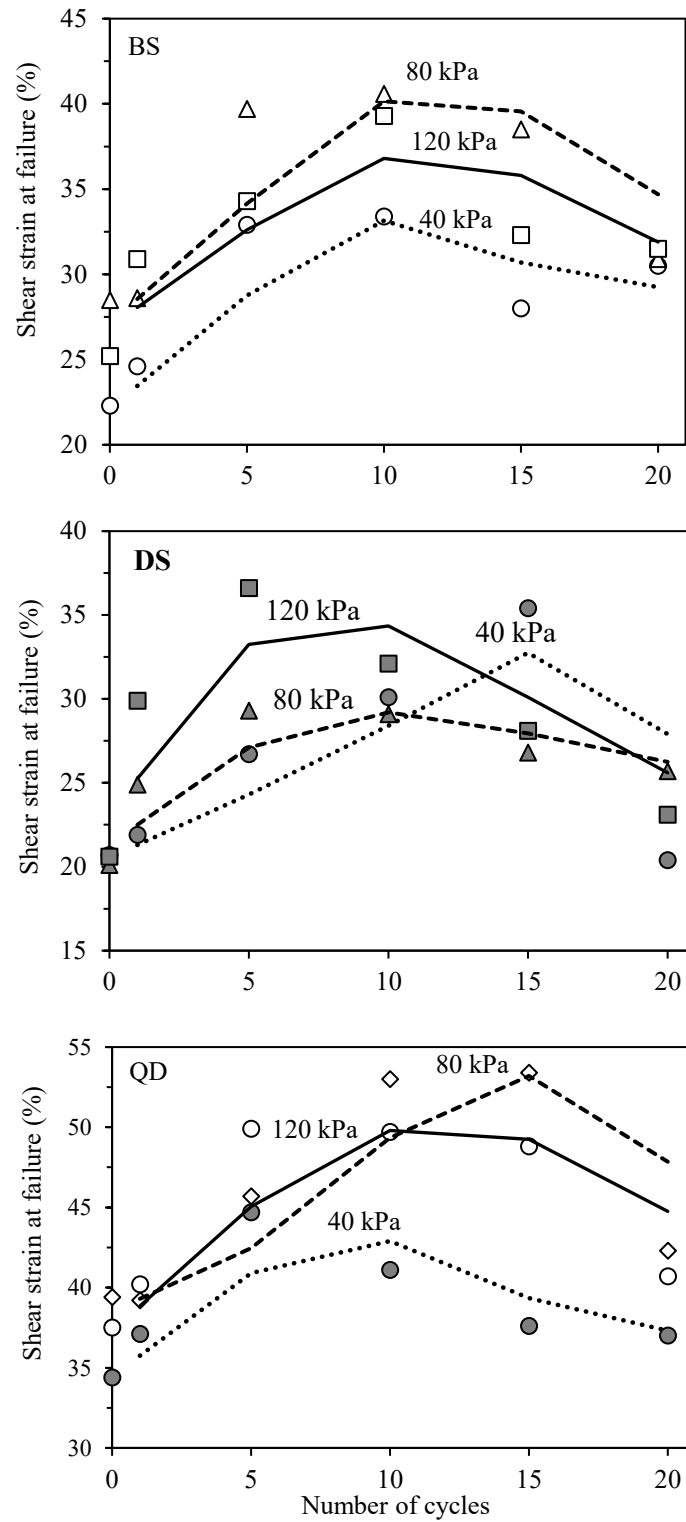


Figure 38. Effects of FT cycles on the shear strain of sand samples

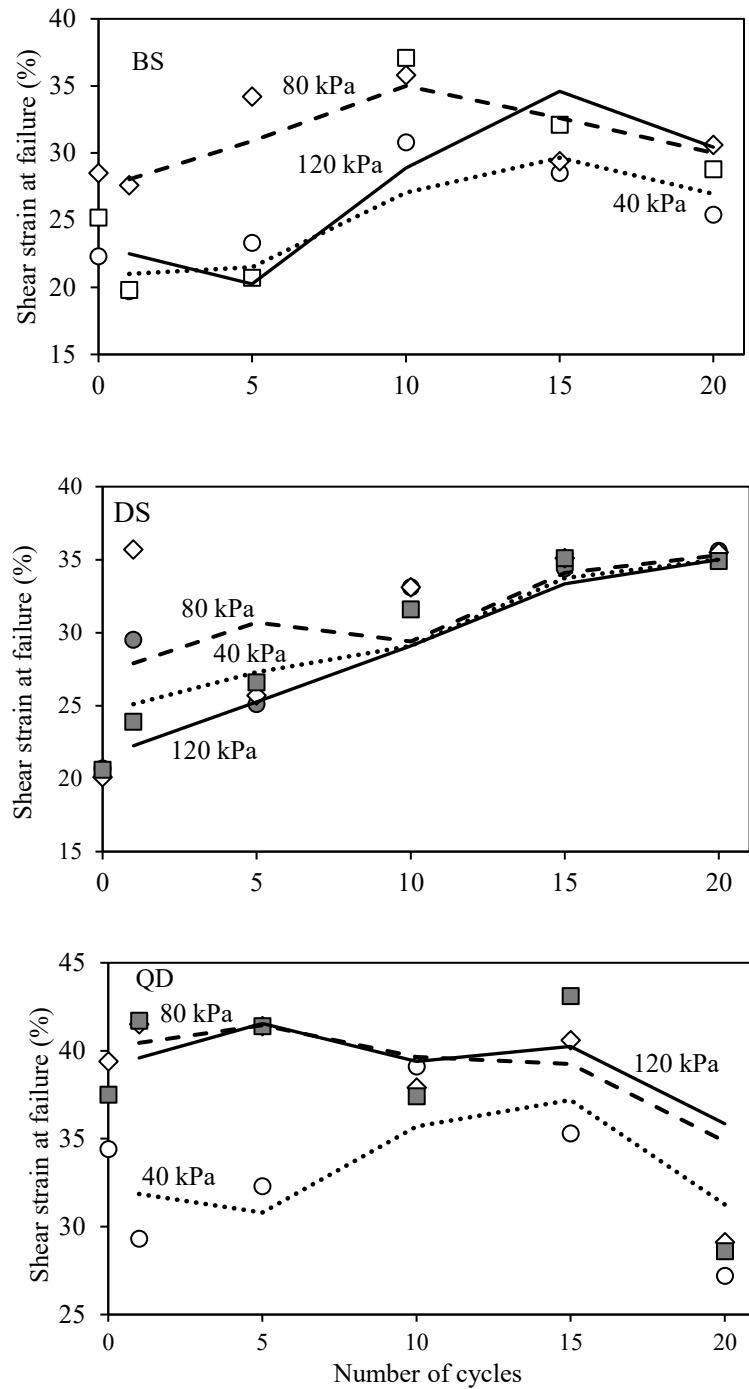


Figure 39. Effects of WD cycles on the shear strain of sand samples

Figure 40 presents the effects of HC cycles on shear strain at failure of the sand samples. BS samples experienced a strain reduction for the first 5 cycles and thereafter progressively increased. The increase in shear strain after the 20th cycle was about 22-58%. Unlike BS, DS had a gradual increase in a shear strain that nearly

doubled the initial value at all normal loads. The increase in shear strain at failure was attributed to the increase in weak oxides like CaO in DS and MgO in BS.

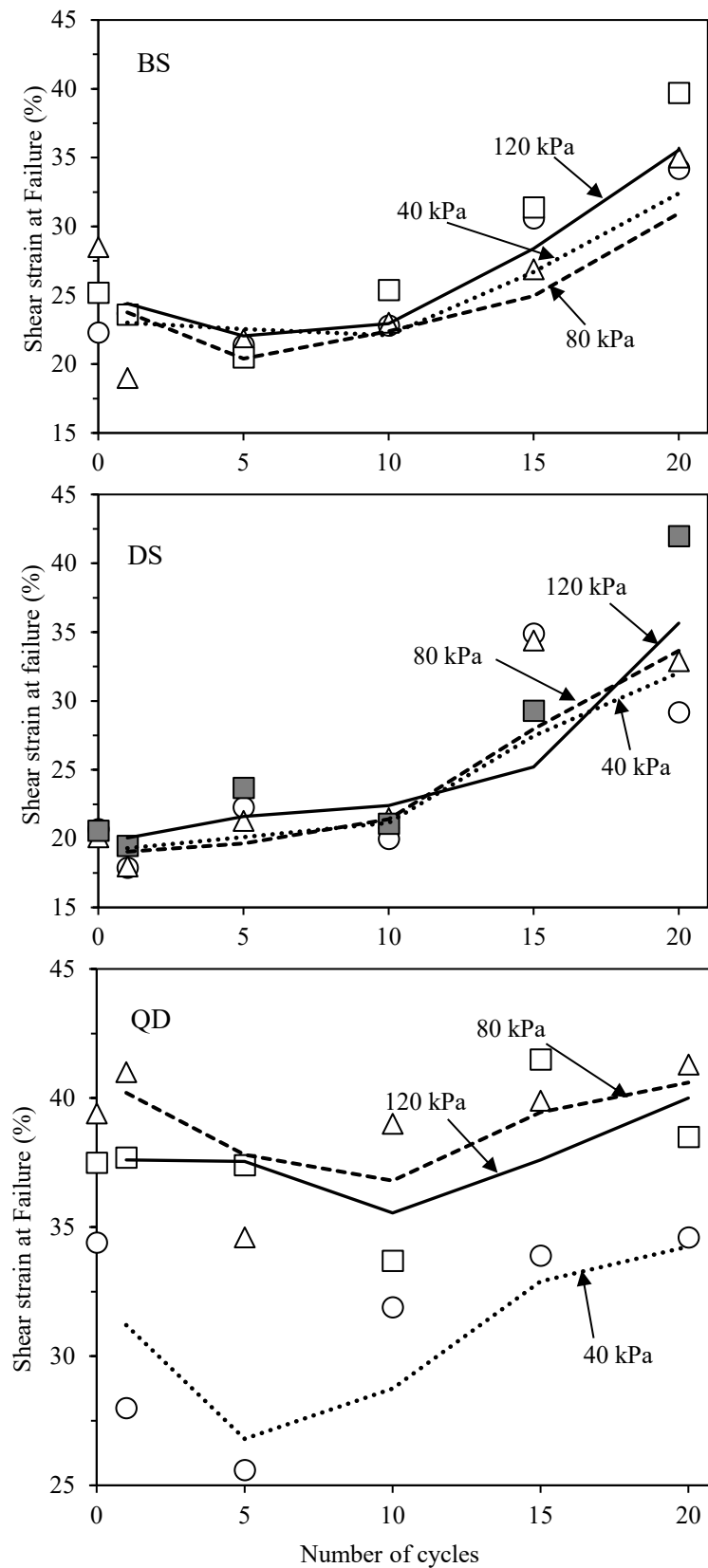


Figure 40. Effects of HC cycles on the shear strain of samples

The shear strain of QD initially reduced for the first 10 cycles and later increased to a value close to the original strain. The maximum reduction in the shear strain was obtained at the 10th cycle in a range of 7-100%. The shear strain at failure being relatively the same as that at the 20th cycle was due to the slight reduction in calcite which was replaced by an equal amount of dolomite (14%). Relating this study to the previous studies, a progressive strain reduction with an increasing number of cycles has been reported in the recent past [76]. However, this was later contradicted by Weng et al. [79] where a continuous strain increase with increasing cycles was reported.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, three sand samples of different origins which includes beach Sand (BS), dune sand (DS), and quarry Dust (QD) were subjected to 20 freezing-thawing (FT), wetting-drying (WD), and heating-cooling (HC) cycles. Shear strength, microstructure, mineralogy, and chemical composition were evaluated at various cycles. The following observations were noted.

1. The original mineralogy strongly varied in DS followed by BS and later QD. In DS, Feldspar was reduced by 69% in FT, 59.5% in WD, and 48.9% in HC. BS experienced a 7.4% reduction in feldspar for the FT and a 12.6% increase for the WD as well as a 15% increase in HC. In QD, there was no change, a 35% reduction, and a 14% decrease in calcite for the FT, WD, and HC experiments respectively.
2. DS experienced a 44.8, 22.3, and 13.5% reduction in SiO_2 after the 20th cycle as recorded in HC, WD, and FT experiments, respectively. BS had a 10.8% reduction in SiO_2 (in FT), a 21.1% increase (in WD), and no change (in HC). QD experienced a 70.3, 67.2, and 66.4% reduction in CaO as noticed in FT, WD, and HC, respectively.
3. A rough surface texture was observed in BS for the FT and WD. A very smooth surface texture was noticed in DS for all the experiments. The changes in surface texture for QD could not be established because of the surface being coated with dust.

4. The shear strength in BS and DS progressively reduced for the first 10th cycles and later increased whereas QD depicted a continuous strength reduction with an increasing FT cycle. In the HC and WD experiment, the shear strength for BS initially reduced and thereafter increased to a constant value. There was a slight strength increase in QD and a continuous strength reduction in DS.
5. The friction angle for BS progressively increased with the cycles. It continuously reduced the DS. In QD, it initially increased and later reduced for the FT and WD. This was the opposite in HC for QD.
6. The shear strain at failure progressively increased and later reduced in FT of all sands and WD for QD and BS. A continuous increase was noticed in the HC experiment of all sands and WD for DS.

5.2 Recommendations

The challenging problem is to investigate a wide range of variables and their method of measurement. Therefore, the following suggestions may be adopted to improve the forthcoming research in this area.

- (a) Assessing the changes in chemical composition, mineralogy, microstructure, and grain size distribution at various cycles.
- (b) A higher number of cycles may be adapted to assess their effects.
- (c) Exposing soils to extreme environmental conditions (higher temperature and pore fluid chemistry).
- (d) Using a closed (constrained) freezing-thawing system.
- (e) Evaluating the mechanical behavior and particle crushability at higher confining stresses.

It has been established that soil mineralogy, chemical composition, and microstructure are greatly affected by the experimental cycles which directly affect the strength and deformation behavior of the soil. Through this research, it is advised to investigate the changes in these parameters due to the anticipated environmental condition (for sensitive projects like a nuclear power plant).

CHAPTER 6

OUTCOME FROM THE STUDY

A journal publication is under review:

Hassan Tumwiine, Mubashir Aziz, Umair Ali, Omar S. B. Al-Amoudi, Shamsad Ahmad, and Abdulazeez Abdulraheem. “Microstructural and Strength Variations of Sands Exposed to Freezing-Thawing, Wetting-Drying, and Heating-Cooling Cycles” – Journal of Construction and Building Materials. Impact factor: 7.603, Cite score: 10.6, Quartile: Q1.

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