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Investigations into engineering characteristics and inherent variability in bituminous sand

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ABSTRACT

Bituminous sand is an important geomaterial due to its numerous engineering applications and great economic potential. The occurrence is diverse in nature and therefore, it is crucial to study the engineering behaviour and understand the inherent variability in the engineering parameters needed in exploitation, design, and construction in and/or on them. This study presents laboratory investigations into the engineering behaviour and the inherent variability in bituminous sand considering index, physical, fabric and geochemistry, mineralogy, oedometer, and strength characteristics on the samples in the intact and reconstituted states. The findings can be summarised as follows: (1) The gradings are characterised by different particle sizes and hence, the bituminous sands are well-graded, (2) The fabrics are heterogeneous and isotropic, composed mainly of bituminous materials-coated particles aggregations into clusters with inter- and intra- particle/cluster voids, (3) Silica and quartz dominate the composition and mineralogy with other elements and minerals in lesser proportions, (4) Bituminous sands have convergent behaviour and the compressibility is dependent on fines content, (5) Intact behaviour shows the presence of significant structure, (6) The inherent variability is high in some engineering grading descriptors, clay mineral, yield stress and strength, and low in the fines content, quartz mineral, compressibility and in situ specific volume, and (7) Depending on the properties needed by the practitioners, interpolation and extrapolation from one point/location to another could be made in these geomaterials..

Keywords: *Bitumen, Engineering behaviour, Fabric, Mineralogy, Variability.*

1. Introduction

At an early stage of an engineering project where data may not be readily available, the usual practice by design engineers is to interpolate and extrapolate between the data that they have for nearby locations and/or prior information. However, one of the major characteristics associated with geomaterials is the variability in their geotechnical parameters. Here, inherent variability results primarily from the natural geological processes involved in the deposition or formation of geomaterials. The enormous industrial and engineering applications make bituminous sand an important material sought worldwide. Over 31 billion tons of bituminous sand are available in Nigeria [1] and the exploitation and various applications are gaining tremendous consideration. Special attention is accorded this material because of its extensive availability and potential for economic growth contributions. Due to this, it is essentially important to investigate the geological and geotechnical characteristics in order to understand their behaviour and the variability in the properties of these materials which may be a challenge for the economic and safe design of engineering structures in them.

Although some studies have investigated the behaviour of bituminous sand [1-4], research on these materials is still few and much more limited for Nigeria's massive deposit. Just recently, Okewale et al. [5] and Okewale and Grobler [6] studied similar material, but while Okewale et al. [5] investigated the mechanical behaviour of silica-rich bituminous sand along a vertical profile, Okewale and Grobler [6] studied the geochemical signature and prediction of mechanical characteristics of bituminous sand. Besides, these studies investigated certain aspects of behaviour and no study has investigated the inherent variability of these materials compared to clays, sands, and others [7-12]. This work presents the investigation into the behaviour and inherent variability in Nigeria bituminous sand. For soil data at a specific site, it is ideal to select a factor based on the variability and where there is no site-specific data, variability is useful as a first-order approximation. This study is very important, because establishing the inherent variability values will assist the design engineers in appreciating the variability inherent in the overall estimation of common design material parameters and ultimately in identifying different geotechnical variabilities. However, it is very difficult to generalize the findings about geomaterials, because they are commonly site-specific and bituminous sand will not be an exception. It is better to investigate the bituminous sand studied here and present the findings we obtained, considering what has been reported for the same and relevant materials all over the world.

This was achieved by conducting extensive laboratory tests to estimate the physical and index properties, microstructure, geochemical and mineralogical characteristics, and the evaluation of mechanical properties (compression indices, in-situ specific volume, and unconfined compressive strength). Also, the coefficient of variation (CoV) was determined in order to estimate overall inherent variability for different properties. Apart from these, several data from other studies were re-analyzed and also included in the analysis. This work is very vital and innovative for this particular material of abundant economic value that is gaining massive consideration. This research is

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new in the way the fundamental framework that accounts for the effects of natural structure, which has been used extensively for the mechanics of sedimentary soils, is applied to bituminous sand in compression. The applicability of this framework to this type of geomaterial has received very little attention. Also, novel for these materials is the way in which the inherent variability in properties is determined so that it will be easy for practitioners to estimate the needed properties when they are not readily available

2. Materials and methods

Bituminous sands were used in this paper. They were collected from four different locations and two different points from each location in the two local government area of Ondo State Nigeria. Samples were collected as blocks from each location. The coordinates of the locations are; 6°39′20.070″ N, 4°53′29.236″ E; 6°43′52.731″ N, 4°49′51.879″ E; 6°39′16.353″ N, 4°53′28.796″ E and 6°36′35.824″ N, 4°49′49.458″ E for Irelejare, Ilubirin, Gbelejuloda, and Temidire, respectively. They were collected using the Japan Geotechnical Society [13] method which has been used for other geomaterials [11]. The details of the characteristics of the samples tested and other studies re-analysed are given in Table 1. For clarity, acronyms are used and the letters indicate sample locations, while Arabic numerals represent the collection point of the samples which is based on the depth starting from the top. The IR stands for Irelejare, IL represents Ilubirin, GB indicates Gbelejuloda, and TE is for Temidire. IR (1) means samples obtained from Irelejare at 0.94 m depth.

Tables1. The details of sample characteristics and index properties.

Samples /Acronym	Depth (m)	D_{50} (mm)	C_u	C_c	F(%)	Reference
IR (1)	0.94	0.12	9.04	0.62	36.1	This study
IR (2)	1.85	0.14	9.09	0.90	29.4	This study
IL (1)	0.85	0.06	5.29	0.58	51.2	This study
IL (2)	1.35	0.04	59.0	6.77	61.9	This study
GB (1)	0.45	0.20	13.5	0.74	29.3	This study
GB (2)	1.23	0.11	7.5	0.87	34.2	This study
TE (1)	0.75	0.04	50	0.25	55.9	This study
TE (2)	0.95	0.04	50	0.25	55.9	This study
Irelejare	0.75	0.15	133.3	4.0	38.0	Okewale et al. (2023), Okewale and Grobler (2024)
Irelejare	1.45	0.15	133.3	4.0	37.0	Okewale et al. (2023)
Irelejare	2.0	0.15	133.3	3.0	40.0	Okewale et al. (2023)
Ilubirin	0.3	0.09	26.7	1.7	40.6	Okewale et al. (2023), Okewale and Grobler (2024)
Ilubirin	0.6	0.12	48.9	1.6	36.7	Okewale et al. (2023)
Gbelejuloda	0.5	0.08	56.3	6.3	42.3	Okewale et al. (2023), Okewale and Grobler (2024)
Gbelejuloda	0.9	0.12	93.8	15.0	30.2	Okewale et al. (2023)
Gbelejuloda	1.3	0.16	137.5	4.5	34.6	Okewale et al. (2023)
Temidire	0.4	0.08	125	4.4	46.8	Okewale et al. (2023), Okewale and Grobler (2024)
Temidire	0.8	0.09	125	5.0	44.5	Okewale et al. (2023)
Temidire	1.5	0.06	125	2.9	50.8	Okewale et al. (2023)
Athabasca	77	0.17	9.37	7.04	4	Okewale and Grobler (2024), Doan et al. (2012), Delage et al. (2013)
Ilubirin	20-60	0.28	55	6.11	24	Okewale and Grobler (2024), Ola (1991)

D_{50} mean particle size, C_u the coefficient of uniformity, C_c the coefficient of curvature, F_c fines content, IR Irelejare, IL Ilubirin, GB Gbelejuloda, and TE Temidire.

A combination of wet sieving and sedimentation techniques was used to determine the grading characteristics of the samples [14]. Classification tests were carried out to determine the index properties. The microstructure and geochemistry were analysed using a Phenom ProX scanning electron microscope (SEM) that was equipped with an energy dispersive spectrometer (EDS). A Rigaku diffractometer (XRD) with an automatic divergence slit with software was used for the mineralogical analyses of the samples in powdered form. Proper care was ensured so that no external materials were introduced during sample preparation. The machine operated at 40 kV and 15 mA and the radiation is Cu-Kα. The samples were scanned at an interval of 0.02°/0.30 seconds. The minerals were identified within the range of $2° \leq 2\theta \leq 70°$.

One-dimensional compression tests were conducted using a conventional front-loading oedometer. A closed-base fixed and floating-type confining rings were used. Reconstituted samples are those in which natural bonding and fabric have been removed. 18 reconstituted tests were conducted on the samples. Intact samples were prepared by careful trimming of the block samples, excavated ahead of the ring and the ring was pressed with a small downward pressure. 25 intact tests were carried out on the samples.

The compressibility parameters were the slope (λ), when a natural logarithmic stress scale is used and the intercept (N) at 1 kPa vertical effective stress of the normal compression lines. The λ and N were obtained from the oedometer test data. Within the range of the stresses tested, the normal compression lines are assumed to be straight lines. The slope of the normal compression line (NCL) was taken as $\lambda = Cc/2.303$, where Cc is the compression index, defined in terms of vertical effective stress.

The initial specific volumes (v) of the samples were estimated using initial dimensions and water content. The final v was determined using final dimensions and water content while back calculating the initial v using vertical strain obtained in the tests [15-18]. The equations of v used were three and they were made to be as independent as possible as shown in Eqs. 1 to 3:

$$v_i = \frac{\gamma_w\,(1 + w_i)\,G_s}{\gamma_{bi}} \tag{1}$$

$$v_i = w_i G_s + 1 \tag{2}$$

$$v_i = \frac{w_f\,G_s + 1}{(1 - \varepsilon_v)} \tag{3}$$

where v_i = initial specific volume, G_s = specific gravity, w_i = initial water content, w_f = final water content, γ_w = unit weight of water, γ_{bi} = initial bulk unit weight, and ε_v = vertical strain.

The unconfined compressive strength (UCS) was conducted on moulded samples. The samples used for the UCS were 50 mm in diameter and 82 mm in height. The moulded samples were prepared utilising three layers, applying 25 blows each with a 2.5 kg rammer falling from a height of 304 mm using a 944 cm^3 mould. A total of 20 tests were conducted on the samples. The coefficient of variation (CoV) was determined by estimating the standard deviation (σ) and normalizing it with the mean (μ) of the properties.

$$CoV = \frac{\sigma}{\mu} \tag{4}$$

3. Results and discussions

3.1. Grading, microstructure and compositions

Figure 1 presents the particle size distributions of the samples as obtained from the wet sieving and sedimentation technique. For clarity and simplicity, the figures are divided into two and they are distinguished by different lines and symbols. However, the same colours and markers are used for samples from the same formation. The gradings are divided into fine and coarse contents. Generally, the samples are well-graded with different particle sizes, similar to related studies [1], [5-6]. The details of engineering grading descriptors (mean particle size D_{50}, coefficient of uniformity Cu, coefficient of curvature Cc and fines content Fc) are given in Table 1. These descriptors are commonly used by practising engineers to provide insight into the behaviour of geomaterials. The D_{50} ranges from 0.04 mm to 0.20 mm and the values are close for all the samples except for the TE samples. The values of Cu vary between 7.5 and 59 which further confirms the well-graded nature of the samples. The Cc ranges from 0.25 to 6.7 and the Fc values vary from 29.3 to 55.9. These values are similar to what has been reported by other studies [1-6].

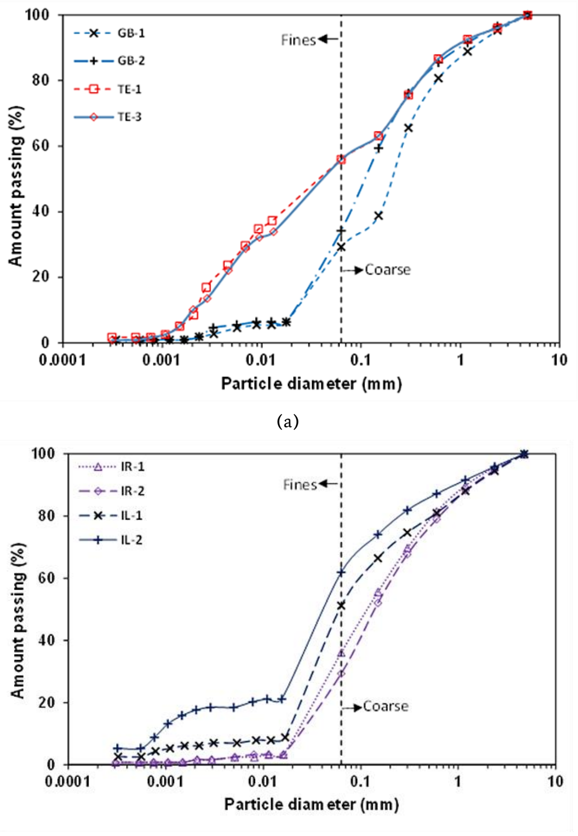
Figure 2 shows the typical fabrics of the samples obtained through the SEM images. For all the samples, the micrographs are shown for a 200 μm field of view. The SEM images provide insight into the fabric characteristics of the samples. The SEM shows the particle size, particle shape, particle distribution, and arrangement, as well as the pore spaces. However, all these only give the qualitative description of the fabric. It would have been nice if the quantitative description were provided for the samples for example, using the mercury intrusion porosimetry (MIP) but unfortunately, we do not have the facility to do this. The microstructure of the IR samples is characterised by particles that are coated by bituminous materials. These materials and the particles aggregated to form clusters with inter-particle and inter-cluster voids. There is no particle orientation and the fabric is heterogeneous. The fabric of the IL sample indicates particles with less agglomeration and the existence of inter-particle voids. Also, the fabric is heterogeneous. The GB fabric is characterised by the agglomeration of particles and bituminous materials, forming continuous clusters with large inter-cluster voids. There is no particular orientation of the particles and the fabric is heterogeneous. The microstructure of the TE samples is characterised by continuous clusters with large inter-cluster voids.

Table 2 shows the compositions of the samples as obtained from the SEM equipped with EDS. Silicon is the most prominent and other elements with significant values are aluminium, carbon, sulphur, and iron. However, the other elements are in trace amounts. The details of mineralogy are given in Table 3. Quartz dominates the mineralogy for all the samples which endorses the presence of silica in the composition of the samples. This is also followed by clay minerals (kaolinite and illite) and the other minerals present are marialite, clinochlore, sakhalite, and graphite in different proportions.

3.2. Mechanical characteristics of the samples

Figure 3 presents the behaviour of the reconstituted samples in one-dimensional compression. This behaviour is caused mainly by the constituent particles. For clarity, only a few compression paths are shown and one-dimensional compression lines (NCLs) are not presented. The initial specific volumes that could be reached are variable for different samples and the compression paths are similar for samples from the same location. The compression curves converge to a unique normal compression line, similar to related materials [5-6], clays [19], granular materials [20-22], and other materials [23].

Figure 4 shows the intrinsic behaviour of the samples as represented by the NCLs. Within the range of stresses investigated, the NCLs were estimated at the higher stress where the compression curves are converging and they are assumed to be a straight line. The NCLs are parallel for the samples from the same location. The compressibilities of the samples are variable and apart from the IL samples, the compressibility reduces with depth. The compressibilities are lowest in the IR and GL samples, followed by the IL samples, while the TE samples have the highest values of compressibility.



(a)

(b)

Fig. 1. Grading curves of the samples; (a) IR and IL, and (b) GB and TE.

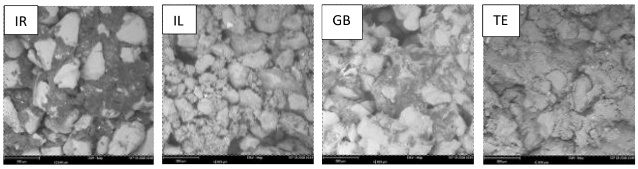


Fig. 2. Typical SEM images of the intact samples.

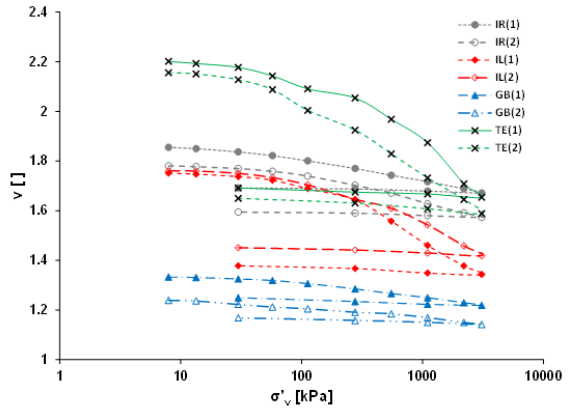


Fig. 3. Oedometer tests for the reconstituted samples.

Table 2. Elemental composition of the samples.

Element/ Symbol (wt %)	Samples							
	IR(1)	IR(2)	IL(1)	IL(2)	GB(1)	GB(2)	TE(1)	TE(2)
Silicon/Si	42.02	45.85	37.04	23.01	40.69	35.83	35.21	34.93
Oxygen/O	26.47	24.14	21.85	20.46	23.12	19.72	23.16	22.82
Carbon/C	8.29	6.38	1.21	1.09	4.06	5.93	1.27	0.96
Aluminium/Al	3.55	5.01	14.21	16.68	10.24	9.77	12.54	14.38
Sulphur/S	4.23	2.28	1.25	8.71	4.63	4.06	0.78	1.05
Iron/Fe	3.50	2.03	9.42	13.52	7.44	11.03	9.12	9.22
Potassium/K	1.31	1.31	1.88	2,38	1.79	1.91	2.61	2.76
Niobium/Nb	2.27	2.18	1.80	2.12	1.79	2.01	1.48	1.47
Yttrium/Y	3.04	2.42	3.57	3.46	1.15	2.05	1.64	1.65
Silver/Ag	2.03	2.70	1.83	1.82	0.92	2.71	1.73	1.52
Calcium/Ca	0.94	1.32	1.70	2.14	0.81	1.05	4.91	4.42
Chlorine/Cl	0.84	0.89	1.07	0.87	0.76	0.99	0.66	0.76
Magnesium/Mg	0.60	0.80	0.59	1.05	0.56	0.66	1.03	0.76
Sodium/Na	0.45	0.62	0.44	0.53	0.50	0.43	1.05	0.43
Phosphorous/P	-	0.40	-	0.19	0.66	0.44	0.52	0.47
Nitrogen/N	-	-	-	0.46	0.21	0.21	0.55	0.18
Titanium	-	0.52	2.01	1.52	0.66	1.21	1.72	2.22
Vanadium/V	-	0.51	-	-	-	-	-	-

The lower values of compressibility in the IR and GL samples can be linked to the least fines content as obtained from the grading characteristics. The higher compressibility in the IL samples and the highest values in the TE samples can also be attributed to the gradings. These types of behaviours have been reported in similar materials [5-6], tropical clays [11], and other geomaterials [12].

Linking the fabric of the samples to the compressibility, the compressibility of the IR samples is low due to the coating of the particles with the bituminous material which resulted in few inter-particle and inter-cluster voids (Fig. 2). The relatively high compressibility in the IL samples could also be attributed to the fabric associated with non-coated particles. Similarly, the compressibility of the GL samples is low due to the coating of the particles with the bituminous material and the highest compressibility in the TE samples could be attributed to the fabric associated with non-coated particles. These characteristics are similar to what has been reported by related studies [5-6].

The chemical compositions could also be linked to the compressibility of the samples. The samples with high silicon contents (IR and GB) generally have low compressibility and the samples with low silicon contents have high compressibility (IL and TE) (Table 2). Another important composition is the carbon content and samples with high carbon content (IR and GB) have low compressibility. Also, the samples with low carbon content (IL and TE) have high compressibility. Okewale et al. [5] reported similar findings on similar materials. Relating the mineralogy to the compressibility of the samples, there is no clear effect of mineral compositions on the compressibility as can be seen in Table 3.

Table 3. Mineralogy of the samples.

Minerals (%)	Samples			
	IR	IL	GB	TE
Quartz	53.2	60.0	53.0	56.0
Kaolinite	12.5	9.0	3.0	6.0
Illite	9.4	4.0	5.0	13.0
Marialite	16.1	9.0	14.8	5.0
Clinochlore	0.66	15.0	18.0	0.5
Sakhalite	7.2	3.0	5.7	18.0
Others	0.94	-	0.5	1.5

The behaviour of the intact samples is presented in Figure 5. Again, a few compression paths are shown for clarity. The initial in situ specific volumes are variable and the compression curves of the samples from the same location are fairly similar. The paths of the IR and GB samples are very stiff, while those of the IL and TE are less stiff. This shows that the structure (bonding and fabric) in the IR and GB samples is robust and this could be linked to the fabrics which are characterised by the clusters of particles and bituminous materials as seen in Figure 2. The higher gradient in the compression paths of the IL and TE samples can also be attributed to the less agglomeration of particles forming clusters (Fig. 2). As expected, the yield stresses are higher in the IR and GB samples due to their very stiff nature and the values for the IL and TE samples are lower in that order. Figure 6 shows the stress-strain behaviour of the samples. The stress rises monotonously with strain to a peak and then reduces with strain. The strength of the samples was estimated as the peak point on the curves. The strength of the samples ranges from 40 kPa to 166 kPa (Fig. 6).

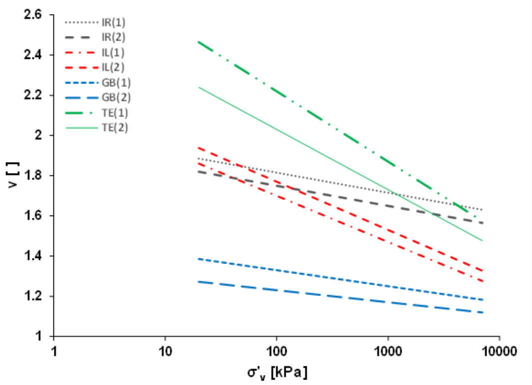


Fig. 4. Intrinsic behaviour of the samples.

3.3. Variability in the samples

Table 4 presents the details of the inherent variability of different parameters through the coefficient of variability (CoV). For the engineering grading descriptors, the variabilities are low, high, and very high for the fines content (Fc), mean particle size (D_{50}), and coefficient of uniformity (Cu), respectively. This shows that the grading characteristics of this important material vary from one location to another. Okewale and Grobler [6] studied the predictability of mechanical parameters using the grading indices used in this study and it was found that Fc has significant correlation, while D_{50} and Cu have poor correlation statistics. Since the variability is low for the Fc, it will be safe for practicing engineers to estimate mechanical properties and interpolate and extrapolate unknown mechanical parameters where data are not available. The variability of quartz mineral is very low and that of clay is relatively high. This shows that the quartz composition in bituminous sand does not vary widely. It has also been reported that quartz and clay minerals could not be used to predict the mechanical characteristics of bituminous sand [6].

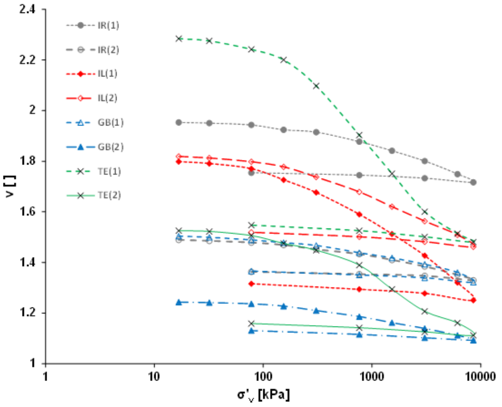


Fig. 5. Intact behaviour of the samples.

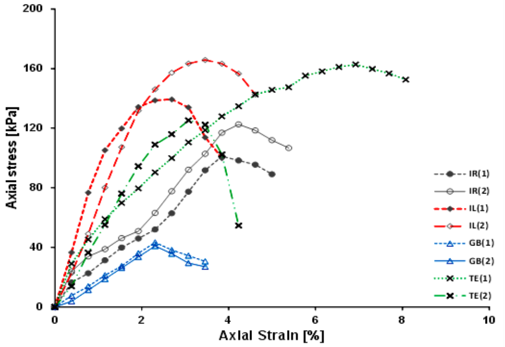


Fig. 6. The stress-strain behaviour of the samples.

Table 4. Variability of the properties.

Properties		Variability		
		μ	σ	CoV
Engineering Descriptors	D_{50}	0.097	0.054	0.56
	Cu	64.45	52.44	0.81
	Fc	42.54	8.84	0.20
Mineralogy	Q	55.56	4.61	0.08
	Cl	19.31	7.41	0.38
Compressibility	N	2.156	0.377	0.17
	λ	0.080	0.039	0.48
In situ state	v	1.628	0.240	0.14
	σ_y	509.68	279.57	0.54
Strength	UCS	85.07	50.75	0.59

μ mean, σ standard deviation, CoV coefficient of variation, Q quartz, Cl clay, N intercept of NCL at 1 kPa, λ slope of the NCL, v in situ specific volume, σ_y yield stress, and UCS unconfined compressive strength.

The average variability of the compressibility (N and λ) is low. This indicates that the compressibility does not vary widely for the samples from different locations. Compressibility is one of the important parameters in design and due to low variability, it will be easy for practicing engineers to interpolate and extrapolate from known to unknown in bituminous sand. The in situ state represented by specific volume (v) and yield (σ'_y) is very important, because they are commonly combined with stresses to fully describe the behaviour of geomaterials. The variability of the in situ v is low and that of yield stress is high. The low variability in the situ v will allow easy interpolation and extrapolation where data are not available. The yield stress defines the point of structural breakdown and gives the idea of the effect of structure. This shows that the effect of structure varies for the samples from different locations. The variability of the strength of the samples is high. This indicates that the strength of bituminous sand varies widely and care should be taken by practicing engineers when interpolating and extrapolating when strength data are needed. Okewale and Grobler [6] also reported that many indices were not able to successfully predict the strength of bituminous sand. In general, the inherent variability is high in the mean particle size, coefficient of uniformity, clay mineral, yield stress and strength, and low in fines content, quartz mineral, compressibility, and in situ specific volume of the bituminous sand.

4. Conclusions

An extensive study has been made into the behaviour and inherent variability in bituminous sand from different depths and locations. This was achieved by conducting comprehensive laboratory tests (index, physical, microstructural, geochemical, mineralogical, one-dimensional compression, and strength) on the samples in the intact and reconstituted states. The following summary can be made: (a) The gradings of the bituminous sands are well-graded in nature, (b) The microstructures of bituminous sand are characterised by coated particles with bituminous materials, particles aggregation forming clusters with inter-particle and inter-cluster voids and the fabric is heterogeneous and isotropic, (c) Silicon is dominant and aluminium, carbon, sulphur and iron have significant percentages, (d) The mineralogy comprises quartz, clay minerals, marialite, clinochlore, sakhalite, and graphite in different proportions, (e) The bituminous sands' compression curves are similar for samples from each location and the paths converge to a unique normal compression line, (f) The lower the fines content, the lower the compressibility of bituminous sand, (g) The intact compression curves are stiff and this indicates the presence of a strong structure, (h) The stress increases monotonously with strain to peak and then decreases with strain, (i) The grading characteristics of bituminous sand vary from one location to another, (j) The variability of compressibility and in situ specific volume is low for the bituminous sand and practicing engineers can interpolate and extrapolate within these materials using any of the needed properties, and (k) Further work is needed for this important geomaterials particularly for samples at greater depths.

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Notations

C_c	coefficient of curvature
Cl	clay mineral
CoV	coefficient of variation
C_u	coefficient of uniformity
D_{50}	mean particle size
F_c	fines content
N	intercept of the NCL at 1 kPa
NCL	one-dimensional normal compression line
Q	quartz
UCS	unconfined compressive strength
v	in situ specific volume
σ_y'	yield stress
λ	slope of the NCL
μ	mean
σ	standard deviation

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