On the laboratory investigations into the one-dimensional compression behaviour of iron tailings

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Abstract. The failures of tailing dams have caused irreparable damage to human lives, assets and environment and this has ultimately resulted in great economic, social and environmental challenges worldwide. Due to this, investigation into mechanical behaviour of tailings has received some attention. However, the knowledge and understanding of mechanics of behaviour in iron tailings is still limited. This study investigates the mechanics of iron tailings from Nigeria considering grading, effects of fabric resulting from different sample preparations and the possibility of non-convergent behaviour. This was achieved by conducting series of one-dimensional compression tests in conjunction with index, microstructural, chemical and mineralogical tests. The materials are predominantly poorly graded, non-clayey and non-plastic. The tailings are characterised by angular particles with no obvious particle aggregations and dominated by silicon, iron, aluminium, haematite and quartz. The compression paths do not converge and unique normal compression lines are not found and this is an important feature of the transitional mode of behaviour. The behaviour of these iron tailings therefore depends on initial specific volume. The preparation methods also have effect on the compression paths of the samples. The gradings of the samples have an influence on the degree of transitional behaviour but the preparation methods do affect the degree of convergence. The transitional mode of behaviour in these iron tailings investigated is very strong.

Keywords: Tailings; compression; fabrics; geotechnical properties; transitional behaviour

1. Introduction

The materials obtained after the extraction of valuable minerals from as-mined ores are called tailings. The gradings and mineralogies vary widely as a result of different extraction and treatment processes as well as different compositions of the parent materials of the ores (e.g., Li and Coop 2019, Li et al. 2018). The materials are susceptible to liquefaction either by static or seismic loading due to the small particle sizes and high water contents. Therefore, the majority of studies on tailings have been concerned about the stability performance of tailings dams (e.g., Fourie et al. 2001, Fourie and Papageorgiou 2001, Zandarin et al. 2009, Carrera et al. 2011, Ozer and Bromwell 2012, Schnaid et al. 2013, Zhang et al. 2015). Some studies have also investigated the mechanics of tailings (e.g., Chang et al. 2011, Bedin et al. 2012, Li et al. 2018, Reid et al. 2018, 2019). However, the study of these materials is still limited and the knowledge about them is not widespread compared to other geomaterials. Also, different behaviours have been reported for tailings and more studies are necessary to provide further insight into the mechanical behaviour of these important materials.
For example, Coop (2015) evaluated test data for fluorite tailings and reported that the samples

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obtained from different depths and with the same grading did not have convergent compression behaviour. In contrast, Carrera et al. (2011) investigated the same tailings although with different gradings and found convergent behaviour. The non-convergent behaviour is a termed a transitional mode of behaviour and this has been highlighted in different geomaterials (e.g., Martins et al. 2001, Shipton and Coop 2012, Hyodo et al. 2017, Todisco et al. 2018, Okewale and Coop 2020, Reid et al. 2020). This behaviour is characterised by non-unique normal compression and critical state lines (NCL and CSL) for the samples with different initial states (densities, void ratios or specific volumes). Also, effects of fabric on the mechanical behaviour of tailings and other materials were reported by some studies (e.g., Chang et al. 2011, Lade et al. 2009, Xu et al. 2009). Li and Coop (2019) studied the effects of grading and fabric on the mechanical behaviour of an iron tailings. Also, they investigated the presence or absence of the transitional mode of behaviour in iron tailings. The study showed that the fabric did not have large effect on the behaviour of iron tailings and no transitional behaviour was observed. However, the study of this material is still very scanty and the knowledge in the international community is limited.

This paper presents an extensive laboratory study of the mechanical behaviour of different iron tailings from Nigeria. The possibility of transitional behaviour was determined and comparisons were made between the current study and related studies on other iron tailings as well as other tailings. This study is new and novel in the sense that samples tested were new and collected from different depths, influences of preparation methods on compression paths were investigated, effects of gradings on the degree of convergence were studied and the influences of sample preparations were also determined. This was achieved by conducting comprehensive oedometer tests on samples prepared using different methods. Apart from this, index properties were determined using classification tests, microstructure and chemical compositions were studied using scanning electron microscope (SEM) equipped with EDS and the mineralogy investigated using X-ray diffraction (XRD).

2. Materials and methods

The materials used were different iron tailings, collected from the Itakpe tailings dump in Kogi State North Central Nigeria. The samples were collected at different points but across different depths. **A** typical example of samples used is presented in Fig. 1. The samples were labelled as top sample (T) which was taken at the surface, middle sample (M) collected at 1 m and base sample (B) taken at 2 m and the details are given in the Table 1. They were grouped into two (1 and 2) based on the area in which they were collected. Acronyms are used for clarity and in the acronyms the letter stands for the description of the location of sample with respect to the depth and number indicates the area at which the samples were taken.

The gradings of the samples were determined from a combination of wet sieving and the sedimentation technique. The samples were tested in their natural gradings. A quantitative geochemical analysis of the samples was conducted using a Phenom ProX scanning electron microscope (SEM) equipped with energy dispersive spectrometer (EDS). The samples were air-dried, pulverised, placed in a sample holder and then pushed into the machine for the EDS analysis. The mineralogy of the samples was studied using a Shimadzu XDS 2400H diffractometer equipped with the JCPDFWIN software. The equipment operated at 40 kV and 55 mA and the minerals were identified in the range of $5° \leq 2\theta \leq 70°$ with Cu-Kα radiation. The samples were scanned at an interval of 0.02°/0.30 s and the samples were analysed in powder form.

The compression behaviour was investigated using a conventional front loading oedometer. A closed base fixed confining ring of 50 mm diameter and 20 mm height was used. A smaller ring of 30 mm diameter and 20 mm height was also used. The ring in the smaller oedometer is a floating ring type which allows higher stresses to be reached and without excessive wall friction. The load was applied in an incremental manner up to 65 kg.

Table 1. Details of characteristics of different samples

Sample	D_{50} (mm)	C_u	C_c	I_{GS}	CF (%)	F_c (%)	LL (%)	Reference
T-1	0.22	27	2.1	0.0084	10	28	-	This study
B-1	0.9	112	68	0.0080	8	18	-	This study
T-2	0.31	84	19.04	0.0036	10	18	21.75	This study
M-2	0.26	70	6.70	0.0034	10	14	19.8	This study
B-2	0.25	55	9.89	0.0041	10	18	20.3	This study
Iron (UB)	0.22	10.4	2.6	0.021	1	16	-	Li et al. (2018), Li and Coop (2019)
Iron (MB)	0.035	10	1.1	0.0035	2	62	-	Li et al. (2018) , Li and Coop (2019)
Iron (PO)	0.023	6.7	2.2	0.0034	2	92	-	Li et al. (2018) , Li and Coop (2019)
Gold	0.065	7.0	2.3	0.0092	4	68	-	Bedin et al. (2012)
Gold	0.011	7.3	1.4	0.0015	10	94	-	Li et al. (2018)
Gold (UB)	0.096	24.1	2.2	0.0039	7	33	-	Chang et al. (2011)
Gold (MB)	0.053	10.5	0.8	0.0050	3	53	-	Chang et al. (2011)
Gold (PO)	0.006	2.6	1.6	0.0023	8	98	-	Chang et al. (2011)
Copper	0.031	5.1	1.5	0.0060	2	92	-	Li et al. (2018)
Fluorite sand	0.180	2.5	1.1	0.072	-	-	-	Carrera et al. (2011)
Fluorite silt	0.026	9.7	2.6	0.0026	8	92	-	Carrera et al. (2011)

D_{50} mean particle size, C_u coefficient of uniformity, C_c coefficient of curvature, I_{GS} grain size index, CF clay fraction, F_C fines content, LL liquid limit, T-1 and B-1 are top and base sample from first location respectively, T-2, M-2 and B-2 are top, middle and base sample from second location respectively, UB, MB and PO are tailings taken from upper beach, middle beach and pond of tailings dam respectively.

The closed base ring allows the moist weight of samples to be taken more easily as it prevents loss of water at the base of the ring after the tests and does not require using filter paper which is a major source of error in the measurement of the initial specific volume (Rocchi and Coop 2014).
The samples were prepared using dry compaction (DC), wet compaction (WC) and slurry (SL). Dry compacted samples were prepared from the samples as retrieved in situ and wet and slurry samples were prepared by adding varying amounts of water. The dry compacted samples were spread slowly and gently into the oedometer ring and then tamping lightly with different numbers of impacts using a plastic rod with a light steel head to obtain samples with different densities. For the wet compacted

samples, they were compacted in three layers using lesser and greater efforts to achieve samples of different initial densities. The samples were placed in oedometer ring and the height carefully measured under a small nominal load. They were then flooded for 24 hours to allow full saturation before incremental loading to 2.7 MPa or 8.5 MPa.

Fig. 1 Typical example of the samples

The specific volumes (v = 1+e, where e is void ratio) were calculated using different measurements. It must be accurately calculated in order to ensure that the behaviour of the samples is correctly measured. Several methods were used to improve confidence using the methods highlighted by similar studies (e.g., Okewale and Coop 2017, Rocchi et al. 2017, Okewale and Grobler 2020a, 2020b, 2021a, 2023a, 2023b). The initial dimensions, water content and sample weight were used to estimate initial v and final measurements and final water content were used for verification by back-calculating the initial v employing the vertical strains determined in the tests. A variety of equations similar to other studies were used (e.g., Okewale and Coop 2020, Okewale 2020, Okewale and Grobler 2021b, Okewale et al. 2023). By comparing different methods to obtain v, it can be estimated that the approximate accuracy of the value is about ± 0.02.

3. Results and discussions

Figure 2 presents the particle size distribution curves of the samples as obtained from the wet sieving and sedimentation techniques. The majority of the grading curves are characterised by long tails in the earlier part followed by nearly vertical sections which form most of the grading thereby giving high coefficients of uniformity. They are therefore not well-graded but poorly graded and this is similar to what was seen and reported by other studies (e.g., Li and Coop 2019). For the samples from area 1, T-1 plots above B-1 showing that the sample is finer and this can be attributed to sedimentation after the discharge from the processing plant. The samples from area 2 do not have a particular pattern and the grading curves are fairly similar.

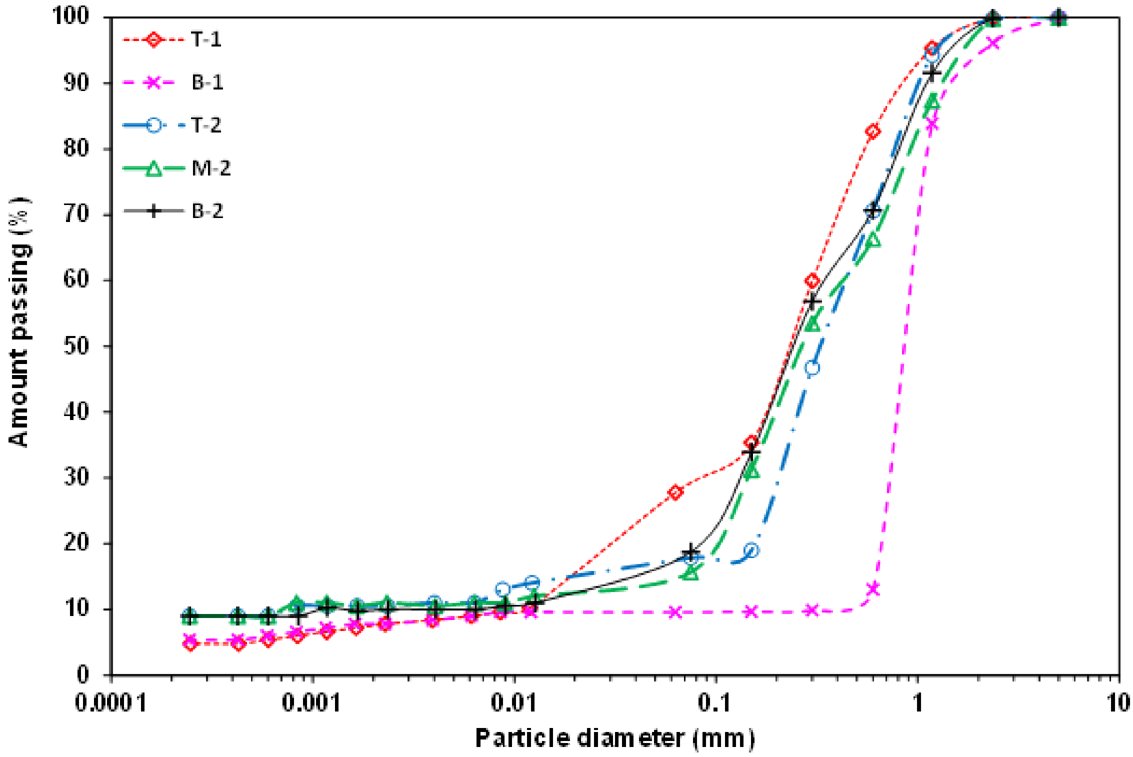
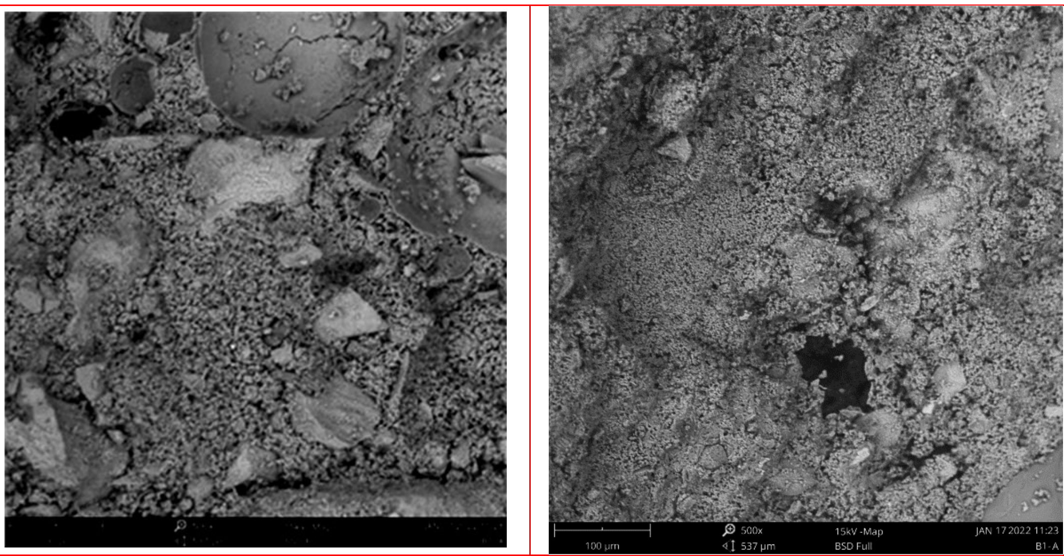


Fig. 2 Grading curves of the samples

The details of engineering grading descriptors (mean particle size D_{50}, coefficients of uniformity and curvature C_u C_c, grain size index I_{GS}, clay fraction CF and fines content Fc) for the samples and other tailings studied are shown in Table 1. It should be noted that the majority of the common descriptors describe the grading curve with only one value and that is the reason the grain size index (I_{GS}) proposed by Cola and Simonini (2002) is included here. The I_{GS} describes the grading curve with two values. The first value defines the shape of the curve (poorly graded or well-graded) and the other describes its location arising from the size of the particles. The I_{GS} is the ratio of normalised D_{50} to C_u ($I_{GS} = (D_{50}/D_0)/C_u$)) where D_0 is taken as 1 mm to make the relationship dimensionless.
The D_{50} ranges between 0.22 and 0.90 and the values are very close in all the samples except one. The D_{50} increases from top to base sample for area 1 and again, this can be attributed to sedimentation of the material during discharge. However, the D_{50} of B-1 is higher than those of other tailings and the iron tailings used here are generally coarser than the other tailings (Table 1). Compared to other iron tailings, the D_{50} is fairly comparable to one of the iron tailings (UB) and higher than the other iron tailings (MB and PO) studied by Li and Coop (2019). Also, the samples are coarser than the gold tailings (Li et al. 2018, Bedin et al. 2012, Chang et al. 2012) and fluorite tailings (Carrera et al. 2011). The C_u and C_c of samples are higher (Table 1) giving the appearance that the samples are well-graded. However, as discussed earlier, this results from the long tails in the earlier part of the grading curves. In comparison, the C_u of theses samples are generally higher

than those of other tailings (Li et al. 2018, Bedin et al. 2012, Chang et al. 2012, Carrera et al. 2011) The CF values of the samples are low and relatively similar and this shows that the tailings are essentially non-clay materials. Their values are comparable to those in some other studies (Table 1). Sample T-1 has the highest Fc value and this can be linked to finer grained nature. The Fc values decrease from the surface sample to the base sample and again this can be linked to the sedimentation of samples after discharge. Compared to other tailings and apart from the UB iron tailings studied by Li et al. (2018) and Li and Coop (2019), the Fc values in this study are generally low. The liquid limits (LL) were obtained for some samples using Atterberg limit tests. The values are relatively similar (Table 1) but the plastic limit test was not feasible and overall the samples are non-plastic.

Figure 3 shows the microstructures of samples in SEM images of horizontal and vertical sections. The fabrics of the tailings are characterised by particle clusters with no obvious particle aggregations or orientations (Figs. 3a and 3b).



(a) Horizontal section | (b) Vertical section

Fig. 3 Typical SEM images of the reconstituted samples

Also the fabrics are heterogeneous and isotropic and have few inter and intra-cluster voids. This is however similar to what has been found by other studies (Li et al. 2018, Chang et al. 2011). Table 2 presents the details of their elemental compositions. They are predominantly silicon (Si), iron (Fe), aluminium (Al) and other elements in lower proportions. The mineralogy of the samples is presented in Table 3 and a typical XRD spectrum showing the mineralogy is given in Figure 4. The mineralogy is dominated by haematite, quartz, plagioclase, chlorite and other minerals like calcite, kaolinite, and hornblende in smaller quantities. Similar minerals have been reported by other studies on iron tailings (Li and Coop 2019) but for other types of tailings, the mineralogies are very different.

Table 2. Details of elemental composition

Element name/symbol	T-1	B-1	T-2	M-2	B-2
	Wt (%)	Wt (%)	Wt (%)	Wt (%)	Wt (%)
Silicon/Si	57.6	34.9	34.9	39.8	53.9
Iron/Fe	31.4	55.3	17.3	26.0	9.2
Aluminium/Al	5.5	4.7	14.4	10.2	9.3
Sodium/Na	1.4	0.9	0.3	0.56	1.0
Magnesium/Mg	1.4	1.2	0.3	0.4	0.6
Sulphur/S	0.9	0.3	4.2	6.2	0.7
Phosphorus/P	0.9	0.9	0.1	-	0.2
Manganese/Mn	0.5	0.3	1.5	-	-
Potassium/K	0.4	1.2	5.0	4.4	0.3

Table 3. Details of mineralogical composition

Mineral (%)	T-1	B-1	T-2	M-2	B-2
Haematite	40.0	40.9	67.3	66.9	49.6
Quartz	8.7	20.8	8.5	7.7	27.5
Kaolinite	4.1	2.2	19.2	3.7	15.5
Plagioclase	15.2	18.0	-	-	-
Chlorite	14.0	10.0	-	-	-
Calcite	-	3.3	5.0	3.8	7.4
Hornblende	1.2	5.0	-	-	-

Figure 5 presents the one-dimensional compression behaviour for T-1 samples prepared using different methods. Similar data were found for the other materials. The results are shown for samples compressed only to lower stresses (2776 kPa) and only a few tests are shown for clarity. About 102 tests were conducted on the five tailing samples. The details of the oedometer test data are given in Table 4. The test descriptions are shown in the table and the letters represent preparation methods followed by test number. Also shown in the table are the initial specific volume, the specific volume at the end of compression and the maximum effective stresses reached in the tests.

Table 4. Details of oedometer tests

Sample	Test	v_i	v_f	$\sigma'_{v,\ max}$
T-1	DC-01	1.500	1.377	2776
	DC-02	1.602	1.447	2776
	DC-03	1.552	1.409	2776
	DC-04	1.486	1.362	2776
	DC-05	1.481	1.347	2776
	DC-06	1.493	1.356	2776
	WC-01	1.477	1.415	2776
	WC-02	1.447	1.373	2776
	WC-03	1.485	1.407	2776
	WC-04	1.535	1.475	2776
	WC-05	1.416	1.348	2776
	WC-06	1.497	1.419	2776
	SL-01	1.558	1.488	2776
	SL-02	1.512	1.415	2776
	SL-03	1.609	1.500	2776
	SL-04	1.559	1.433	2776
	SL-05	1.564	1.461	2776
	SL-06	1.568	1.449	2776
T-1	DC-01	1.743	1.491	8541
	DC-02	1.549	1.412	8541
	DC-03	1.785	1.585	8541
	DC-04	1.621	1.471	8541
	DC-05	1.610	1.480	8541
	DC-06	1.664	1.506	8541
	WC-01	2.009	1.582	8541
	WC-02	1.844	1.537	8541
	WC-03	2.165	1.692	8541
	WC-04	2.064	1.606	8541
	WC-05	1.850	1.589	8541
	SL-01	1.797	1.591	8541

	SL-02	1.733	1.535	8541
	SL-03	1.799	1.611	8541
	SL-04	1.654	1.480	8541
	SL-05	1.754	1.491	8541
	SL-06	1.674	1.470	8541
	SL-07	1.715	1.527	8541
	SL-08	1.764	1.515	8541
	SL-09	1.763	1.471	8541
B-1	DC-01	1.577	1.456	8541
	DC-02	1.540	1.433	8541
	DC-03	1.579	1.460	8541
	DC-04	1.565	1.463	8541
	DC-05	1.593	1.474	8541
	DC-06	1.563	1.454	8541
	WC-01	1.852	1.541	8541
	WC-02	1.806	1.541	8541
	WC-03	1.794	1.529	8541
	WC-04	1.660	1.453	8541
	WC-05	1.734	1.464	8541
	WC-06	1.604	1.371	8541
	SL-01	1.634	1.469	8541
	SL-02	1.393	1.117	8541
	SL-03	1.514	1.357	8541
	SL-04	1.695	1.358	8541
	SL-05	1.318	1.243	8541
	SL-06	1.634	1.514	8541
	DC-01	1.560	1.435	8541
	DC-02	1.572	1.453	8541
	DC-03	1.644	1.488	8541
	DC-04	1.770	1.604	8541
	DC-05	1.595	1.458	8541
	DC-06	1.636	1.490	8541
	WC-01	1.774	1.521	8541

T-2	WC-02	1.676	1.503	8541
	WC-03	1.738	1.457	8541
	WC-04	1.923	1.665	8541
	WC-05	1.670	1.478	8541
	WC-06	1.881	1.589	8541
	SL-01	1.428	1.264	8541
	SL-02	1.481	1.235	8541
	SL-03	1.504	1.417	8541
	SL-04	1.578	1.467	8541
	SL-05	1.659	1.531	8541
M-2	DC-01	1.654	1.520	8541
	DC-02	1.968	1.686	8541
	DC-03	1.640	1.488	8541
	DC-04	1.638	1.469	8541
	WC-01	1.868	1.562	8541
	WC-02	1.812	1.548	8541
	WC-03	1.811	1.519	8541
	SL-01	1.949	1.735	8541
	SL-02	1.801	1.605	8541
	SL-03	1.752	1.475	8541
	SL-04	1.729	1.539	8541
B-2	DC-01	1.521	1.324	8541
	DC-02	1.575	1.368	8541
	DC-03	1.325	1.117	8541
	DC-04	1.622	1.379	8541
	DC-05	1.154	1.002	8541
	DC-06	1.615	1.363	8541
	WC-01	1.547	1.369	8541
	WC-02	1.622	1.467	8541
	WC-03	1.700	1.468	8541
	WC-04	1.690	1.458	8541
	WC-05	1.397	1.226	8541
	WC-06	1.717	1.502	8541

	SL-01	1.821	1.519	8541
	SL-02	1.852	1.562	8541
	SL-03	1.524	1.292	8541
	SL-04	2.039	1.688	8541
	SL-05	1.583	1.250	8541
	SL-06	1.733	1.357	8541

v_i initial specific volume, v_f specific volume at the end of compression, $\sigma'_{v,\ max}$ maximum vertical effective stress

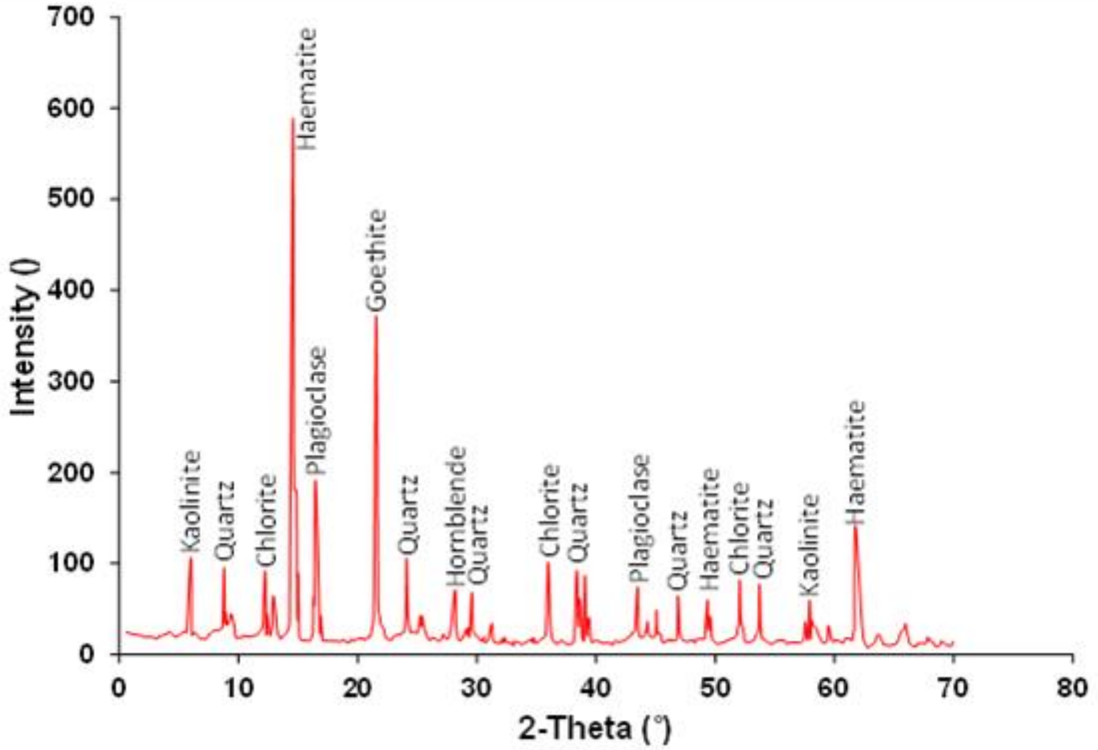


Fig. 4 XRD spectrum showing mineralogy

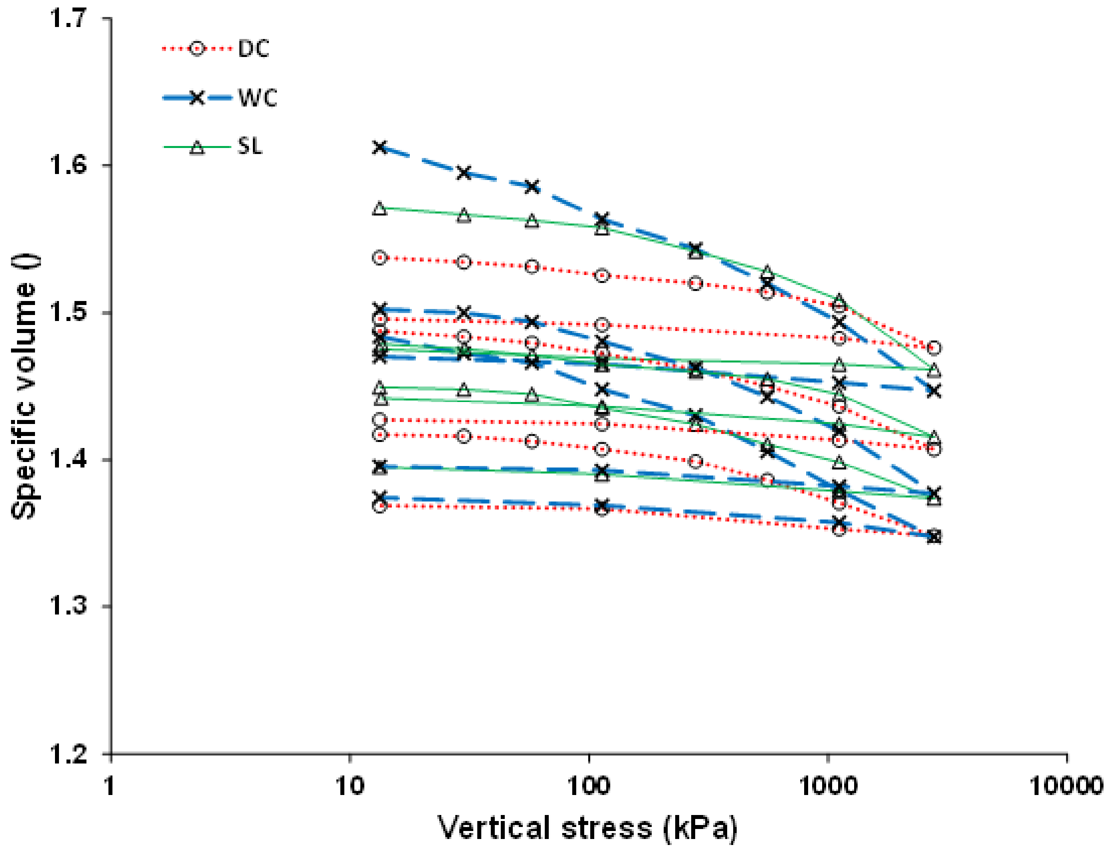


Fig. 5 Compression behaviour at 2776kPa (Dry compaction DC, wet compaction WC, Slurry SL)

Overall, for all the locations, the tests comprise 34 dry compacted (DC), 32 wet compacted (WC) and 36 slurry (SL) samples. The compression curves are variable and for the DC samples, it can be seen that the compression paths are flat and not converging. The compression paths of WC samples are slightly steeper but again they are not converging to a unique normal compression line. The compression curves of SL samples are again less flat but not as steep as the WC samples. This shows that unique normal compression lines cannot be observed because samples with different initial states still have different states at the end of the tests. This indicates that some elements of the initial fabric must still being preserved so that the compression paths are not converging even if the volumetric strains are relatively large. This is a transitional mode of behaviour, similar to some other tailings (e.g., Al-Tarhouni et al. 2011, Li et al. 2018) and various other geomaterials (e.g., Xu and Coop 2016, Okewale and Coop 2020). Generally, the compression behaviour depends on the initial densities of the samples and to a lesser extent on the fabric resulting from sample preparation.

To show that the transitional behaviour is not resulting from inaccuracies in the measurement, the accuracies of initial specific volume were estimated based on methods used by Okewale (2019). The average accuracy is ±0.02 and the offsets between the densest and the loosest samples are 0.13, 0.10 and 0.09 for DC, WC and SL respectively. The offsets are much higher than the accuracy which indicates that the non-convergence is significant. Since non-convergent behaviour was obtained at these lower stress levels, additional tests were conducted for T-1 samples reaching higher stresses. Typical examples of T-1 samples tested at higher stresses and their corresponding estimated normal compression lines are presented in Figure 6. The initial specific volumes are variable for the different samples and the WC samples generally have higher values. For the DC samples, the compression paths are fairly flat before yielding and this similar to what is observed in Fig. 5. At the highest stresses reached in the tests, the paths are still not converging and this confirms the transitional behaviour in the samples. The compression curves of the WC samples are steeper, similar to Fig. 5 and the curves are also not converging. The behaviour of the SL samples is also similar to that observed in Fig. 5 and no unique normal compression line can be seen. An SEM image of a typical sample is presented in Fig.7. Aggregation of particles to form a heterogeneous and isotropic fabric can be observed but the clusters are less continuous and this could be linked to disturbance resulting from extrusion of the samples from the ring after the tests.

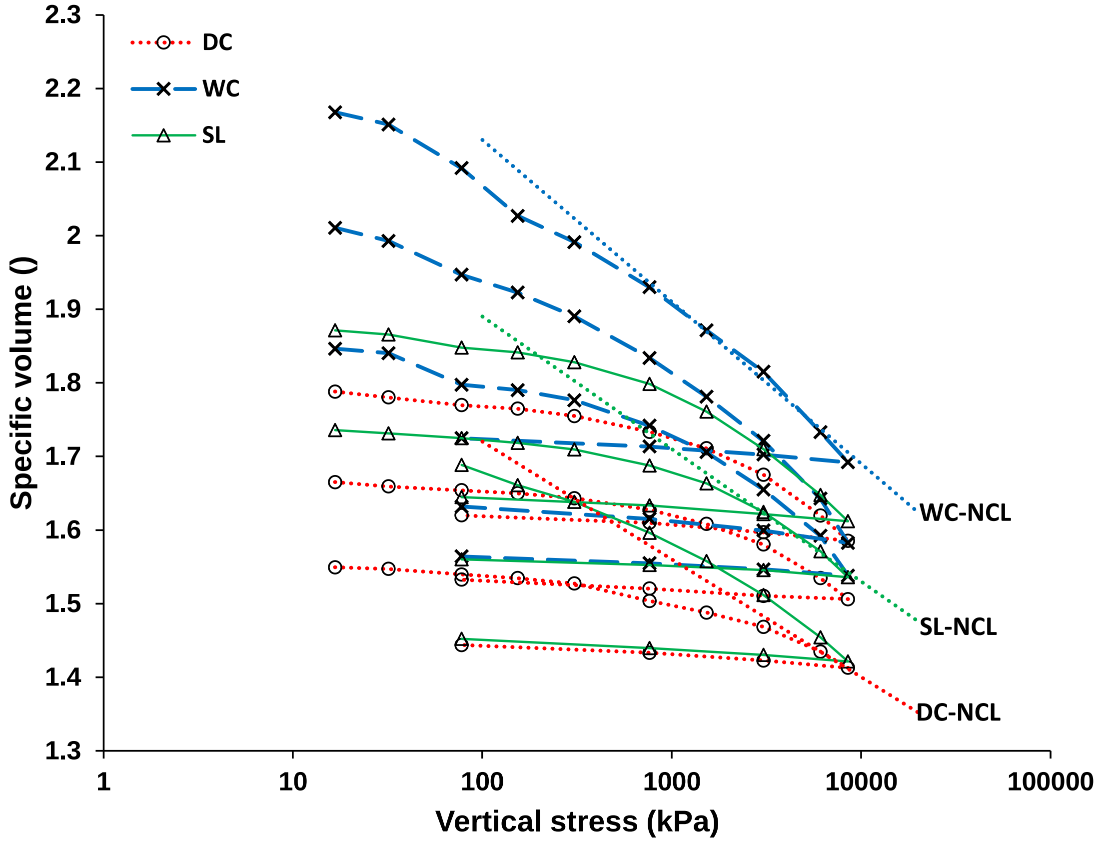


Fig. 6 Typical compression behaviour of samples (T-1) at higher stresses (8541 kPa)

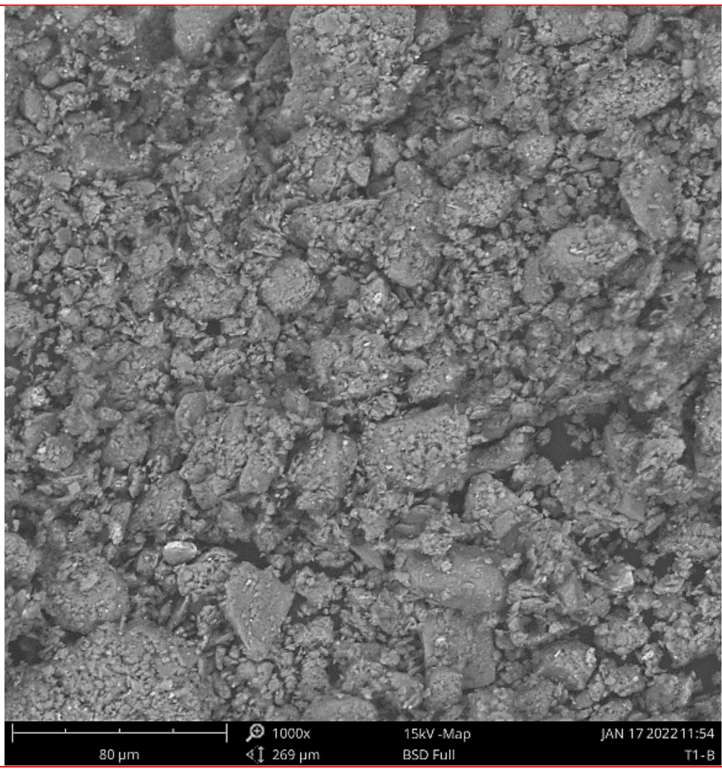


Fig. 7 Typical fabric of a sample after the test

Since the compression curves are non-convergent, different NCLs are used but the gradient is uniform for each sample. In order to evaluate the compression indices of the samples, the NCLs are assumed to be a straight line (Fig. 5) and they are taken at higher stresses where the compression paths appear to be parallel. In this way, compression index (Cc) is the most useful parameter that can be used to describe the compressibility of the samples. The average compression indices for the T-1, B-1, T-2, M-2 and B-2 samples are 0.180, 0.140, 0.153, 0.150 and 0.146 respectively. Apart from T-1 samples, the overall compressibilities of the samples are fairly similar. The compressibility of the samples reduces slightly with depth. Comparing different sample preparations, the average compression indices are 0.12, 0.15 and 0.19 for the DC, SL and WC samples respectively. For all the samples, the values are relatively close for samples prepared in the same way. The DC samples are the least compressible, followed by the SL and the WC is most compressible.

The compressibilities in these samples are lower than those reported for gold tailings by Chang et al. (2011), Li et al. (2018) and the middle beach and pond tailings of Bedin et al. (2012). They are also less than for the upper and middle beach iron tailings of Li and Coop (2019) and the copper tailings of Li (2017). Also, the compressibilities are similar to the values found for 90% sand – 10% silt fluorite tailings tested by Carrera et al. (2011) but higher than those reported for the 70% sand – 30% silt and 50% sand - 50% silt samples. However, the key difference between the tailings tested here and the previous examples is not in the values of the compressibilities, but in the fact that these tailings are transitional, while none of these in the literature were.

Ponzoni et al. (2014) proposed a parameter m to quantify the degree of transitional behaviour based on oedometer test data. The m value is calculated by plotting the initial specific volume taken at 20 kPa (v_{20}) against the specific volume at the highest stress (v_{final}) reached in the test. The m values range from 0 to 1. A fully non-transitional behaviour will have an m value of zero and fully transitional behaviour with no convergence of compression curves will have an m value of one. Figure 8 presents the degree of convergence for samples tested to 2776 kPa. The DC samples plot below the WC and SL samples, indicating also an effect of fabric on the compression behaviour. The steeper compression paths have higher values than the flatter. The m values range between 0.78 and 1.0 but the overall m value for all the samples is 0.76. The non-convergent behaviour in the iron tailing is therefore very strong.

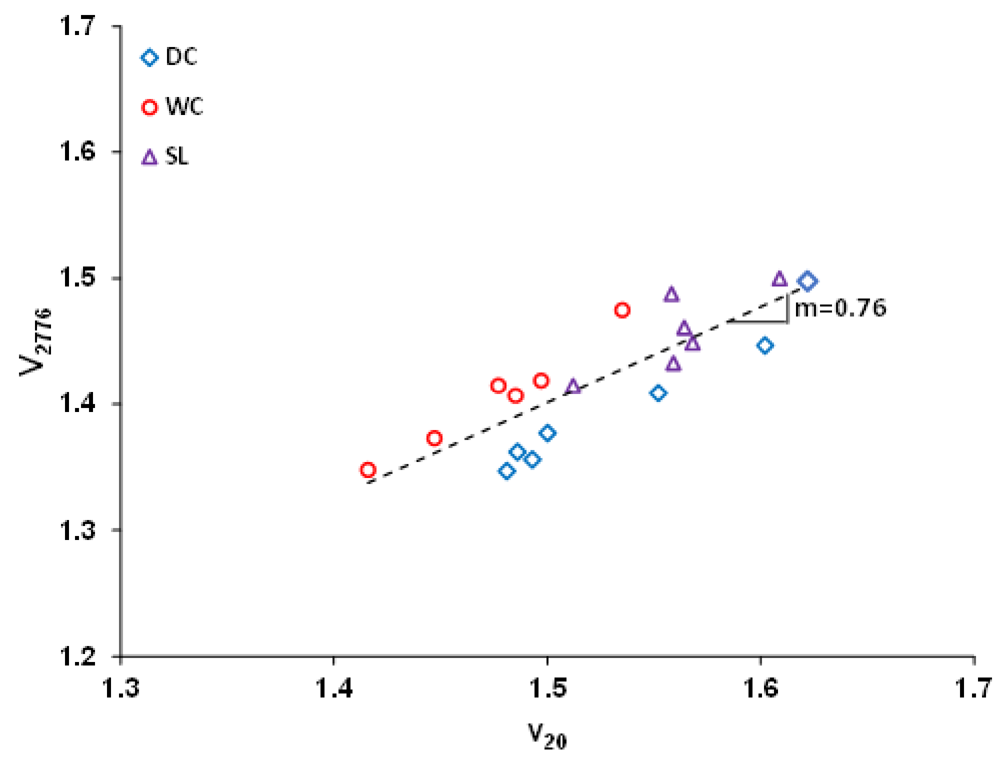
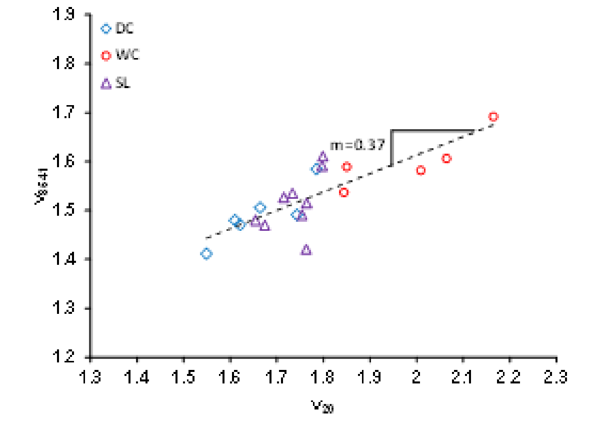
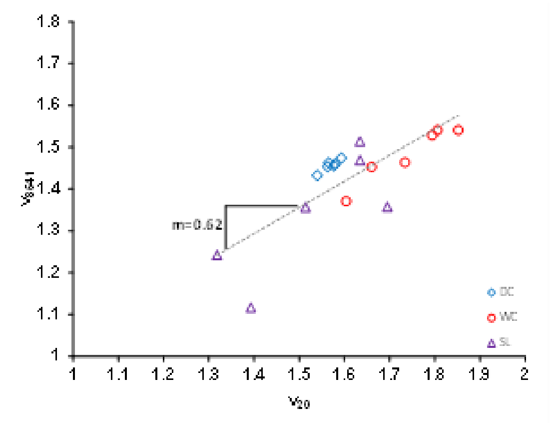


Fig. 8 Degree of convergence for samples (T-1) at 2776 kPa

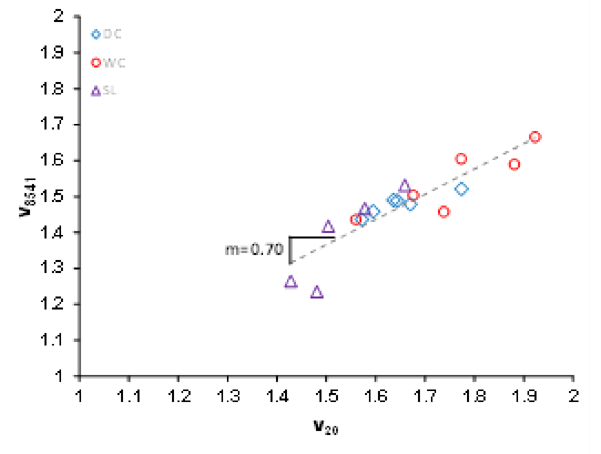
Figure 9 presents the degree of convergence for all the samples at 8541 kPa. The WC samples generally plot with higher v values than the DC and SL in all the samples. But the tendency for the DC samples to plot below the trend line is no longer present at higher pressures. It can be observed that the compression curves of T-1 samples are slowly converging as the m value has reduced to 0.37 (Fig. 9a). However, the m value still indicates the presence of transitional behaviour in the sample. Comparing the samples from the same area, the m value is higher in B-1 than T-1 (Figs. 9a and 9b) and this might probably be as a result of different gradings. Samples T-2, M-2 and B-2 (Figs. 9c to 9e) have relatively similar m values and this can also be attributed to the gradings of the samples. Overall, the degree of transitionality of these iron tailings is high.



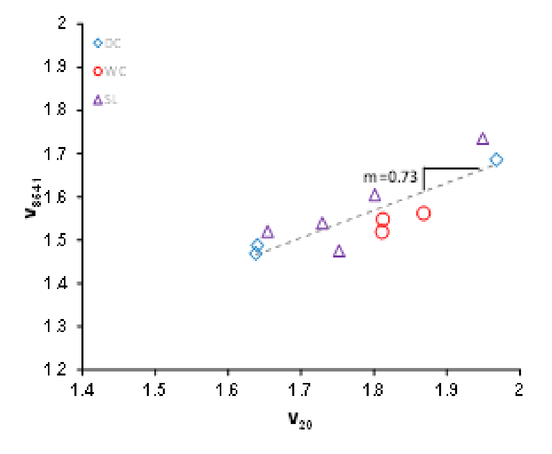
(a) T-1



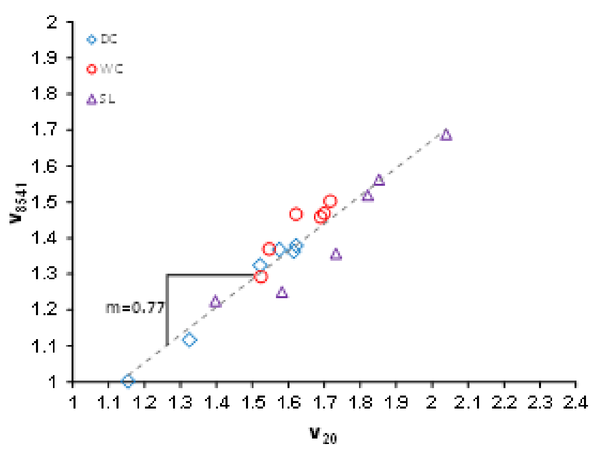
(b) B-1



(c) T-2



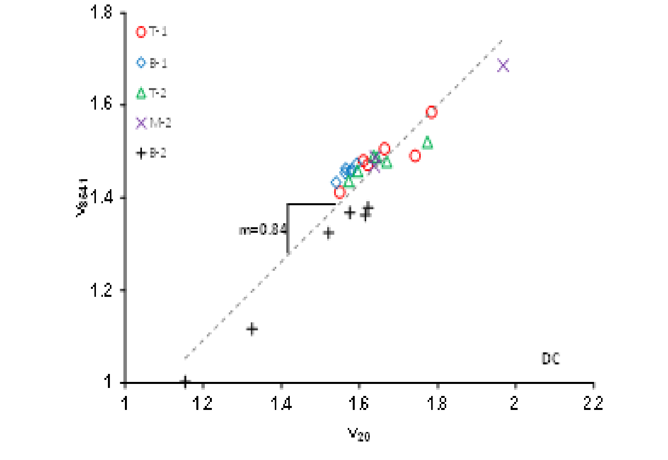
(d) M-2



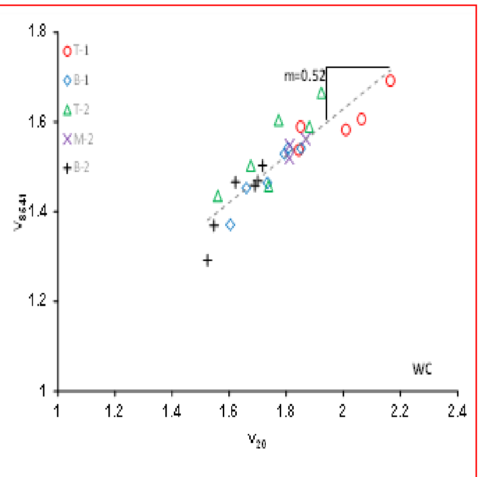
(e) B-2

Fig. 9 Degree of convergence for the samples at 8541 kPa

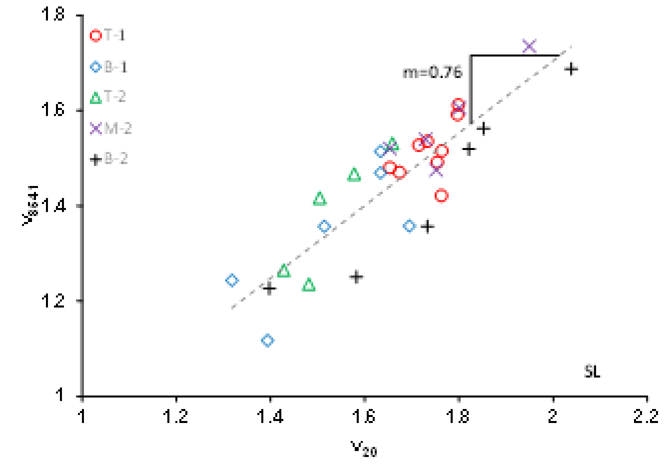
Figure 10 shows the degree of convergence of different samples but considering different sample preparations. Irrespective of sample preparation, sample T-1 plots with higher values than B-1 and this may be linked to gradings of the samples. However, samples T-2, M-2 and B-2 do not show this difference. The m value is highest (0.84) in DC samples, followed by SL samples (m = 0.76) and WC samples is the least (m = 0.52).



(a) DC



(b) WC



(c) SL

Fig. 10 Degree of convergence for different sample preparations

Figure 11 presents a more direct comparison of the influence of sample preparation on the convergence of the samples. The WC samples seem to have a lower m but this occurs largely as a result of three low data points at high v values for the T-1 samples. So within the data scatter the differences are otherwise small. The overall degree of convergence of iron tailings investigated in this work is represented by black regression line in Fig. 11. With an m value of 0.66 at 8541 kPa, the iron tailings studied exhibited a strong transitional mode of behaviour.

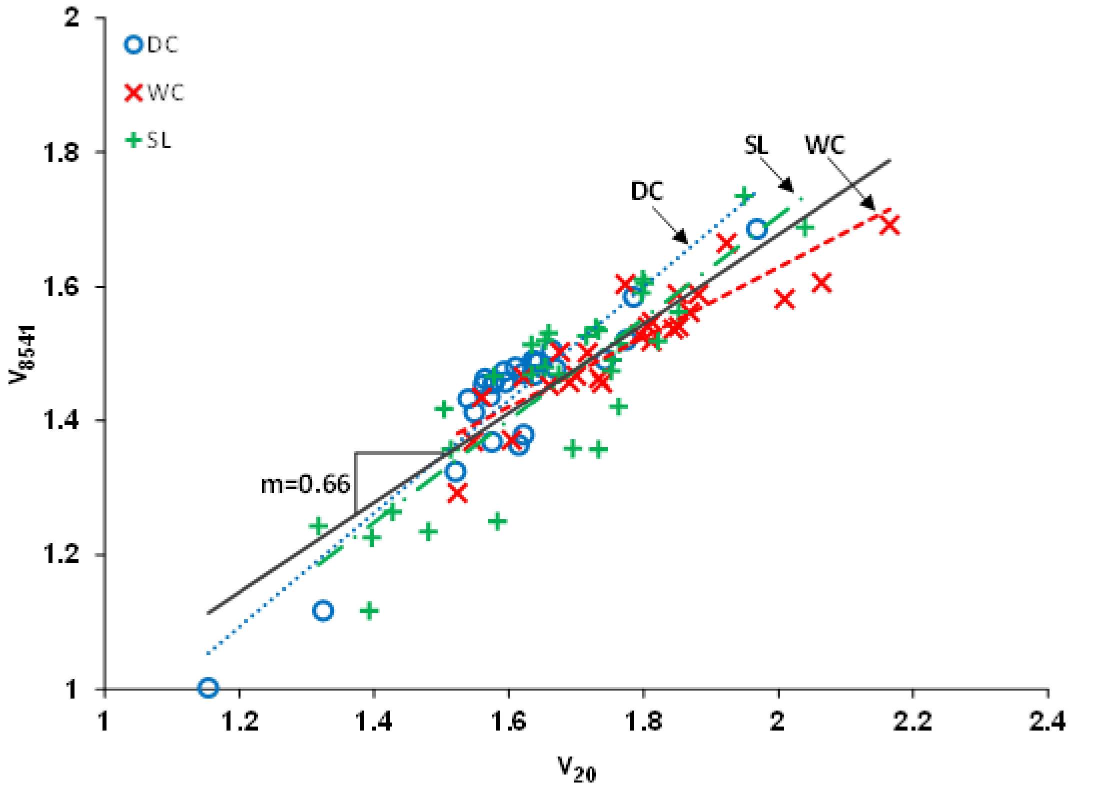


Fig. 11 Effect of sample preparations on the convergence and the overall degree of convergence for the iron tailings

4. Conclusions

A detailed laboratory study of the compression behaviour of iron tailings has been conducted together with index and classification tests, microstructure and chemical analysis as well as mineralogical analysis. Samples were prepared using dry compaction DC, wet compaction WC and slurry SL methods. The samples seem well-graded but they are actually poorly graded with an extended tail on the gradings. The clay fractions and fine contents are low and the materials are generally non-clayey in nature. The fabrics of the tailings are characterised by particle clusters with no obvious particle aggregations or orientations. The compositions are dominated by silicon, iron and aluminium in different percentages. The mineralogy is dominated by haematite, quartz, plagioclase, chlorite and other minerals in smaller quantities like calcite, kaolinite, and hornblende. The compression curves of the samples are variable and the compression paths of DC samples are flat, while those of SL samples are less steep and those of the WC samples are the steepest. The preparation methods have an influence on the compression paths of the samples. The compression paths of all the samples depend on the initial specific volume and do not converge to unique normal compression lines. The initial fabric is still being preserved so that compression paths are not converging and hence, there is a transitional mode of behaviour. Determining the degree of convergence using m values, the values are variable and generally high for these iron tailings. The gradings of the samples have an effect on the degree of convergence. Despite some differences in the shape of the yielding on the compression curves, the preparation methods gave similar trends in terms of m but in some cases the sample preparation method affected the range of initial v values. The iron tailings studied reveal a strong transitional mode of behaviour. The overall implications are that each soil must be considered separately and the complete characterisation would have to account for the non-uniqueness of their normal compression line. While transitional behaviour has been seen for many other soils, there has been no previous experimental investigation that had identified unambiguously transitional behaviour in a tailing nor how the degree of transitional behaviour varied with grading and depth according to the grading and also with sample preparation method.

Acknowledgments

The authors would like to thank National Research Foundation (NRF) of South Africa for the award of fellowship which led to this paper. The authors would like to appreciate Aja yi M., Adeniran V., Olaiya T. D., Obabiyi K. Y., Yusuf A. A.., Saka M. S. and Gbogi A. S. for their assistance in the laboratory in the course of conducting this research.

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