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Compressibility and Creep Behaviour of Hydraulically Placed PFA and Mine Tailings Fills

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ABSTRACT: Many industrial processes result in the production of silt sized waste materials which may be disposed of by being pumped as a slurry to settling lagoons where the solids settle to form fills which often have a high voids ratio. These are described as hydraulic fills. These processes are commonly found in the coal based power generation and mining and mineral processing industries, amongst others. The geotechnical behaviour of such deposits is of interest with respect to the integrity and safety of the impoundment systems and possible future use and redevelopment of the sites. Such deposits are very difficult to sample and in many cases it is almost impossible to obtain notionally undisturbed samples, and so it is necessary to prepare samples in the laboratory using techniques which simulate field conditions. The paper describes the results of a series of one dimensional compression tests, up to very high stress levels, on pulverised fuel ash (PFA) and fluorspar mine tailings. Sample preparation methods attempting to recreate the in-situ structure and density are described. The results presented consider the initial 1-dimensional loading of the initially loose specimens, their unloading response and their creep behaviour. An attempt is made to define the normal consolidation line for these materials and the importance of the initial voids ratio is discussed. A general conceptual model of one dimensional compression behaviour is presented. The secondary compression, or creep, response is discussed, and creep behaviour may be important in considering their behaviour. The creep behaviour displays a linear relation in e-log(t) space. Contours of equal time of creep (isotaches) are suggested which are parallel to the normal consolidation line.

1 Introduction

In industry, particulate waste materials may be disposed of by mixing with water and then pumping to a void where the particles sediment out and the excess water is removed, generally by a simple overflow mechanism. Such waste disposal methods are commonly used in the mining and mineral processing industries and in coal fired power generation, amongst other industries. The void space may be an existing void resulting from open cast mining, for example, or may be specially created for the disposal process by the construction of embankments. These processes can result in very large volumes of material which are described as being 'hydraulically placed fills'. Hydraulically placed fills consist of particles with a wide variety of sizes (varying in general from fine sands to clays). These man-made deposits are usually considered to behave as a normally consolidated. However, compared to natural normally consolidated soils these are generally much younger, with the possible exception of deltaic deposits, for example. These deposits are often very loose due to their method of placement and difficult to sample and test. This makes assessment of the safety of impoundment methods or development of these sites problematical. The hydraulic placed fills treated in this study are from pulverised fuel ash (PFA) and fluorspar tailings deposits and correspond to materials with particle sizes ranging from fine sands to silts.

The study of the normal compression of geomaterials more commonly used in geotechnical engineering is generally divided by their particle size into coarse (sands) and fine grained soils (clays). Coarse grained soils such as sands are known for showing a compressibility which displays an initial compression that is almost flat (in e-log σ'_v) from low to high stresses, followed by a linear portion with a steeper gradient which is considered as the normal compression line (NCL) at very high stresses. In general, it is accepted that the behaviour of coarse granular materials is dominated by particle rearrangement (sliding and rolling) and crushing at high stresses (Marsal, 1967; Vesic and Clough, 1968; Miura and Yamanouchi, 1973; Hardin, 1985; Hagerty et al., 1993; Yamamuro, et al., 1996; Nakata et al., 2001a and Nakata et al. 2001b). Secondary compression (i.e., the deformation of a soil under sustained load) is usually ignored for these types of soils.

On the other hand, the compressibility behaviour of fine grained soils such as clays is divided according to the stress history of the deposit, in either normally consolidated or overconsolidated soils. Normally consolidated clays exhibit a linear compressibility in e-log σ'_v, notionally parallel to the NCL, with a gradient equal to the compressibility index (C_c). Overconsolidated clays show two distinct portions on the compressibility curve, an initial recompression curve followed by a linear compression portion (or virgin compression) at stresses higher than the pre-consolidation stress (σ'_c). This behaviour points towards a similarity between the behaviour on these types of soils and that observed in sands (as pointed out, among others by Atkinson and Bransby (1978)). Compressibility behaviour for the case of soils of intermediate particle sizes (i.e. silts) is still regarded for some researchers as a combination of sand and clay behaviour although recently the hypothesis of the existence of a third type of soils has been proposed by Martins et al. (2001) and Nocilla et al. (2006). This hypothesis is still being investigated.

Novello and Johnston (1989) suggest that the normal compression of granular materials is a general phenomenon, regardless of their particle size and density range. A strong support for this idea can be found in the more recent hypothesis of fractal crushing proposed by McDowell et al. (1996) and McDowell and Bolton (1998). They maintain, based on experimental and numerical modelling (e.g., Cheng et al., 2003), that the linearity of the normal compression curve is related to the fractal crushing of an array of particles regardless of their size.

The study of the consolidation phenomenon in geomaterials, in particular for fine grained soils, is made by using the general theory for one dimensional consolidation proposed by Karl Terzaghi. However, it is also generally accepted that this theory ignores the effect of secondary compression, also labelled as creep (e.g., Taylor, 1948) and that in many cases the effect of creep must be included in settlement calculations, especially for very soft soils. While primary consolidation is due to the dissipation of excess pore water pressure, secondary compression is a plastic time lag phenomenon whose actual mechanism remains undefined (Mitchell, 1992). It is believed, however, that creep in soil is due to a rearrangement of particles from unstable to more stable arrays (or packets). This idea has been verified, for example, by the study of creep and microstructural deformation of dense granular materials by Bowman and Soga (2003). Secondary compression of fine grained soils is deemed to be proportional to C_c (Mesri, 1973) and is regarded to be an important part of the consolidation settlement for soft fine grained soils and organic soils such as peats. Based on Taylor’s notion of secondary compression Bjerrum (1967) depicted the compressibility of Norwegian clays as a family of curves of equal time of secondary compression (labelled as isotaches).

The secondary compression of hydraulically placed fills is usually excluded in design considerations either because the most important feature is primary consolidation (Schiffman et al., 1988) or because creep deformations are considered insignificant from a practical standpoint (Vick, 1990). However, the fact that secondary compression is not regarded as important as primary consolidation does not imply that the effect of creep is always irrelevant (see, for example, Stewart *et al.*, 2006a).

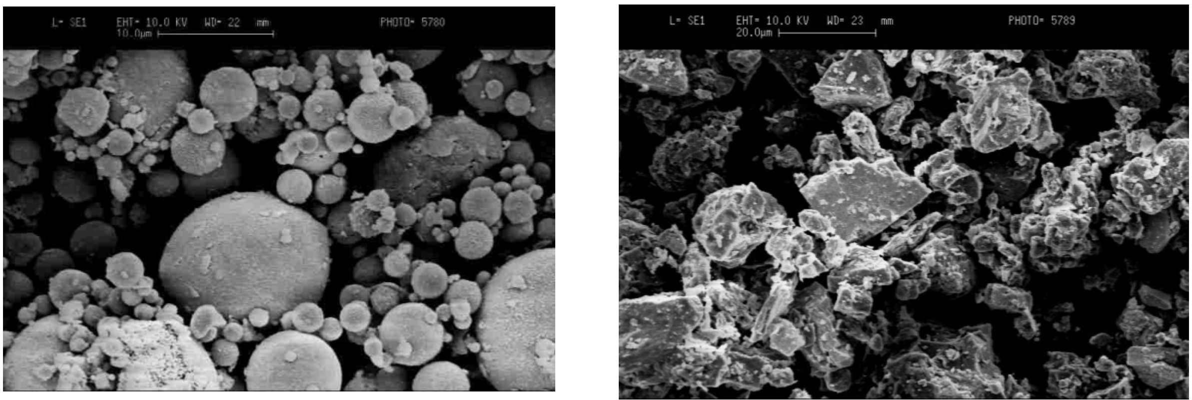
Undisturbed sampling of loose deposits, such as hydraulically placed fills, can be attempted by costly and elaborate techniques such as ground freezing (e.g. Yoshimi and Goto, 1996; Hoffman et al., 2000). This limitation makes more feasible the use of reconstituted specimens in the laboratory for the study of the behaviour of these deposits. This paper describes how water sedimentation techniques were developed in an attempt to model in-situ hydraulic deposition and presents the results of one-dimensional consolidation tests, including creep, over a range of vertical stresses, including high stress levels.

The work described in this paper forms part of a larger study of the behaviour of hydraulically placed fills (Charles-Cruz, 2007). These fills are difficult to sample and test but they are of industrial significance for the potential redevelopment of impoundment sites and the re-use of the fill material.

2 Materials tested

The PFA used in this study was obtained from a site at the disused Skelton Grange Power Station, Leeds, West Yorkshire. The PFA had been hydraulically deposited. A detailed description of this site can be found in Cousens and Stewart (2003). Further descriptions of the Skelton Grange PFA can be found in Stewart *et al.* (2006a) and Stewart *et al.* (2006b). The Skelton Grange PFA used in this study is a low carbonate content type (CaO < 2%) or a bituminous ash. A scanning electron micrograph (SEM) Skelton Grange PFA is included as Figure 1(a). In this picture, the predominantly spherical particles are visible. The diameters range from approximately 1μm to 20μm. The amorphous material is considered to be unburned coal. Properties and characteristics of this PFA are included in Table 1.

Fluorspar tailings were obtained from the active lagoon of the operations of Glebe Mines Ltd., located in Stoney Middleton, Chesterfield, Derbyshire, UK, within the Peak District National Park. Calcium Fluoride (CaF_2) (as the mineral fluorspar) is obtained from mining activities on that site. The parent rock is carboniferous limestone, comprised mainly of fluorspar, barites, limestone, silica and lead (Dunham, 1952; Notholt, 1971). Consequently, the tailings constituents are limestone (predominantly $CaCO_3$), silica and traces of other minerals such as barites. A scanning electron micrograph of Glebe tailings is included as Figure 1(b). In this image angular and sub angular particles are present. Agglomeration of particles and larger particles with small particles adhered to their surface are observed. The smaller individual particles visible are about 1 μm while the largest are 15 to 20 μm. Properties and characteristics of fluorspar tailings are included in Table 1.



(a) (b)

Figure 1. SEM images of: (a) Skelton Grange PFA, and (b) Fluorspar tailings.

Table 1. Characteristics of the materials tested.

	G_s	C_u	d_{50} (mm)	%fines[a]	LL	PL	PI	e_{max}[b]	e_{min}[c]
PFA	2.30	4	0.090	43	41.3	--	--	1.62	0.50
Glebe	2.90	17	0.012	89	26.6	21.8	4.8	1.43	0.53

[a] %fines: Particles passing the 63 μm sieve.
[b] Determined by wet pluviation.
[c] Determined by compaction.

3 Experimental methods

Three conventional fixed ring consolidation apparatuses (ELE Model EL25-0402) were used, with the application of load by dead weight transmitted to the sample through a lever arm (lever arm ratio 10:1 in general, but 11:1 in selected tests). Deformations were recorded manually using a dial gauge with a range of 5 mm and a resolution of 0.001 mm. Two different diameters of sample were used: 38 mm and 70 mm. Testing was performed in a temperature controlled room set at 21°C +/- 1°C.

In an attempt to model the in-situ sedimentation process, and replicate the soil structure and voids ratio, specimen preparation was performed by a wet pluviation technique. The original consolidation cell was provided with extension tubes which fitted inside the sample ring and the cell. The extension tubes were formed from acetate film. Once the tubes were properly sealed, water was poured to reach a height of 15 cm in both tubes. Dry PFA, passing through a 200 μm sieve, was then poured uniformly and at regular intervals over the entire cross-sectional area of the internal ring. Previous trials had shown that 80 grams of dry material was sufficient to produce a specimen with an initial height just below the top of the sample ring. In some tests with PFA the material was mixed with water at a moisture content of 35%, and then poured into the inner tube in an effort to produce a more homogeneous sample, as it was felt that forming the sample in a series of lifts using dry powder might result in vertical layers. For Glebe tailings it was observed that the use of initially dry material caused the formation of large flocs which settled rapidly to the bottom of the cell. For this reason, an alternative procedure of slurry pluviation through water was used. In this method the tailings were thoroughly mixed with water, giving a moisture content of 40%, to ensure complete dispersion. The degree of saturation reached by these samples (>99% for the PFA and >95% for the Glebe tailings) shows that this technique is acceptable.

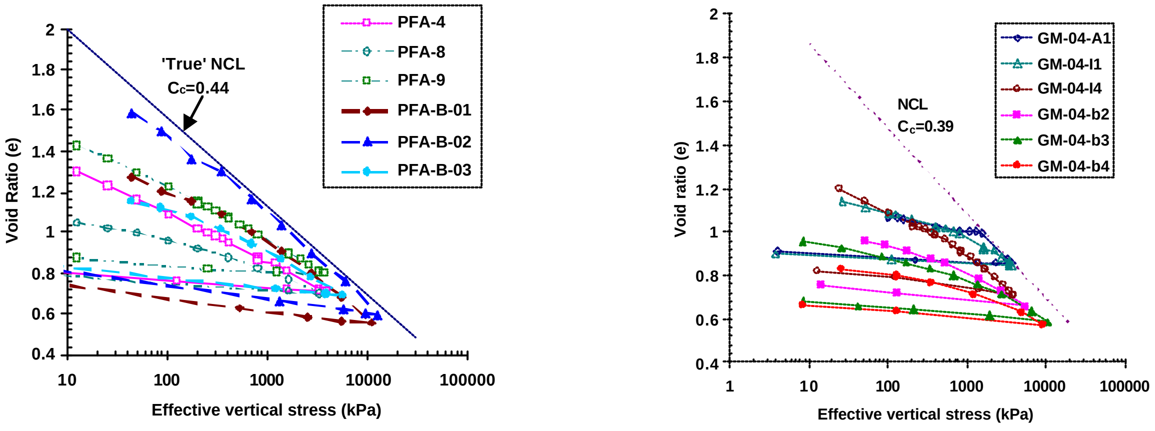
The PFA samples were allowed to sediment for two hours and Glebe tailings for slightly less than one hour. Water was then siphoned from the extension tubes and care was taken to avoid a differential water head between the inner and outer tubes. The samples usually had a surface which was acceptably horizontal. The extension tubes were then removed and the loading cap placed very carefully. The samples were generally very sensitive to disturbance and sudden vibration would cause the sample to collapse.

After sample preparation, loads were applied to the specimens and maintained for a 30 minutes period. This interval was longer than the time required to achieve 100% of primary consolidation for both materials. This time was determined from trial tests as being from 15 to 20 minutes. The load was doubled at each stage, with only slight variations due to the dead weights available. Thus the Load Increment Ratio (LIR) was equal to 2 or slightly higher (a typical loading sequence started at 0.25kg, and reached up to approximately 160kg). Unloading of the specimen consisted of at least three load decrements in order to define the swelling curve properly. Each unloading stage was maintained for 30 minutes, although it was noticed that after approximately 15 minutes the dial gauge readings were essentially constant.

Selected creep tests were performed in selected consolidation tests when the load was maintained for periods of longer than 30 minutes. Creep stages were usually of 24 and 48 hrs, although intervals of up to 24 days for Glebe tailings samples were used. Instead of doubling the load after a creep stage, the loading was continued in smaller increments to allow the shape of the curve to be accurately determined.

4 Results

Typical plots of voids ratio against vertical effective stress for PFA and fluorspar tailings are shown in Figure 2. Figure 2(a) shows for PFA a variation in the voids ratios at the beginning of the tests ranging from 1.6 to 1.04. The lowest e was in test PFA-8 where PFA slurry was used instead of dry material. The test results show an initial section of increasing gradient with increasing stress which tends to a linear response at high stresses (approximately 1 MPa). A C_c of approximately 0.44 can be estimated for the PFA. Unloading gives a linear response.

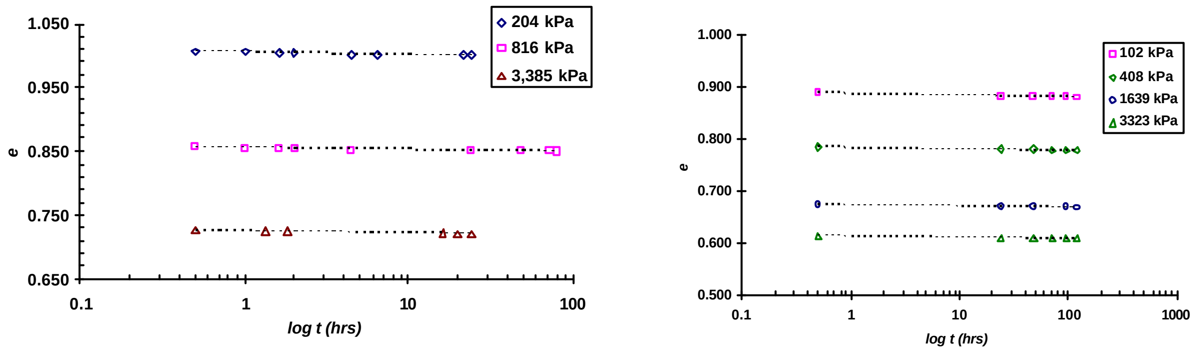


(a) (b)

Figure 2. Compressibility curves: (a) Skelton Grange PFA, and (b) Fluospar tailings.

The fluorspar tailings results shown in Figure 2(b) indicate that initial voids ratios for this material were between 1.2 and 0.9. The response is similar to that of PFA. The first loading stage for the Glebe tailings is curved with a gradient which increases with the stress level. The NCL for fluorspar is reached at a yield stress of approximately 3 MPa. C_c is approximately 0.39. The unloading curve is linear. The swelling curve gradient (C_e) for both PFA and Glebe mine tailings is approximately 0.04.

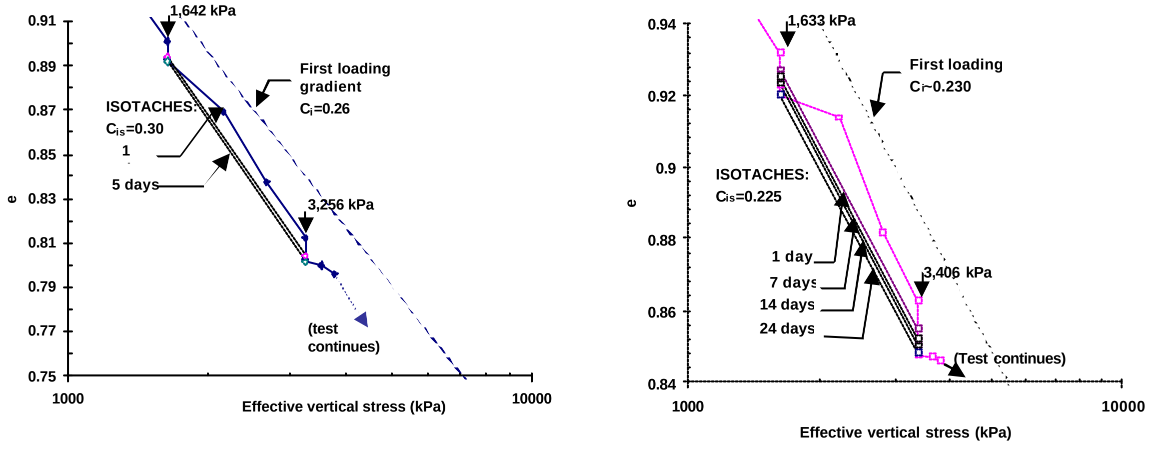
The creep stages indicate a linear relationship between e and the logarithm of time. Plots of typical secondary compression stages for PFA and fluorspar tailings are shown in Figure 3. The creep stages can be seen as vertical downward shifts on the e vs. log σ'_v plots. The coefficient of secondary compression (C_α) for both materials at different stress levels is given in Tables 2 and 3. The ratio C_α/C_c is also included in the tables. Values of C_α/C_c appear to be lower than values found in the literature [e.g., for organic silts C_α/C_c varies between 0.03 - 0.06 (Holtz and Kovacs, 1981)]. Variations of C_α with stress were not observed in the limited dataset obtained.



(a) (b)

Figure 3. Typical creep stages results for: (a) Skelton Grange PFA (Test PFA-04) and (b) Fluorspar tailings (Test GM-04I-5).

The creep test data enabled the definition of isotaches, i.e. lines of e vs. log σ'_v at equal loading time intervals, as shown in Figure 4. The isotaches appear to be parallel with a gradient lower than C_c. The estimated isotache gradients (C_{is}) are 0.30 for PFA and 0.225 for fluorspar tailings.



(a) (b)

Figure 4. Typical isotaches obtained for: (a) PFA Skelton grange, and (b) fluorspar tailings.

Table 2. Summary of creep results for PFA.

Test ID	Stress Level [MPa]	Secondary Compression Ratio (C_α) [x 10^{-3}]	C_α/C_c
PFA-4	0.238	4.140	9.41 x10^{-3}
	3.297	4.600	1.05 x10^{-2}
PFA-6	0.203	4.375	9.94 x10^{-3}
	3.380	3.684	8.37 x10^{-3}
PFA-7	0.204	4.140	9.41 x10^{-3}
	3.380	4.830	1.10 x10^{-2}
PFA-9	0.204	4.835	1.10 x10^{-2}
	0.408	4.145	9.42 x10^{-3}
	1.642	3.684	8.37 x10^{-3}
	3.256	4.374	9.94 x10^{-3}

5 Discussion

The plotting of the test results is affected by the initial value of e. This proved difficult to measure precisely due to difficulties in determining the final height of the specimen after the sample was extruded from the mould. The 1-D behaviour of the pluviated PFA and fluorspar tailings is considered to be very sensitive to the initial e of the specimens. At the same time, there seems to be a 'clastic yield' stress (as defined by McDowell and Bolton, 1998) which is compatible to that observed in sands. Comparison with previous determinations of Cc for PFA, included in Figure 5(a), seem to indicate that in the past, the stress levels used in 1-D consolidation tests were not sufficiently high to determine an accurate Cc, i.e. previous tests may not have reached the NCL. There is no information in the literature for fluorspar tailings. However, the value of Cc obtained is within the ranges observed for gold slimes (Cc=0.35) and bauxite slimes (Cc between 0.26 and 0.38) as reported by Vick (1990).

Table 3. Summary of creep results for fluorspar tailings.

Test ID	***Stress Level [MPa]***	***Secondary Compression Ratio (C_α) [x 10^{-3}]***	***C_α/C_c***
GM-04I-01	1.630	4.140	1.06 x10^{-2}
	3.410	4.600	1.18 x10^{-2}
GM-04I-04	0.206	4.610	1.18 x10^{-2}
	0.410	3.910	1.00 x10^{-2}
	0.851	4.380	1.12 x10^{-2}
	1.690	4.610	1.18 x10^{-2}
	3.840	5.070	1.30 x10^{-2}
GM-04I-05	0.102	2.990	7.67 x10^{-3}
	0.408	2.530	6.49 x10^{-3}
	1.639	2.300	5.90 x10^{-3}
	3.323	2.530	6.49 x10^{-3}

Based on the results obtained, a schematic representation of the compressibility behaviour is suggested in figure 5(b). This figure shows that the initial portion of the curves is a 'first loading stage' as observed for coarse granular materials (e.g., Atkinson and Bransby, 1978; Coop and Lee; 1993). This first loading compressibility is termed 'initial compressibility' (C_i). The materials will eventually reach the NCL at vertical normal stresses in the range of 1 MPa for PFA and of 1 to 3 MPa for Fluorspar tailings. It is believed that this yield stress is related to the crushing strength of the mineral components of the materials.

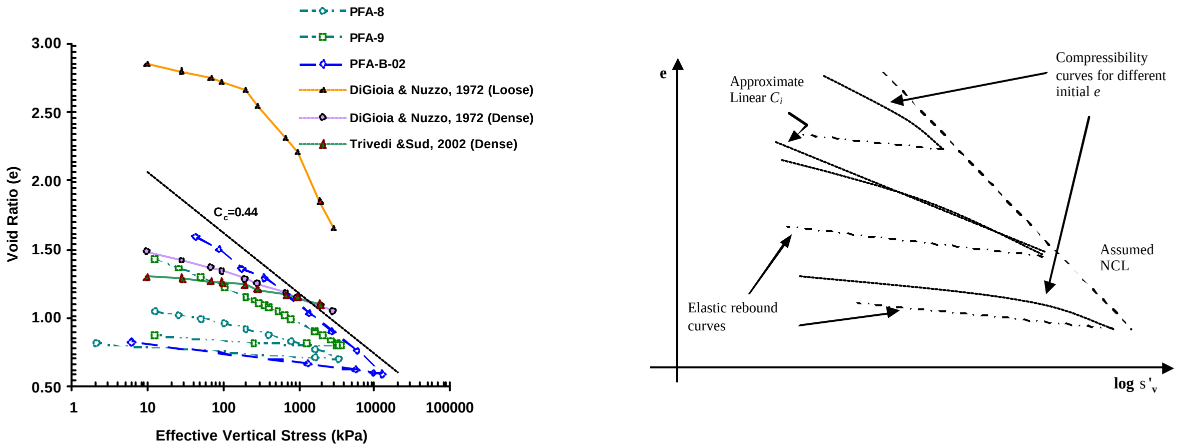


Figure 5. (a) Compressibility of PFA from previous studies, (b) Schematic representation of compressibility for hydraulically placed fills of this kind.

The effect of creep on the calculation of settlements for these types of deposits may be evaluated by using the experimental results of test PFA-04. The consolidation settlement for the stress increment from 102kPa to 206kPa can be calculated for an assumed stratum with a thickness of 15 m and free drainage. The primary consolidation settlement (ΔH_c) can be calculated as:

$$\Delta H_c = \frac{\Delta e}{1+e_0} H_d \qquad (1)$$

Where Δe is the change in voids ratio for the stress increment of interest, e_0 is the initial voids ratio and H_d is the effective drainage path of the stratum. For PFA-04: In Figure 2(a) Δe=(1.089)-(1.019)=0.07, e_0=1.45, H_d=7.5 m, and thus ΔH_c=0.11 m. The secondary compression settlement (ΔH_s) can be calculated by using the equation:

$$\Delta H_s = \frac{C_a}{1+e_p}\log_{10}(t_{creep}/t_{90}) \tag{2}$$

Where C_α=4.14x10^{-3}, e_p is the voids ratio at the start of creep; t_{creep} is the time elapsed since the initiation of the stress increase; and t_{90} is the time for 90% of consolidation of the stratum. e_p is obtained from Figure 2(a) and is 1.019 for this test; t_{90} for the deposit can be estimated by using the relationship $t_{specimen}/H_{specimen}^2=t_{field}/H_{field}^2$, resulting in a t_{90}=5 years for a t_{90} of 4 minutes for test PFA-04 with a specimen with a height of 18mm. The value of t_{creep} can be proposed for several intervals larger than t_{90}. Table 4 shows the results for 5, 10, 20 and 50 years of creep after t_{90}. Table 4 shows that secondary compression becomes significant after a period of 5 years, when it amounts to 1.03% of the estimated primary consolidation.

Due to the limited space available here it is pertinent to mention that a similar approach may be followed for the fluorspar tailings material. Given the fact that the values of t_{90}, C_α and C_c for fluorspar tailings are comparable between both materials, the effect of creep on the settlements would be of a similar order of magnitude than that found for PFA.

These results show that creep may be of significant importance for a young deposit and should be taken into consideration if construction is to be carried out over the consolidated deposits. Although for these materials the experimental results suggest that creep behaviour is linear with the logarithm of time, it is also recognized that the field behaviour of the long term settlement of the fill may present significant variations due to environmental changes.

Table 4. Settlements for various creep times for PFA-04.

Settlement	Creep (years)			
	5	10	20	50
ΔH_s (m)	0.0044	0.0071	0.0105	0.0157
$\Delta H_s/\Delta H_c$ x 100 (%)	4.15	6.62	9.76	14.63

6 Conclusions

The results of the one dimensional compression tests on PFA and Glebe tailings seem to indicate that the compressibility of these materials is compatible to that of sands, with a first compression portion and a normal compression line reached at higher stresses. However, the first compression stage for these materials is not as flat as for sands. It is suggested that for PFA the gradient of this first compression portion has been mistakenly assumed to be C_c in previous investigations. Stresses higher than 1 MPa are recommended to obtain reliable estimates of C_c for PFA. The NCL for fluorspar mine tailings is also reached at high stresses, in the vicinity of 1 to 3 MPa. The unloading curve of these types of materials is commonly neglected, but the elastic rebound appears to be significant and was observed to be approximately linear. Creep results indicate that the behaviour is linear with logarithm of time and that parallel isotaches are depicted. The gradient of the isotaches is comparable to C_c but further testing is required to define it more accurately. The creep results indicate that in hydraulically placed fills the secondary compression component may be significant and should be taken into account in settlement calculations. An important shortcoming of the specimen preparation technique used is the difficulty in obtaining e at the end of testing which may affect the precision of the voids ratios obtained.

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