Effects of particle breakage on the compression behaviour of gap graded carbonate sand–silt mixtures

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Abstract

Isotropic compression tests were conducted on a series of gap graded mixtures of a carbonate sand (CS) from the South China Sea and a fine crushed quartz silt to reveal how particle breakage of the CS can affect the compression behaviour of these soil mixtures. The weaker CS originally exhibited a unique compression line whereas the stronger quartz silt originally had a stable soil fabric leading to non–convergent compression lines. It was found that the threshold fines content (FC) indicating a change from CS to silt dominated soil matrix, together with the suppression of particle breakage, have governed the change from converging to non–converging compression behavior and from non–stable to stable soil fabric for these gap graded soil mixtures. For FC ≤ 30%, the soil mixtures exhibited a unique compression line because of the substantial breakage of the weaker CS particles in the CS dominated soil matrix. However, for FC ≥ 40% (threshold FC), non–convergent compression lines were observed for the soil mixtures. It was suggested that since the weaker CS particles did not actively participate in load bearing of the silt dominated soil matrix, there was insignificant particle breakage of the CS and the initial soil fabric remained stable at high stress level.

Key words: calcareous soils, silts, compressibility, particle crushing

1. Introduction

Understanding the mechanical behaviour of gas hydrate bearing sediments is crucial for modelling the geotechnical related gas exploitation problems in the potential gas hydrate reservoirs. Recent studies on the silt and silty clay sediments taken from the South China sea have shown that gas hydrate was found in the fine–grained sediments containing substantial amount of foraminifera (Wang et al. 2011, Liu et al. 2012). Foraminifera fossils are shells of carbonate, which can be larger than silty particles, containing abundant intra–particle voids. These features of carbonate fossils can enhance the formation of gas hydrate in the fine–grained sediments. Past studies have revealed that some fine–grained soils like clayey silts and silty clays can exhibit non–convergent compression lines where the compression behaviour depends significantly on initial density (Nocilla et al. 2006, Shipton & Coop 2012). This was referred to as transitional soil behaviour. On the other hand, a unique compression line can be identified for coarse–grained soils like carbonate sand (CS) as breakage of sand particles at high stress level can erase the effects of initial soil structures leading to the more stable soil fabric (Coop 1990, Leleu & Valdes 2007, Miao & Airey 2013). This is the typical critical state soil behaviour. However, the compression behaviour of gap graded mixtures of coarse and fine grained soils is more complicated. It is important to understand the behaviour of these gap graded mixtures before further investigating the hydrate-bearing soils in the South China Sea.

Previous studies on sand–fines mixtures mostly focused on quartz sands (Ni et al. 2004, Yang et al. 2006*b*, Chiu & Fu 2008, Rahman et al. 2008). A threshold fines content (FC) can be observed to distinguish a sand or fines dominant soil matrix (Thevanayagam 1998, Thevanayagam et al. 2002). In sand–fines mixtures where the FC is above the threshold value, fines are the major components and play a dominant role in soil skeleton. As a result, sand grains take an insignificant part in the strong force chains of soil mixture (Minh & Cheng 2013, Minh et al. 2014), and vice versa. Grain mineralogy is one of the factors governing the type of compression behaviour of soil mixtures (Ponzoni et al. 2017, Nocilla et al. 2019). Recent studies on binary mixtures of different mineralogies have shown that a unique compression line was identified for the mixtures containing larger grains of a weaker type (e.g. carbonate) regardless of the proportion (Ponzoni et al. 2017). This paper presents how the FC of a fine-grained soil that initially exhibits stable soil fabric affects the compression behaviour of CS–fines mixtures, and the laboratory test results are discussed based on the concepts of particle breakage and threshold FC.

2. Materials and methodology

The tested soils were a CS and a non–plastic fine–grained crushed quartz silt. The two soils were commercial products with different mineralogies. The CS was taken from a shallow water seabed of the South China Sea consisting of angular and shelly carbonate particles of low sphericity. The crushed quartz silt was taken from a quarry. The specific gravity of the CS and silt are 2.77 and 2.63, respectively. Five different CS–silt mixtures were formed by mixing 20, 30, 40, 60 and 80% by dry weight of silt (fines) to the CS. The particle size distribution (psd) of the soil mixtures, shown as the solid lines in Fig. 1, were determined by the sieve and hydrometer analysis. The CS is a uniform sand with average particle size (D_{50}) of 0.75 mm, and the silt size are between 5 and 75 μm and its d_{50} is 43 μm. Thus, the size ratio R (D_{50} / d_{50}) is about 17.4. It is observed that the soil mixtures with FC between 20 and 80% are gap–graded soils. The maximum and minimum void ratios of the soil mixtures are presented in Fig. 2 as the solid lines. They initially decrease with increasing FC until reaching a threshold value at 40% FC, after which the void ratios increase. The trough and this threshold FC denote the transition between coarse and fine grained dominated soils (Lade et al. 1998, Zuo & Baudet 2015). For FC below 40%, CS plays a dominant role in the soil mixture and vice versa. The observed threshold FC of the tested soils is higher than those reported in the literature. Based on the sand–fines mixture with a size ratio R between 10 and 15, several studies (Yang et al. 2006*a*, Papadopoulou & Tika 2008, Dash et al. 2010) have revealed a threshold FC between 20 and 30%.

Isotropic compression tests were conducted on specimens 50 mm in diameter and 100 mm in height using a high pressure triaxial apparatus. A total of 19 isotropic compression tests were conducted. Specimens of each specific mixture ratio were compacted to reach two or three different initial relative densities (between 20 and 90%) using the moist tamping method (MT) with an undercompaction procedure to minimise the amount of segregation as well as to create uniform specimens with a wide range of void ratio (Ladd 1978, Ishihara 1993, Fourie and Papageorgiou 2001, Yang and Liu 2016). Each specimen was compacted inside a split mould in 5 layers at an initial water content of 5% using a special design compaction tool similar to the one presented in Ng and Chiu (2003). For a D_r of 20%, it was found that the bottom layer was undercompacted to a density 10% lower than the target density and the density increases linearly from the bottom to the top layer. However, no specific tests were conducted to examine uniformity and segregation of specimen. Further work, such as epoxy impregnation (Yamamuro et al. 2008) and X-ray tomography (Thomson and Wong 2008) could be carried out to evaluate these two issues for MT specimen.

Saturation of specimen was conducted in two stages. Specimen was first flushed by de-aired water slowly from its bottom under a vacuum of 15 kPa. Thereafter a back pressure of 800 kPa was applied to saturate the specimen. The pore pressure parameter B of all specimens has reached a minimum value of 0.95. The specimens were then isotropically compressed using a multiple-step loading until reaching a maximum effective stress of 30 MPa. It should be noted that the volumes of two solid constitutes (CS and silt) were calculated separately based on the corresponding weight and specific gravity to determine the void ratio of the soil mixtures. The initial void ratio was evaluated from the initial dry weight and average dimensions of specimen. After the compression test, the final void ratio of specimen was determined by the gravimetric method based on its final water content. Freezing of the specimen and its membrane was performed to minimise the loss of water during disassembling (Sladen and Handford 1987). By comparing the initial void ratio, change in void ratio during compression and the final void ratio, it is found that the collapse of specimen during saturation is insignificant.

3. Compressibility

Figs. 3(*a*) to 3(*c*) depict the isotropic compression curves for five different CS–silt mixtures compacted at different initial dry densities. The compression curves for 0% FC (100% CS) and 100% FC are also shown in the figure for comparison. It is apparent that the compression curves can be classified into two different trends. Fig. 3 (*a*) shows the compression curves of CS–silt mixtures with FC $\leq$ 30%. The compression curves of each of these soil mixtures converge to a unique line at a high effective stress of 30 MPa. The estimated normal compression line (NCL) for each soil mixture is shown as a dotted line. The gradient of NCL decreases with increasing FC. The 0% FC exhibits a unique compression line as expected. It is evident that the type of compression behaviour remains identical by adding to as much as 30% FC. This infers that, within this range, CS particles remains the dominant component and silt particles do not significantly participate in the load bearing mechanism. Breakage of the CS particles is significant in these soil mixtures leading to a unique compression line in the high stress regime. Evidence of particle breakage will be discussed in the next section. Figs. 3(*b*) and 3(*c*) show the compression curves of the CS–silt mixtures with FC ≥ 40% (threshold value). For the range of stress tested, the 100% FC (crushed quartz silt) exhibits non–unique compression lines due to an initial stable soil fabric. It is apparent that the same type of compression behaviour is observed for the soil mixtures with FC ≥ 40%. For FC ⩾ threshold value, the fine–grained silt is the dominant component in the soil mixtures such that the CS particles have a reduced role in the load bearing mechanism. Hence, initial soil fabrics are difficult to be altered by the displacement of particles leading to different compression curves.

Figs. 4(*a*) to 4(*c*) show the compression index evaluated at different effective stress. For each stress increment, compression index is defined as the ratio between change in void ratio and change in logarithm of effective stress. Two different trends are observed. For the majority of compression curves (15 out of 19), the compression index increases with increasing stress until reaching a peak or plateau. Thereafter, the compressibility reduces with further loading. Compared to the soil mixtures with FC ≥ 40%, the trend of compression index for soil mixtures with FC ≤ 30% reaches the peak value at a lower stress (between 10 and 20 MPa) and exhibits a higher post-peak reduction in compressibility (between 30 and 65% of the peak value). For the remaining four compression curves (42 and 62% D_r for 60% FC, 40 and 61% D_r for 80% FC), the compressibility increases with increasing stress. It is also apparent that the rate of increase in compression index becomes mild at the stress of 30 MPa, except the specimen 42% D_r for the soil mixture with 60% FC. It is probable the compression curves of 60% FC would converge if a higher stress was applied. Thus, further compression tests beyond 30 MPa should be conducted to verify the hypothesis that the compression curves of 60% FC do not converge to a unique line.

4. Particle Breakage

Past studies have shown that particle breakage is an important mechanism governing the compression behaviour (Leleu & Valdes 2007, Miao & Airey 2013, Guida et al. 2018). Fig. 1 shows the psd curves before and after compression tests. Before compression tests, there is negligible amount of particles smaller than 5 μm for the tested soils. For the psd curves measured after compression test, only specimens compacted to the lowest D_r for each soil mixture are presented in the figure for clarity. It is apparent that negligible particle breakage is found for mixtures with a FC ≥ 60%. On the other hand, there is a significant amount of particle breakage and the particle sizes can reach as small as 2 μm for mixtures with a FC ≤ 30%. A parameter relative breakage, B_r (Hardin 1985) was adopted to quantify the amount of breakage. B_r is defined as the ratio of total breakage to breakage potential. Breakage potential is the area enclosed by particle size d = 75 µm and the initial psd curve. Total breakage is the area enclosed by the initial and final psd curves. For B_r equals to 0, there is no particle breakage. For B_r equals to 1, the particle sizes are smaller than 75 μm after breakage. McDowell & Bolton (1998) revealed that particle breakage can lead to an ultimate psd curve such that B_r cannot reach a value of 1. If the ultimate psd curve is available, a modified breakage parameter proposed by Einav (2007) will be an alternative parameter to quantify particle breakage. As a first approximation B_r was adopted in this study to estimate the extent of particle breakage after compression test.

B_r is plotted against FC and shown in Fig. 2. For each soil mixture, B_r is evaluated for the highest and lowest D_r specimens. It is found that B_r is negligible for FC ≥ 40%, but it increases substantially to above 15% for FC ≤ 30%. For FC smaller than the threshold FC (40%), coarse–grained CS is the dominant component in the soil matrix. Particle breakage is substantial that can erase the effects of initial soil fabric. Thus, the compression curves of different initial densities converge to a unique compression line. However, negligible amount of particle breakage is observed above the threshold FC. Hence, the initial soil fabric still affects the compression behaviour and the compression curves do not converge at high stress. Fig. 2 also indicates that the lowest D_r specimens exhibit more particle breakage than the highest D_r specimens for FC ≤ 30%. The effect of density on particle breakage is similar to the trend reported in Altuhafi and Coop (2011) for carbonate sand mainly composed of broken shell fragments. McDowell and Bolton (1998) suggested that coordination number decreases with decreasing density resulting in a higher probability of particle breakage. It should be noted that particle breakage may also occur during specimen preparation by moist tamping method as weaker CS is more susceptible to crushing, but breakage should be more pronounced for dense specimen due to higher compaction energy. The pre-test particle breakage of a dense specimen affects the pre-yield part and yield stress of the compression curve. However majority of particle breakage occurs after yielding of compression as suggested by Guida et al. (2018). Further work should be conducted to further investigate the evolution of particle breakage due to specimen preparation and at different stress level of compression.

The observed compression behaviour is different from that of the gap graded soil mixtures reported in Ponzoni et al. (2017). Ponzoni et al. tested gap graded mixtures of carbonate (crushed limestone) and quartz sands featuring a low size ratio R of 3 between the coarse carbonate sand and the fine quartz sand. Unique compression lines were also observed from mixtures with 0, 20, 50, 80 and 100% FC content. The size ratio (R = 17.4) of the tested soils in this study is higher. Shire et al. (2016) suggested that for a binary mixture there is a limiting size ratio (R_L), below which a fine particle cannot fit between coarse particles such that the mixture cannot be considered as gap graded. Based on a two-dimensional consideration of inter-void constrictions, Choo and Burns (2015) took R_L as 2.4 for gap graded soils. Using a three-dimensional discrete element analysis, Shire et al. (2016) showed that for $2 < R < 6$, an intermediate type of gap graded behaviour could occur when fines play a reduced but significant role in stress transfer. As R increases further, the fines pack more efficiently between coarse particles resulting in less contribution in stress transfer. Compared to the fine quartz sand used in Ponzoni et al. (2007), the silt tested in this study plays a less active role in the load bearing for FC below the threshold value, leading to a higher particle breakage of CS (see Fig. 2). Furthermore the CS tested in this study contains intra-particle voids (shelly fragments). Guida et al. (2018) studied the breaking mechanism of a highly porous granular material during compression. It is found that the trend observed in the compression curve can be linked to the evolution of number of surviving particles (no breakage) observed from X-ray tomography. And, the particles with higher internal porosity are more likely to break. Thus, distribution of internal porosity of CS particles is also a factor governing the trend of compression.

5. Conclusions

A series of isotropic compression curves for gap graded mixtures of coarse-grained carbonate sand (CS) and fine-grained crushed quartz silt with size ratio of 17.4 are presented. The weaker CS exhibits an originally unique compression line, but the stronger quartz silt has a stable soil fabric leading to originally non−convergent compression lines. Particle breakage correlates well with the change in compression behaviour for this gap graded soil mixtures from the transitional to unique compression behaviour and from a stable to non-stable soil fabric. This is also related to the threshold fines content (FC) at 40% that distinguishes between the coarse−grained sand and the fine−grained silt dominated soil matrix. For mixtures with FC above and equals to 40%, breakage of the CS particles is insignificant during compression (as is reflected in the negligible value of relative breakage B_r) because fine−grained silt is the dominant component in the soil matrix and CS particles does not actively participate in the load bearing. Thus, the initial soil fabrics of different initial densities are not erased completely leading to non−convergent compression lines. However, for FC below and equals to 30%, CS is the dominant component in the soil matrix which actively participates in the loading bearing. Thus, the weaker CS particles break substantially (as reflected in a high B_r) resulting in a considerable erasion of the initial soil fabrics and a unique compression line at high stress.

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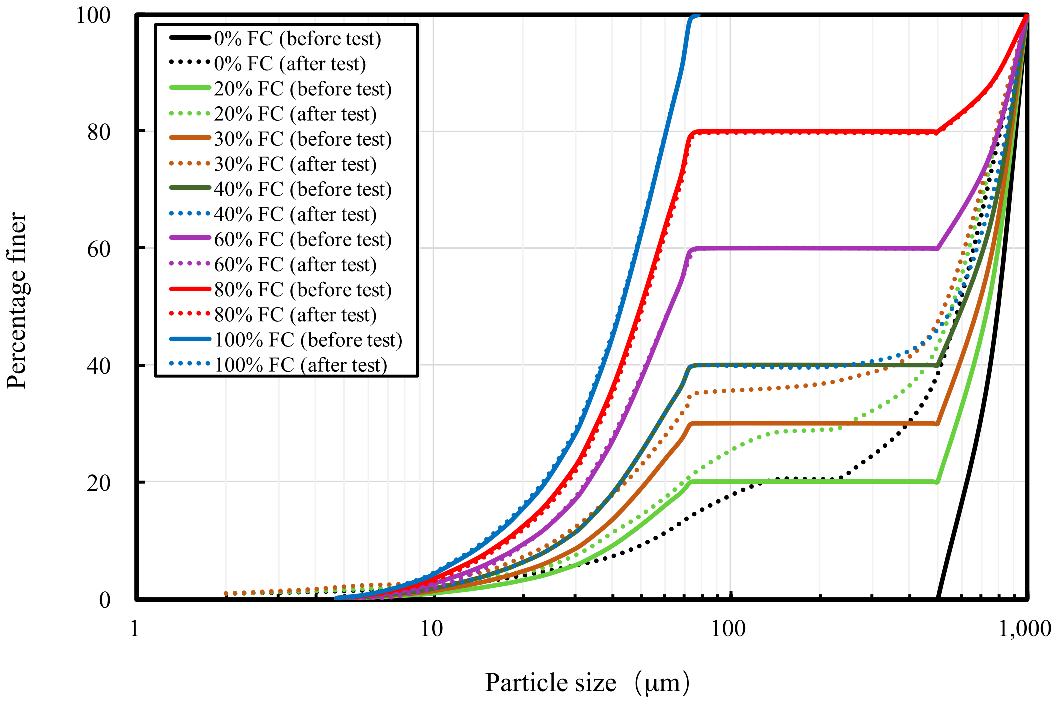


Fig. 1. Particle size distributions of CS–silt mixtures

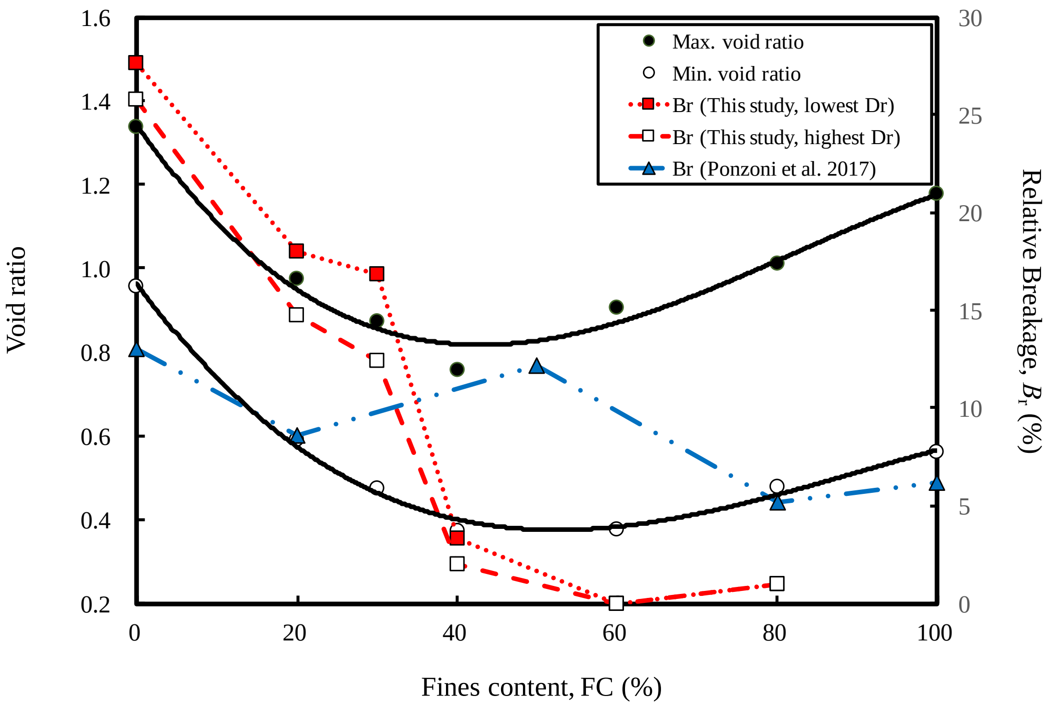
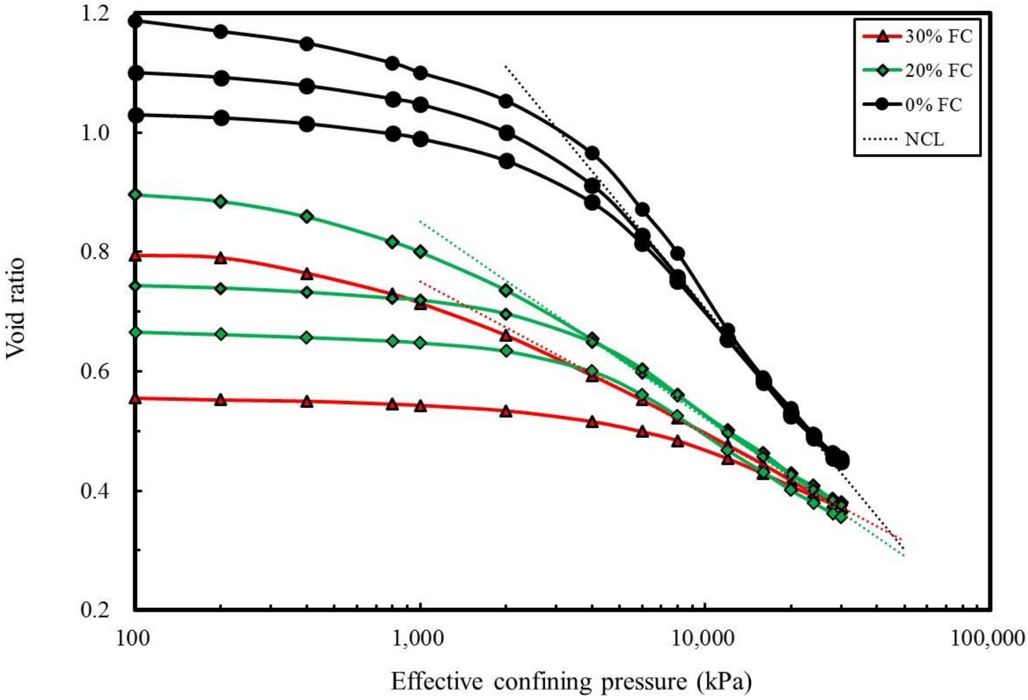
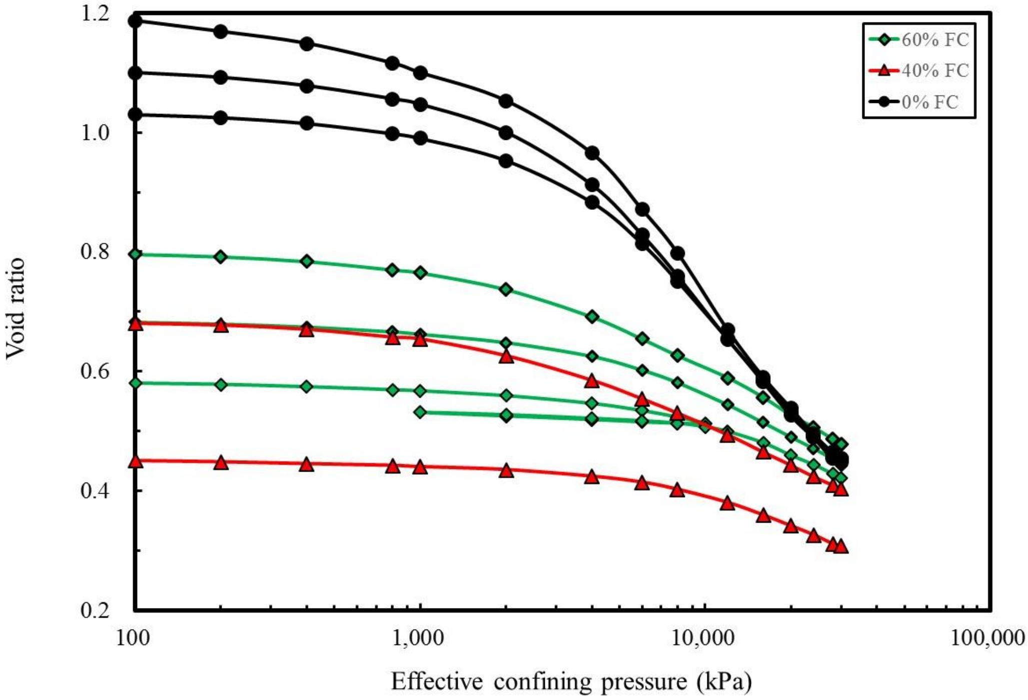


Fig. 2. Effects of fines content (FC) on (i) maximum and minimum void ratios, and (ii) relative breakage (B_r) of CS–silt mixtures

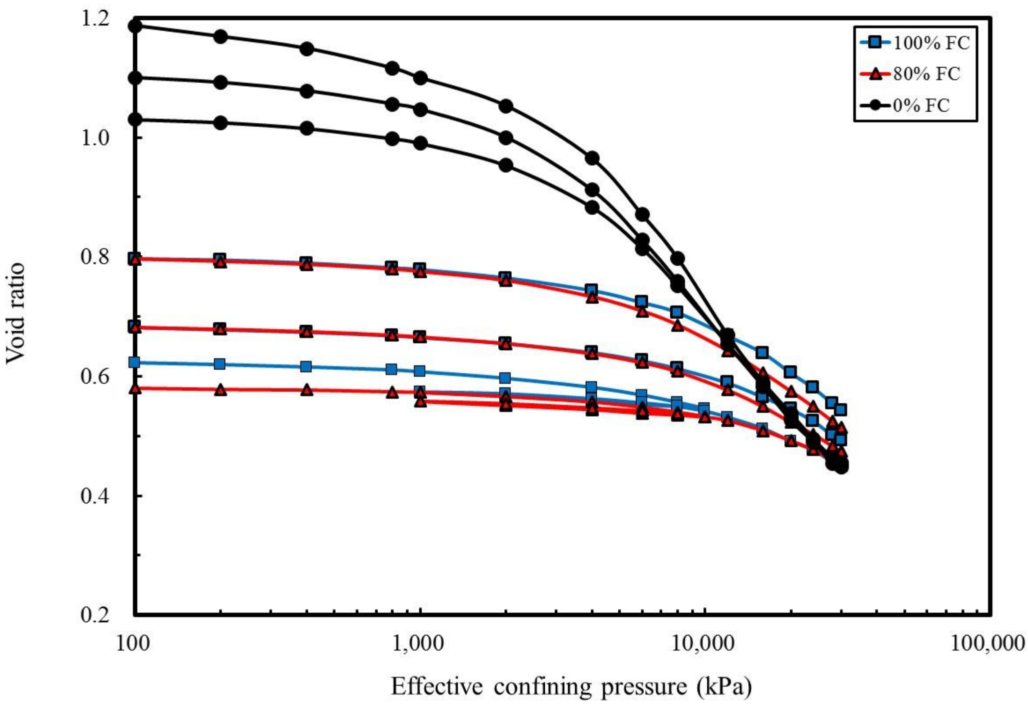


(*a*)



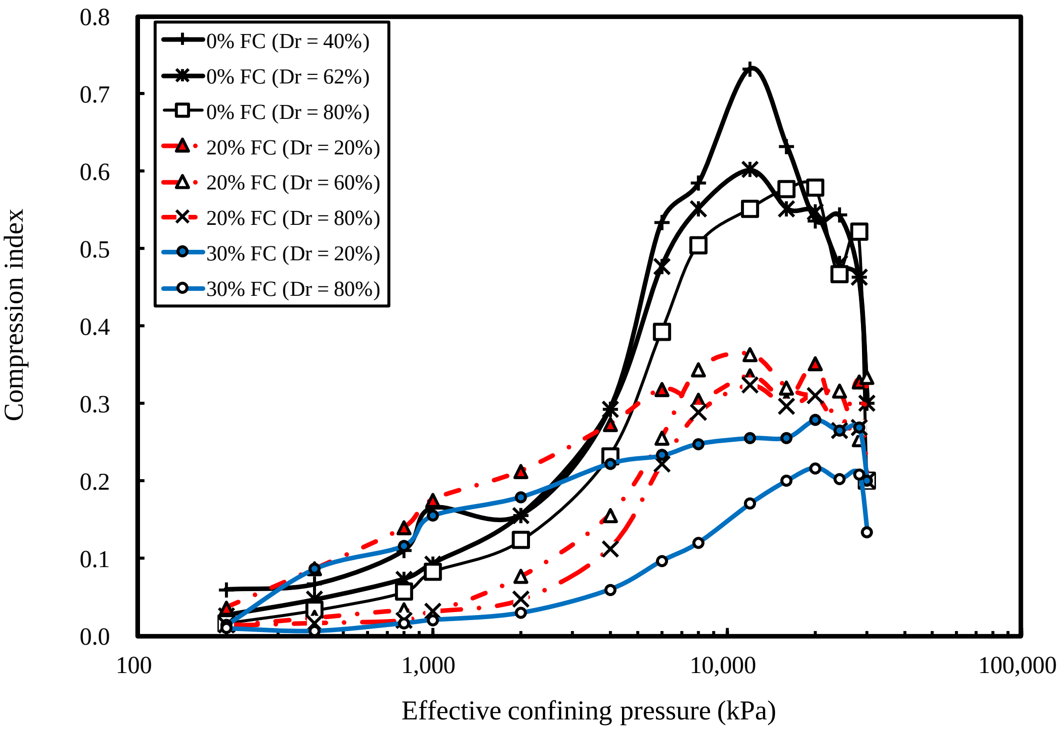
(*b*)

Fig. 3. Comparison of isotropic compression curves between CS–silt mixtures and pure CS (0% FC): (*a*) 20 and 30% FC, (*b*) 40 and 60% FC, and (*c*) 80 and 100% FC

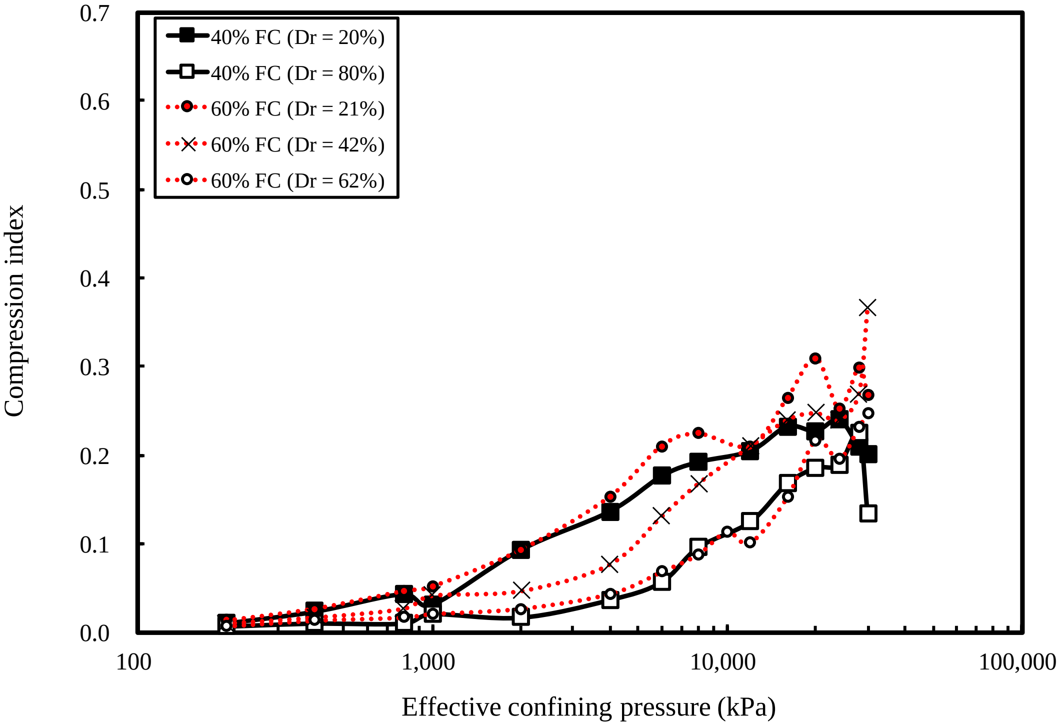


(*c*)

Fig. 3. Comparison of isotropic compression curves between CS–silt mixtures and pure CS (0% FC): (*a*) 20 and 30% FC, (*b*) 40 and 60% FC, and (*c*) 80 and 100% FC

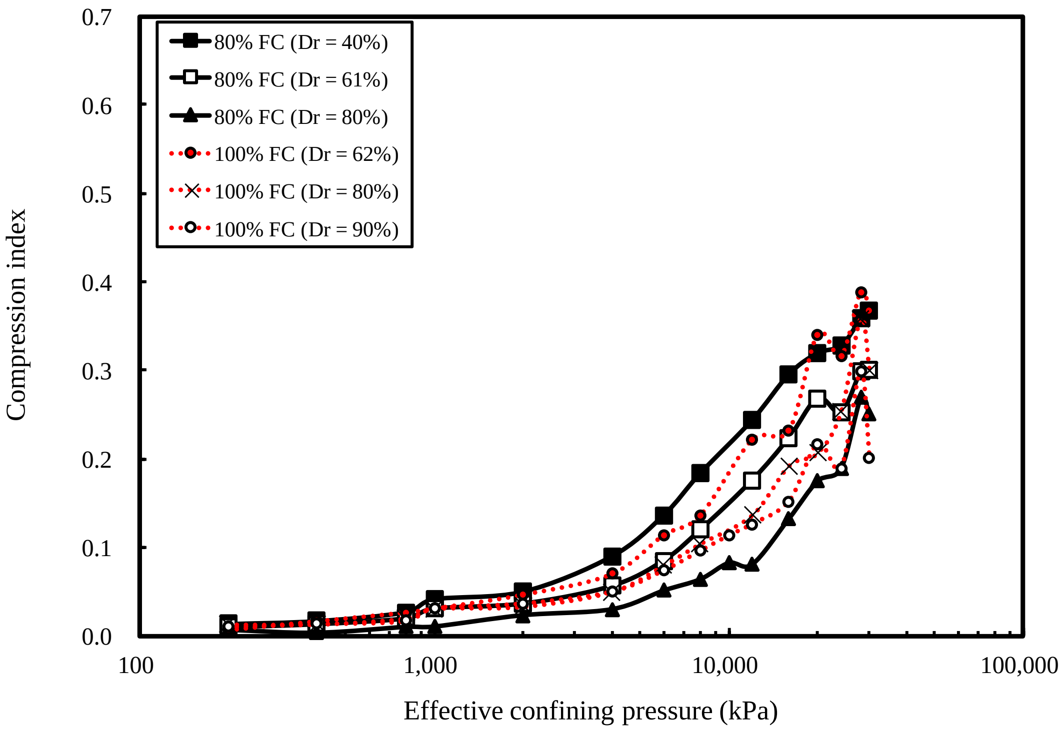


(*a*)



(*b*)

Fig. 4. Variation of compression index with effective confining pressure (*a*) 0–30% FC, (*b*) 40 and 60% FC, and (*c*) 80 and 100% FC



(*c*)

Fig. 4. Variation of compression index with effective confining pressure (*a*) 0–30% FC, (*b*) 40 and 60% FC, and (*c*) 80 and 100% FC