RESPONSE OF MUNICIPAL SOLID WASTE TO MECHANICAL COMPRESSION

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Abstract

The compressibility of municipal solid waste (MSW) is of engineering interest as it affects the short and long-term performance of landfills, as well as their expansion, closure and post-closure development. An assessment of the field settlement behavior of MSW can be reliably executed only when the various mechanisms contributing to the settlement are properly accounted for. A comprehensive large-size experimental testing program that involved a total of 143 one-dimensional compression tests from five landfills, in Arizona, California, Michigan, and Texas of the United States as well as Greece was executed to systematically assess the compressibility characteristics of MSW subjected to a compressive load. Emphasis is given to the influence of waste structure, waste composition, unit weight and confining stress on the compressibility parameters that are used in engineering practice, such as the constrained modulus and compression ratio, as well as long-term compression ratio due to mechanical creep only. The effect of waste composition and unit weight on the compressibility parameters is quantified. It is also found that the type of waste constituent (i.e., paper, plastic or wood), as well as the waste's anisotropic structure can have an effect on the compressibility characteristics of soil-waste

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mixtures. The proposed relationships can be used to estimate compressibility parameters of MSW at any degradation state as long as the waste composition and unit weight are known.

Introduction

The compressibility of municipal solid waste (MSW) has been a topic of significant interest in engineering practice because it affects the short and long-term performance of landfills, and particularly, the performance of gas collection systems and landfill covers, the vertical expansion and closure of landfills, as well as the post-closure development of landfills. Almost all post-closure development projects involve an assessment of the response of the waste mass to a change in stress conditions. In many cases, the uncertainties involved in the estimation of waste compressibility increase the development risk and may adversely affect the decision to develop closed landfills. Increased interest in vertical expansion of landfills also requires an assessment of the compression of the waste in existing landfill cells.

It is not surprising that significant amount of effort has been expended since the early work by Sowers (1973) to characterize the compressibility of MSW. Research has been directed towards the collection of laboratory experimental data (Fei et al. 2014, Fei and Zekkos, 2013; Bareither et al., 2012a; Reddy et al., 2011; Stoltz et al., 2010; Ivanova et al., 2008; Olivier and Gourc, 2007; Hossain et al., 2003; Landva et al., 2000; Kavazanjian et al., 1999; Wall and Zeiss, 1995), field measurement of settlements (Bareither et al., 2012b; Sharma and De, 2007; Yuen and McDougall, 2003; Mehta et al., 2002; Zhao et al., 2001; Spikula, 1997; Stulgis et al., 1995; Bjarngard and Edgers, 1990) and modeling of the settlement behavior (Bareither et al., 2013;

Chen et al., 2010; Gourc et al., 2010; Oweis, 2006; McDougall and Pyrah, 2004; Ling et al., 1998; Edil et al., 1990). An extensive review of the compressibility of MSW has been made by McDougall (2011).

One of the complicating factors associated with assessing the compressibility of MSW in the field, is that there are numerous mechanisms contributing nearly simultaneously to the observed settlement of MSW. These include physical and biochemical processes. Biodegradation of the organic constituents is one of the most critical contributors and often masks immediate and long-term compression of the waste due to load application. However, as demonstrated by field and laboratory evidence, MSW is a soft material that deforms significantly when subjected to a load, and the settlement associated with mechanical compression of MSW may even reach half its original height.

Understanding the various compression mechanisms of MSW and the ability to separate their contribution to the observed total settlement are key to reliably predict settlement behavior during waste filling, post-closure development, or even vertical expansion of a landfill. A fundamental understanding of the factors that affect the mechanical compression of MSW will allow its separation from other mechanisms associated with the biodegradation process of MSW. The mechanisms causing mechanical compression of MSW are physical, whereas in the case of biodegradation, are primarily biochemical.

The objective of this study is to systematically assess the compressibility characteristics of MSW subjected to a compressive load. Emphasis is given to the influence of waste structure, waste composition, unit weight and confining stress on the compressibility parameters that are used in engineering practice, such as the constrained modulus and compression ratio, as well as long-term compression ratio due to mechanical creep only. Settlement associated with biodegradation is beyond the scope of this paper.

Literature Review

Similar to soils, when a vertical load is applied on MSW, either due to overburden layers of waste or another external load (e.g., a structure), there will be deformation of the waste mass. This deformation is associated with a reduction of pore volume between particles, particle slippage, particle movement and re-orientation, and especially for MSW, particle bending, folding and compression or extension of waste constituents that can be soft and thin, as well as raveling of finer particles into large voids within the waste structure (Bjarngard and Edgers, 1990, among others). Thus, it is not surprising that waste commonly compresses more than inorganic soils. A portion of that deformation is recoverable upon unloading (i.e., elastic), and the remaining portion is irrecoverable (i.e., plastic). Depending on the amount of

that is present within the voids, and as voids reduce in size upon load application, excess moisture will squeeze out typically at high rates due to the relatively high hydraulic conductivity of MSW, while some moisture will be retained within the waste matrix.

In one dimensional (1D) compression, in response to an increment of vertical stress, $\Delta\sigma_v$, there is an immediate vertical strain increment $\Delta\varepsilon_{vi}$ that is given by:

$$\Delta\varepsilon_{vi} = \frac{\Delta\sigma_v}{D} \quad [1]$$

In Eq. 1, D is the constrained modulus and has units of stress. Since MSW behavior is confining stress dependent, and the stress-strain response of MSW to a compression load is never linear, D is also not a constant during a compression sequence, but is dependent on the level of stress and the stress or strain increment. In one dimensional compression, vertical stress is commonly used to express the at-rest (K_o) anisotropic confining stress state of the specimen.

A common alternative to the use of the constrained modulus D that is also customarily used in consolidation analysis is to use Eq. 2 when calculating the immediate vertical strain in response to a new stress increment:

$$\Delta\varepsilon_{vi} = C_{c\varepsilon} \times log\left(\frac{\sigma_{v0}+\Delta\sigma_v}{\sigma_{v0}}\right) \qquad [2]$$

where σ_{v0} is the initial vertical stress and $C_{c\varepsilon}$ is the compression ratio assuming that the material has never experienced that stress level before. If the material has previously experienced that stress level, $C_{c\varepsilon}$ can be replaced by the recompression ratio $C_{r\varepsilon}$. It is commonly considered that $C_{c\varepsilon}$ and $C_{r\varepsilon}$ are confining stress independent and constant for a specific ground material. Note also, that the compression index C_c is also used in the literature. However, use of the compression index C_c for calculations of settlement requires also an estimate of the void ratio of the MSW, which is practically impossible to obtain in MSW not only in the field but also in the laboratory. Thus, C_c is not estimated in this study.

From Eq. 1 and Eq.2, it can be deduced that:

$$D = \frac{\Delta\sigma_v}{C_{c\varepsilon}\times\log\left(1+\frac{\Delta\sigma_v}{\sigma_{v0}}\right)} \qquad [3]$$

When subjected to sustained compression loading, waste will continue to deform due to the physical mechanisms described earlier. These mechanisms result in stress redistribution and changes in particle-to-particle stress contacts. Presence of moisture and liquid flow may also cause particle lubrication and particle slippage or raveling. Occasionally, this progressive stress readjustment, and the material loss due to biodegradation, may lead to “unexpected” waste structure collapse that may be reflected at the landfill surface as localized, and highly irregular, differential settlements. Long-term deformation, commonly referred to as secondary compression, can be calculated as follows:

$$\Delta\varepsilon_{v,LT} = C_{\alpha\varepsilon} \times log\left(\frac{t}{t_0}\right) \quad [4]$$

where $C_{\alpha\varepsilon}$ is the modified secondary compression ratio, and t_0 is commonly assumed to be the time until the material first experiences the sustained constant loading (for clays this is considered the near-completion of consolidation, i.e, when excess pore fluid pressures are nearly dissipated). Typical ratios of $C_{\alpha\varepsilon}/C_{c\varepsilon}$ for natural soils are between 0.03-0.06 with ratios for amorphous and fibrous peats being around 0.035-0.085, and for organic silts 0.035-0.06 (Holtz and Kovacs, 1981).

Since MSW is a geo-material, these fundamental principles are also applicable. A large number of studies have used Eq. 1, 2 and 4 to estimate the compression characteristics of MSW. Eq. 4, which was originally developed to capture only mechanical compression (or creep) has also been used to empirically describe long-term settlement due to biodegradation. A synthesis of available 1D mechanical compression laboratory experiments (e.g., Sowers 1973, Landva and Clark 1990, Chen et al. 2009) has been made by Bareither et al. (2012a) and McDougall (2011) and is beyond the scope of this paper. Important recent lessons associated with the compressibility of MSW in response to 1D compression loading include:

- Case histories-based back-calculated values of $C_{\alpha\varepsilon}$ are consistent with results from laboratory studies. Sharma and De (2007) presented a comprehensive review of $C_{\alpha\varepsilon}$ values from a large number of case histories and concluded that the overall range of $C_{\alpha\varepsilon}$ for MSW subjected to an external load generally varies between 0.01 and 0.07. A slightly narrower range (0.014-0.06) was reported for $C_{a\varepsilon}$ of MSW subjected to the waste's self-weight. From a fundamental, as well as a practical perspective, the $C_{a\varepsilon}$ values are the same for self-weight vs. external loading.

- Accommodating the larger particles of MSW in laboratory testing is important to capture the waste's field settlement behavior. Performing tests on the finer fraction (<25 mm or <20 mm) only is not representative of field behavior (Bareither et al., 2012a). Thus, conventional-size devices are not appropriate for waste testing. Experience from compressibility testing (Bareither et al., 2012a), shear strength testing (Bray et al. 2009) and degradation testing (Fei and Zekkos, 2013) shows that a specimen size of 300-mm is probably adequate. Milling of the coarser fraction to accommodate the larger size particles in smaller devices also affects the characteristics of the MSW and its mechanical properties (Zekkos et al. 2008).
- The effect of degradation on the immediate response of MSW to a compression loading remains unknown. Hossain et al. (2003) performed small-scale testing (d=63.5 mm cells) and found that the coefficient of primary compression generally increased as the cellulose and hemicellulose to lignin ratios (C+H/L) decreased, i.e., more degraded waste was more compressible. Reddy et al. (2011) found that for small-size, synthetic solid waste the compression ratio decreased as the waste degradation increased. Bareither et al. (2012a) found a negligible effect of waste decomposition on $C_{c\varepsilon}$ of reconstituted degraded specimens. However, the authors also pointed out that the specimen undergoing degradation experienced a decrease in C_{ce} due to removal of organic content and stiffening of the waste matrix.

Approach - Methodology

A total of 143 large-size (300 mm diameter or 300 mm square) one dimensional compression tests were conducted on MSW from landfills in California, Texas, Arizona and Michigan of the United States and Greece. Specifically, the following tests were conducted: 23 tests on reconstituted MSW from Tri-Cities landfill in north California, 40 on soil-waste mixtures from Xerolakka landfill in Greece, 31 from Sauk Trail Hills landfill in Michigan, 17 from the Austin Community landfill in Texas, 8 from Los Reales landfill in Arizona and 24 from Lamb Canyon landfill in south California.

The Tri-Cities landfill tests were conducted first to evaluate the effect of field waste composition on the mechanical characteristics of MSW. Subsequent tests on reconstituted soil-waste mixtures from Xerolakka landfill were performed to assess the impact of waste structure anisotropy and waste constituent type on the compressibility of the soil-waste mixtures.

A large number of tests were also conducted on fresh reconstituted specimens from Texas, Arizona, and California to assess whether the trends observed in these earlier test programs were generally applicable. All 1D compression tests were conducted prior to shearing and had a duration of approximately 24 hrs (1440 min). Shearing results have been reported elsewhere for Tri-Cities and Xerolakka landfill waste (Zekkos et al., 2010a; Zekkos et al., 2013), and Michigan waste (Fei and Zekkos, 2015) and are not the focus of this paper.

MSW from the Michigan and Texas landfills was not only tested at its fresh state, but also at a fully biodegraded state, using large-size (d=300 mm; h=600 mm) sealed landfill simulators. Detailed description of the experimental setup is provided in Fei et al. (2014), and experimental results are presented in Fei and Zekkos (2015) and Fei et al. (2015). Briefly, fresh, well characterized, waste was placed in these simulators and leachate was recirculated three times per week for a period of three to four years. Biogas was generated and chemically analyzed regularly, and the evolving biochemical characteristics of leachate were also monitored. Volume and mass change was also measured. The waste was considered fully biodegraded when the biochemical characteristics in the leachate indicated no additional activity, biogas generation was completed and settlement of the waste was slowed down. The degraded specimen was removed from the simulator in an undisturbed manner and was loaded to the target vertical stress to assess the compressibility of the waste in response to load application. Upon completion of the test, the material was again fully characterized to record changes in waste composition due to biodegradation, had a visual appearance of degraded material (i.e., appeared to be mostly soil-like) and had no smell.

An example of data collected during 1D compression of a specimen from Tri-Cities landfill is shown in Fig. 1, along with the procedures used to calculate the relevant compressibility parameters. For each test, the strain of immediate compression ($\Delta\varepsilon_{vi}$) due to a vertical stress increment of $\Delta\sigma_v$, $C_{c\varepsilon}$, D, and $C_{\alpha\varepsilon}$ are derived. Note that in the subsequent analyses, the influence of suction stresses is ignored, and the total stresses are assumed to be equal to the effective stresses.

Specimen preparation

Waste composition was well defined for each prepared specimen. The characterization procedures proposed by Zekkos et al. (2010b) were used for all specimens and included an assessment of the amount and type of waste constituents, and a detailed characterization (grain size distribution, Atterberg limits, moisture and organic content) of the <20 mm fraction.

Specimens were compacted through a variety of techniques: (a) Repeated drops of a 4.5 kgr, 100 mm in diameter drop mass on subsequent layers of waste to achieve a high compaction energy level. In this case, specimens of a height of 13 cm were prepared in 4-5 layers of 2.5-3 cm in thickness, and for each layer 2-3 rounds of 9 drops of the drop mass were performed to prepare a dense specimen; (b) moist-compaction in layers using a tamper; and (c) placement of the material without any compaction effort. It was generally found that for specimens with the same waste composition and as-prepared unit weight, the method of specimen compaction was not critical.

An important differentiation among specimens relates to the manner by which waste was placed in the specimen preparation mold. With the exception of the Xerolakka landfill waste, all other specimens were prepared in layers of mixed waste material, i.e., all constituents were mixed together at the target waste composition and placed in layers in the specimen mold and compacted. Observations during compaction showed that, similarly to field conditions, the fibrous waste constituents (majority of >20 mm fraction) tend to become aligned in the horizontal direction, resulting in an anisotropic waste structure (Zekkos, 2013). To investigate this issue further, specimens from Xerolakka landfill were prepared and included only the <20 mm material and one specific waste constituent type only (i.e., plastic, paper or wood). The material was placed in successive layers of <20 mm material and waste constituent separately. This specimen preparation technique resulted in a well-defined waste structure that permitted a more careful assessment of the impact of waste structure and waste type on the compressibility of soil-waste mixtures. A detailed description of this specimen preparation technique is included in Zekkos et al. (2013). Although the soil-waste specimens from Xerolakka landfill are not representative of field conditions because they included only soil and one more waste constituent, their layer-cake structure may not be entirely unrealistic, especially in landfills where soil cover is placed on top of thick layers of waste, as well as at high overburden, where the layering of the waste becomes more pronounced.

Note that all Xerolakka landfill and Tri-Cities landfill specimens were tested at their field moisture content, which was 10% and 12% respectively (for the smaller than 20 mm material, as defined by Zekkos et al. 2010b) and was below field capacity, i.e., the level of moisture retained by the waste mass after gravity drainage. These conditions are typical of MSW landfills that are regulated by Title 40 of the Code of Federal Regulations (CFR) of the Resource Conservation and Recovery Act (RCRA) also known as Subtitle D, i.e., dry tomb landfills. Specimens from Sauk Trail Hills landfill and Austin Community landfill were tested at their field moisture contents (which was 35% and 30-32% respectively), as well as nearly saturated levels of moisture (which was 64-65% and 66-73% respectively). MSW from Lamb Canyon landfill in south California and Los Reales landfill in Arizona were tested at their field moisture content, which was 24% and 32% respectively.

Results

Impact of waste composition and unit weight on compressibility of MSW

As mentioned earlier, the impact of waste composition and unit weight on the compressibility of MSW was systematically assessed using waste from Tri-Cities landfill. As shown in Fig. 2a, $C_{c\varepsilon}$ is affected by the amount of <20 mm material. As the percentage by weight of <20 mm material increases, $C_{c\varepsilon}$ reduces, i.e., MSW becomes stiffer. Waste-rich MSW has $C_{c\varepsilon}$ values that may vary by a factor of two, or more, compared to specimens with 100%<20 mm.

$C_{\alpha\varepsilon}$ is also affected by the amount of <20 mm material, as shown in Fig. 2b. As the <20 mm material increases, $C_{\alpha\varepsilon}$ reduces, i.e., the long-term settlement is lower. Waste-rich MSW has $C_{\alpha\varepsilon}$ that may also vary by a factor of two, or more, compared to 100%<20 mm material.

The observed scatter in the data is largely attributed to the variable compaction efforts involved in preparing the specimens. Highly compacted, denser specimens plot below the regressed line shown in Fig. 2 and looser specimens plot above. Vertical stress does not appear to play a role on the $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$ values. However, as discussed subsequently, an observed small effect of vertical stress on $C_{c\varepsilon}$ is actually an artifact of the effect of compaction on the specimen's compression characteristics, with specimens at low stress levels behaving as "overconsolidated" due to compaction.

Similarly, as shown in Fig. 3, unit weight affects both $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$. In Fig. 3, total unit weight prior to immediate compression (γ_{t0}) is shown. All Tri-Cities landfill specimens have moisture contents of 12% that are lower than field capacity. The observed impact of unit weight on compressibility can be attributed to two main factors: (a) for the same waste composition, specimens that are compacted with more energy input are denser and tend to have lower $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$; and (b) unit weight and composition are strongly correlated. Waste-rich MSW has lower unit weight (3-8 kN/m^3) and soil-rich MSW has higher unit weight (12-17 kN/m^3) for the same vertical (or confining) stress and the same compaction effort (Zekkos et al. 2006). Thus, the range of total unit weight (from 5 to 15 kN/m^3) is also indicative of waste composition.

Note that in Fig. 3b the total unit weight upon compaction γ_{to} is shown. A similar relationship was also observed when the data were plotted against the total unit weight upon completion of the immediate compression, i.e., the density state of the MSW during long-term compression. However, the regression results were similar and so that relationship is not shown. Regression of the data indicates the following approximate relationship for Tri-Cities specimens at moisture contents below field capacity:

$$C_{c\varepsilon} = 0.18 - 0.0098 \times \gamma_{t0} \qquad (R^2=0.41) \qquad [5a]$$

$$C_{\alpha\varepsilon} = 0.016 - 0.00078 \times \gamma_{t0} \qquad (R^2=0.61) \qquad [5b]$$

Impact of waste structure & waste constituent type on compressibility of MSW

A series of tests was also conducted on soil-waste mixtures from Xerolakka landfill. As mentioned earlier, these specimens were prepared in carefully placed successive layers of soil and waste with the intent to assess the impact of waste structure, as well as the impact of specific common waste constituents on compressibility of a soil-waste mixture.

The type of waste constituent (i.e., paper, plastic or wood) is found to affect the stiffness of the soil-waste mixture. Soil-waste mixtures that are compacted with the same compaction effort, and consist of soil-paper only, soil-plastic only, or soil-wood only, have different $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$. Fig. 4 shows test results on specimens that include variable amounts of <20 mm material subjected to compression from 1.8 kPa to 50 kPa. Specimens with soft plastic or paper have significantly higher $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$ than specimens with wood, or specimens that consisted entirely of <20 mm material. The change in $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$ due to inclusion of wood constituents compared to specimens with 100%<20 mm is not comparatively significant.

The amount of waste constituent is also found to affect the stiffness of the mixture, but its influence on $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$ is also dependent on the type of fibrous waste constituent. As shown in Fig. 4, for specimens compressed in the direction parallel to the waste constituent orientation

($i=90^{o}$), as the amount of paper and plastic increases, $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$ increases significantly. $C_{c\varepsilon}$ is highest for plastic fibers, followed by paper fibers, and practically unaffected by the amount of wood fibers. $C_{\alpha\varepsilon}$ is highest for paper, followed by plastic, and then wood.

Previous studies have highlighted the pronounced effect of waste anisotropy on hydraulic conductivity (Landva et al. 1998; Hudson et al. 2009), shear strength of MSW (Bray et al., 2009; Zekkos et al., 2010a), and seismic wave propagation (Sahadewa et al., 2014a; Sahadewa et al., 2014b; Zekkos, 2013). The influence of structure of the soil-waste specimens on the stiffness was also assessed by preparing specimens of soil and waste in layers at different angles compared to the horizontal, with emphasis on having a well-defined orientation of fibrous constituents. As shown in Fig. 5, the stiffness of the specimens is dependent on the relative orientation of the waste fibrous constituent's long axis and the direction of compression loading. Overall, as shown in Fig. 5b, $C_{c\varepsilon}$ varies as much as 2.4 times for specimens of soil-plastic mixtures as a function of the orientation of the waste constituent, but less for soil-paper (factor of 1.7 difference for different waste constituent orientations) and soil-wood mixtures (factor of 1.25 difference). Soil-paper and soil-wood mixtures are found to be the softest (have the highest $C_{c\varepsilon}$) when the fibrous constituents are oriented perpendicular to the load ($i=0^{o}$), but the opposite trend is observed for specimens that include soil-plastic only. These specimens appear to be stiffer when plastic fibers are oriented perpendicular to the compression load ($i=0^{o}$). The results shown point to the significant anisotropy of soil-waste mixtures. This finding is also supported by limited testing on specimens from Tri-Cities landfill, as shown in Fig. 6 that had intermediate waste composition (Zekkos 2013). Tri-Cities fibrous waste constituents were found to become horizontally oriented during compaction, although that was not intentional. Thus, of two identical specimens, one specimen was loaded vertically as is, while the second one was prepared in a custom-made split-mold and was rotated by 90^o prior to being placed in the compression device. When subjected to 1D compression, it was found that the specimen with particle orientation parallel to the vertical compression loading (i=90^o) was stiffer (not more than 20%) than the specimen with particle orientation perpendicular to the compression loading (i=0^o). The results of this study point to the importance of the direction of loading compared to the waste structure in assessing the compressibility of MSW.

Synthesis & recommendations for compressibility of MSW

Tests were also executed on specimens from four additional landfills in the United States and specifically, in Arizona, south California, Michigan, and Texas. A summary figure of the 143 test data is shown in Fig. 7. In this figure, hollow symbols are used for specimens that are nearly uncompacted, whereas full symbols are used for specimens that have intermediate to high compaction efforts. As shown in Fig. 7a, immediate strain ($\Delta\varepsilon_{vi}$) can reach 60% of the specimen initial height, $C_{c\varepsilon}$ ranges from 0.01 to 0.26 and $C_{\alpha\varepsilon}$ ranges from less than 0.001 to 0.014. Specimens that are soil-rich (100%<20 mm) and/or compacted, tend to have lower immediate strains (up to approximately 30%), and lower $C_{c\varepsilon}$ values (up to 0.15), but generally similar $C_{\alpha\varepsilon}$ values. As discussed earlier, no effect of vertical stress on $C_{c\varepsilon}$ (Fig. 7b) and $C_{\alpha\varepsilon}$ (Fig. 7c) is observed.

Figure 8 shows the relationship of $C_{c\varepsilon}$ with waste composition and dry unit weight prior to compression (γ_{d0}). Note that the dry unit weight is used instead of total unit weight, because some of the specimens in the entire dataset are in nearly saturated conditions. $C_{c\varepsilon}$ is better correlated with γ_{d0} (Fig. 8b) instead of the percentage of <20 mm material (Fig. 8a) because compaction effort plays an important role on the achieved specimen unit weight. There is scatter in the data, which is not surprising given the variable waste sources, compositions and testing conditions. Looser and waste-rich specimens have distinctly higher $C_{c\varepsilon}$ values than denser and soil-rich specimens. A relationship between $C_{c\varepsilon}$ and γ_{d0} was derived with an R^2=0.67:

$$C_{c\varepsilon} = 0.39 \times e^{-0.15*\gamma_{d0}} \quad [6]$$

Eq. 6 and the data from this study that it is based on, is also reproduced in Fig. 9 along with data on MSW compressibility from the literature. Specifically, all the test data on specimens that are at least 270 mm in diameter compiled by Bareither et al. (2012a) were included. This dataset includes a total of 39 additional tests generated by Rao et al. (1977), Beaven and Powrie (1995), Chen and Lee (1995), Landva et al. (2000), Olivier et al. (2003), Vilar and Carvalho (2004), Stoltz and Gourc (2007), Olivier and Gourc (2007), and Stoltz et al. (2010). In addition, the $C_{c\varepsilon}$ reported by Bareither et al. (2012a) is used. The relationship from this study seems to also provide a reasonable estimate of $C_{c\varepsilon}$ for the data available in the literature. Some scatter is observed, which is expected, since the dry unit weight of MSW that is used is just indicative of waste composition and unit weight, but cannot possibly capture all the factors that affect waste compressibility. However, the regression analyses indicate higher R^2 values than previously reported in the literature, while the parameter used for the regression is simple, i.e., the dry unit weight of the material. A regression considering the data from this study, as well as the literature, results in similar parameters as shown in Eq. 6. Specifically, in Eq. 6, 0.39 becomes 0.46 and -0.15 becomes -0.16. Alternatively, Bareither et al. (2012a) used the Waste Compressibility Index (WCI), which is a function of waste water content, percentage of biodegradable organic waste and dry unit weight.

Figure 10 shows the variation of $C_{\alpha\varepsilon}$ with waste composition (Fig. 10a) and γ_{d0} (Fig. 10b). Significant scatter in the data is observed for the entire dataset, there is a stronger relationship between $C_{\alpha\varepsilon}$ and the amount of <20 mm material rather than with γ_{d0}. This may not be surprising given the established influence of organic substances on the long-term compressibility of ground materials.

The results are presented in terms of the constrained modulus D in Fig. 11. D is increasing with vertical stress, as shown in Fig. 11a. At the same vertical stress, soil-rich specimens (100%<20 mm) and denser MSW specimens are stiffer, i.e., they have higher D values. Fig. 11b illustrates the relationship between the normalized constrained modulus D' and mean vertical stress σ_{vm} defined as follows:

$$D' = \frac{D}{\sigma_{vm}} \quad [7]$$

where $\sigma_{vm} = \frac{\sigma_{vf}+\sigma_{vo}}{2}$, i.e., the mean vertical stress over the stress increment.

As shown in Fig. 11b, initially, it appears that D' reduces with vertical stress. This observation is consistent with $C_{c\varepsilon}$ increasing with normal stress as shown in Fig. 2a and was also previously reported by Bareither et al. (2012a) in terms of $C_{c\varepsilon}$, who showed an increase in $C_{c\varepsilon}$ up to a stress level beyond which it becomes constant. As also indicated by Bareither et al. (2012a), this apparent trend is merely a reflection of the effect of compaction effort and densification. Compacted specimens are practically overconsolidated and appear to have higher D' (or lower equivalent $C_{c\varepsilon}$) especially at lower normal stresses, (e.g., <50 kPa), i.e., the compacted specimens appear stiffer than the uncompacted ones for stress increments that are below or near the compaction stress level. However, as the stress increment increases to levels higher than the compaction stress levels, the compressibility parameters approach a relatively "constant" value.

The “overconsolidation” observation has also been made in terms of shear wave and p-wave velocity in the field by Sahadewa et al. (2014b) with reported maximum past pressures of up to 50 kPa. Overall, in the normally consolidated regime, D’ is essentially nearly constant and ranges between 4 and 8. This range can be used as a first-order estimate of the constrained modulus of MSW in the absence of site specific data.

Tests on fresh and fully biodegraded specimens were executed on specimens from Michigan and Texas landfills. As explained earlier, biodegradation was executed for extended periods of time using large-size laboratory simulators and the tests were completed when, based on the measured physicochemical characteristics of the solid, liquid and gas phases of the MSW, the specimen was considered fully degraded. The biodegraded specimens were then subjected to 1D compression and the results are also included in the dataset. The degraded specimens are no different than the fresh specimens in their general trend. This observation indicates that the relationships shown in this study should be valid regardless of the state of degradation of the specimen, as long as the waste composition and unit weight of the material is known. However, note that the composition and total unit weight of the degraded specimen are different than those of its fresh counterpart because during biodegradation both the %<20 mm material and dry unit weight increase. Thus, the compressibility parameters of the degraded specimen is different than the same specimen at its fresh state.

Figure 12 illustrates the empirical relationship between $C_{c\varepsilon}$ and D’. Each of the compressibility parameter values shown has been derived from the experimental data independently. The two parameters are expected theoretically to be closely correlated, as shown in Eq. 3. For the data presented, the following simple relationship can be used in practice to quickly calculate $C_{c\varepsilon}$ from D’ and vice versa:

$$C_{c\varepsilon} = \frac{0.90}{D'} \qquad [8]$$

Of interest is also the ratio of $C_{\alpha\varepsilon}$ to $C_{c\varepsilon}$. As mentioned earlier, typical ratios of $C_{\alpha\varepsilon}/C_{c\varepsilon}$ for natural soils are between 0.03-0.06 with ratios for amorphous and fibrous peats being around 0.035-0.085, and ratios for organic silts 0.035-0.06 (Holtz and Kovacs, 1981). The experimental data from this study indicate that typical ratios are 0.01-0.04 for normally consolidated MSW. Note however that, as discussed earlier, in this ratio, $C_{\alpha\varepsilon}$ is representative of mechanical compression (creep) only, and does not include the biodegradation component of the long-term settlement.

CONCLUSIONS

The response of MSW to a compression load has been experimentally investigated by executing a total of 143 large-size 1D compression tests on solid waste from six landfills. The results of this study indicate that the compressibility characteristics of MSW, as expressed by $C_{c\varepsilon}$, D' and $C_{\alpha\varepsilon}$ are largely vertical stress independent. The compressibility characteristics are primarily impacted by waste composition and dry unit weight. Waste composition is a critical factor. The %<20 mm material and the unit weight of the material can be used to provide a reasonable estimate of the compressibility parameters. However, the type of waste constituent (i.e., paper, plastic or wood) can have an effect on the compressibility characteristics of the soil-waste mixture. Also, because of the anisotropic structure of the MSW, the direction of compression load compared to the fibrous constituent orientation may need to be considered. Relationships of $C_{c\varepsilon}$, (or D'), $C_{\alpha\varepsilon}$ as a function of waste composition and unit weight were derived. The relationships shown can be used for specimens of any degradation state, as long as the waste composition and unit weight are known. Typical ratios of $C_{\alpha\varepsilon}/C_{c\varepsilon}$ for MSW are between 0.01-0.04.

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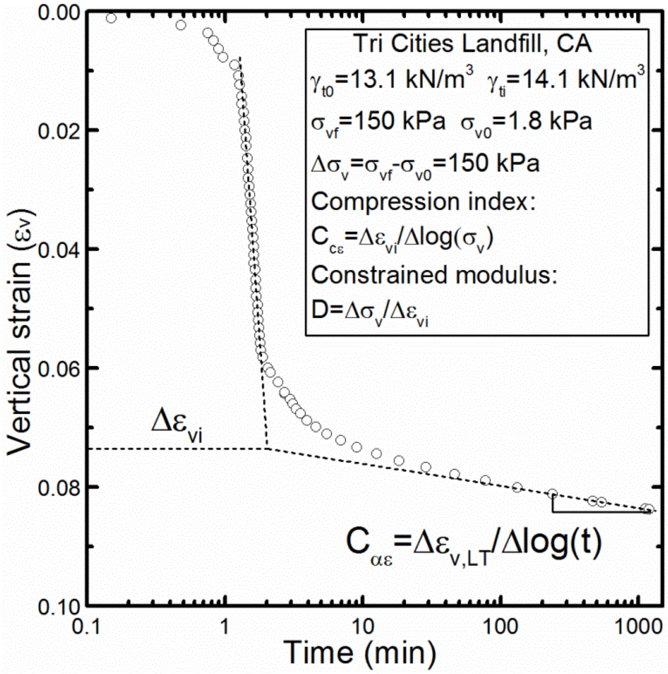

Figure 1: Example compressibility data for a specimen from Tri-Cities landfill, and associated compressibility parameters.

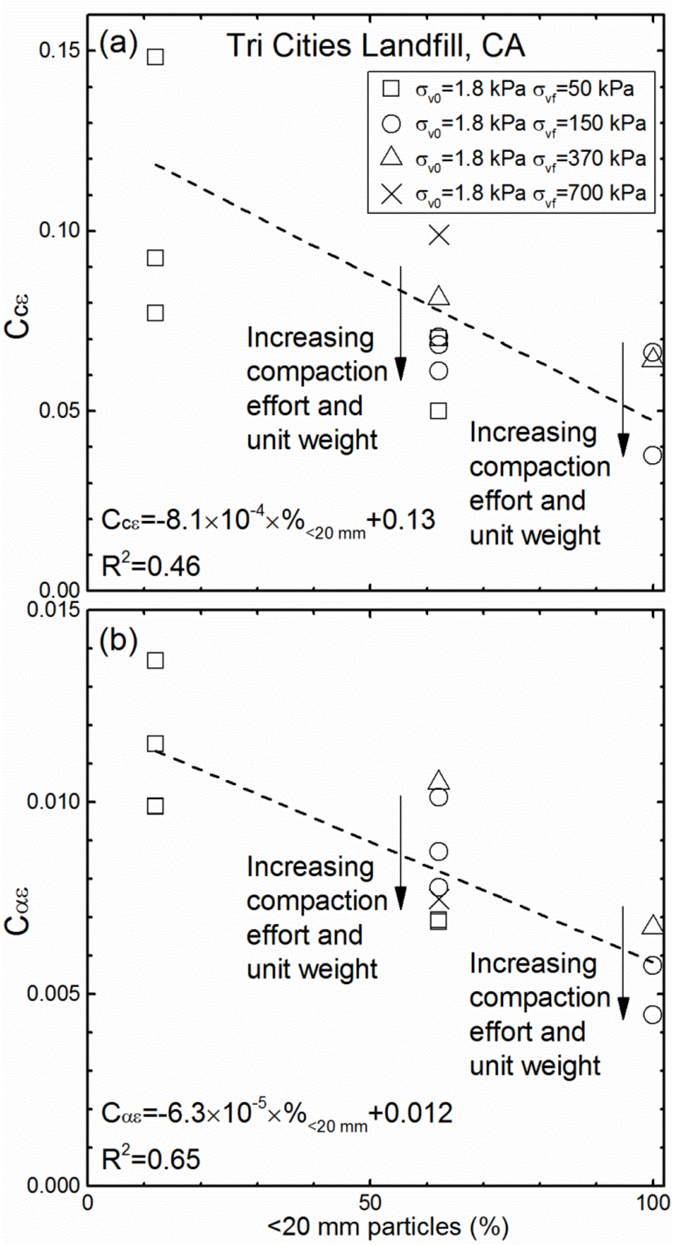

Figure 2: Impact of amount of <20 mm material on $C_{c\varepsilon}$ and $C_{\alpha\varepsilon}$.

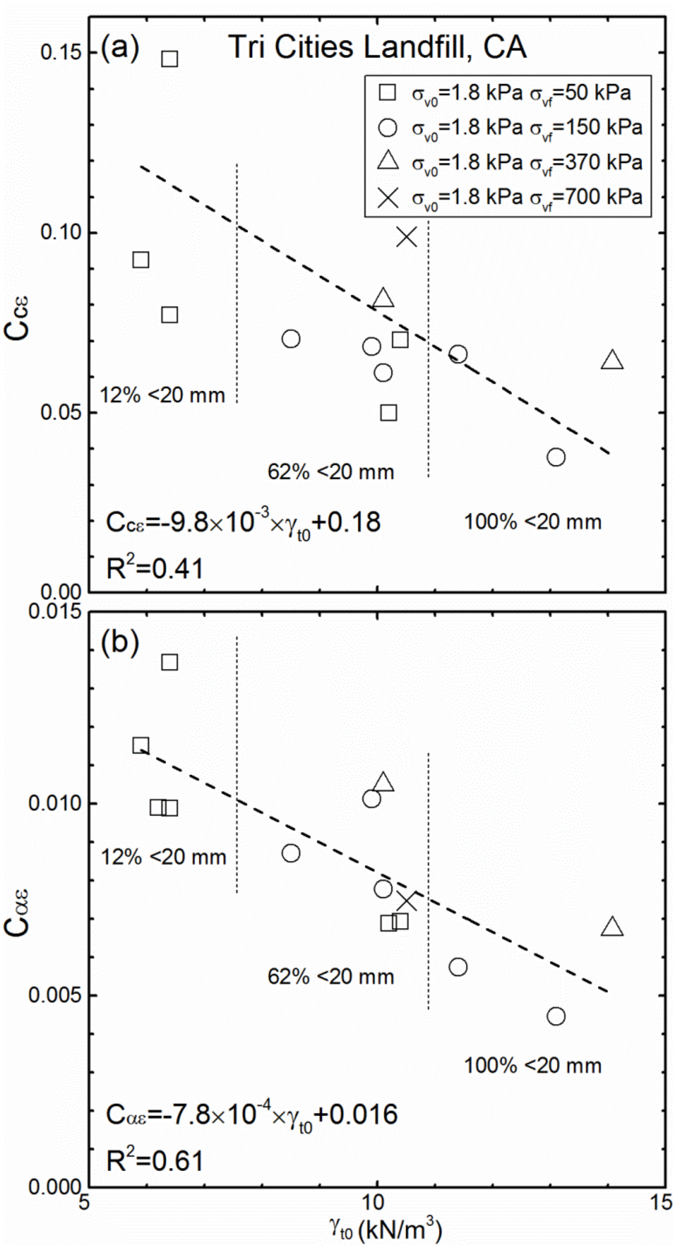

Figure 3: Relationship between (a) $C_{c\varepsilon}$ or (b) $C_{\alpha\varepsilon}$ and total unit weight prior to immediate compression (γ_{t0}).

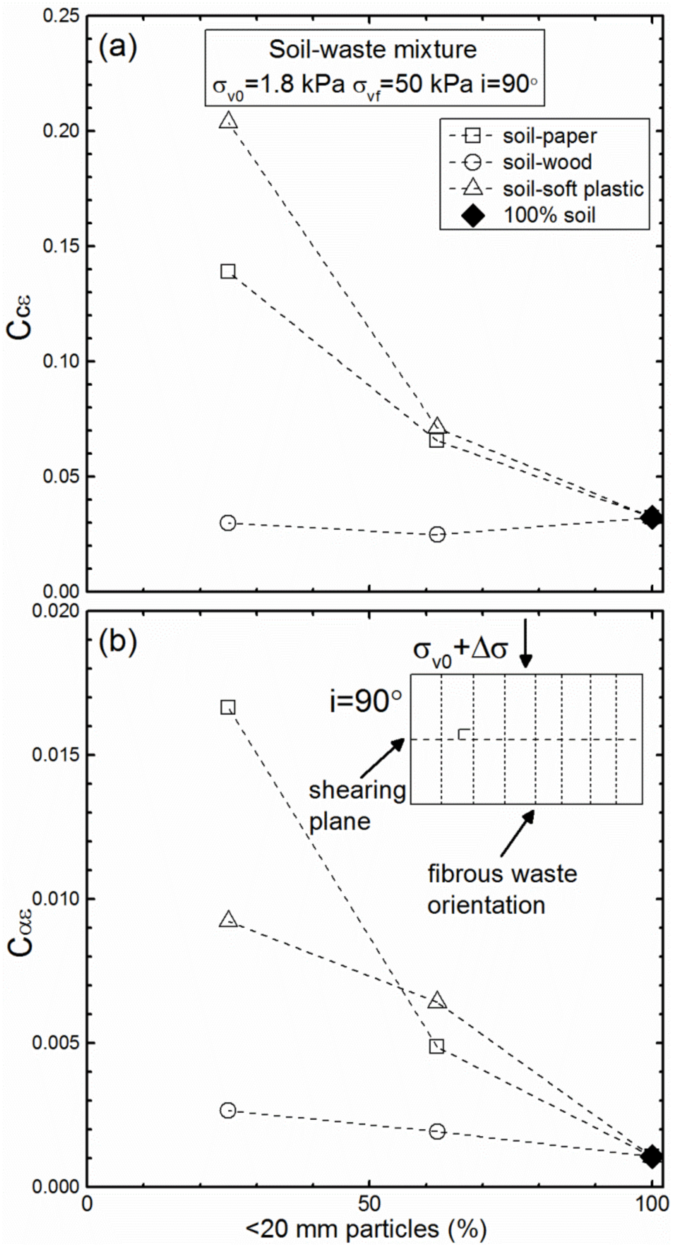

Fig. 4: The impact of waste composition and waste type on (a) $C_{c\varepsilon}$ and (b) $C_{\alpha\varepsilon}$.

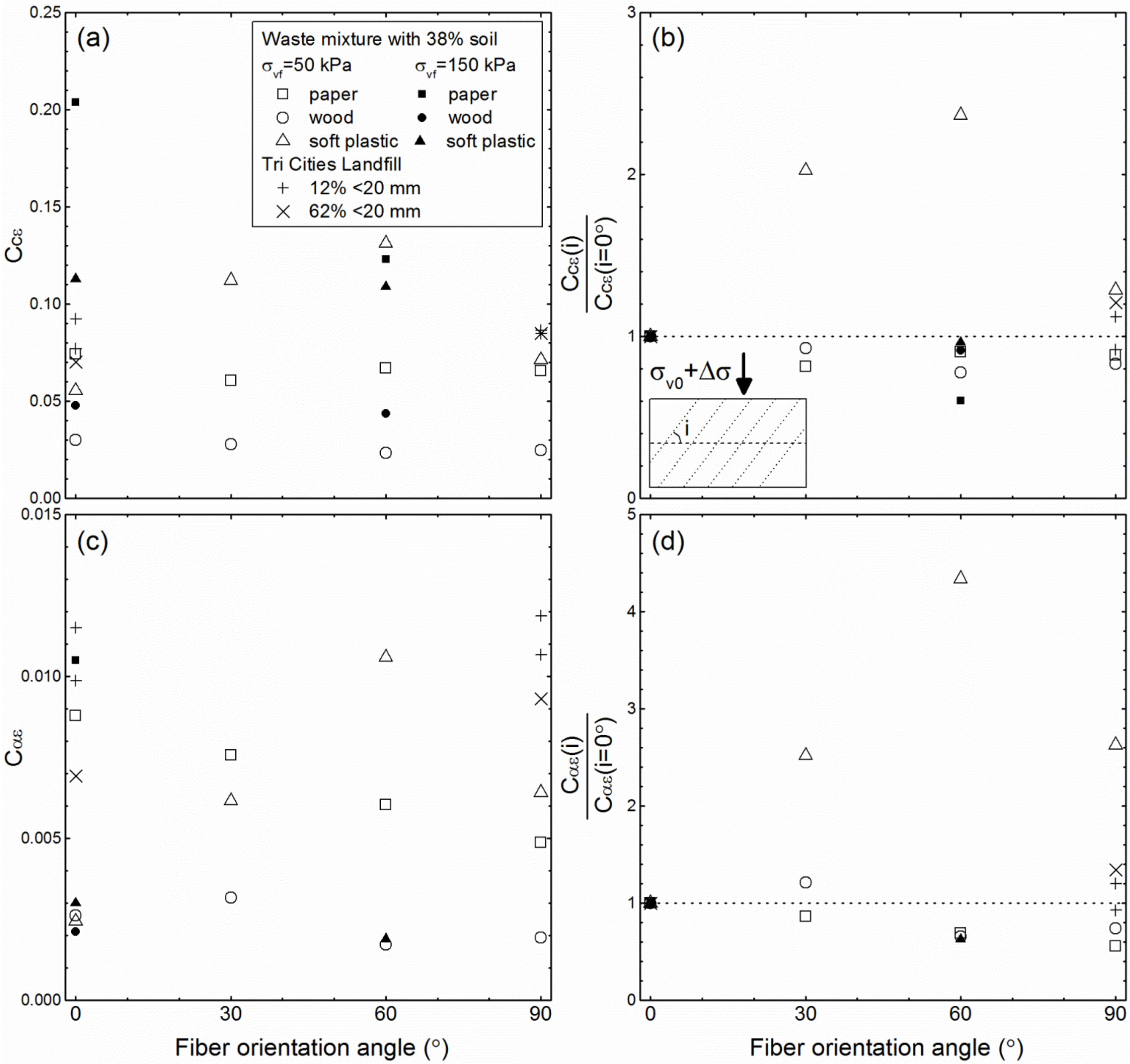

Fig. 5: The impact of fiber orientation angle on (a-b) $C_{c\varepsilon}$ and (c-d) $C_{\alpha\varepsilon}$.

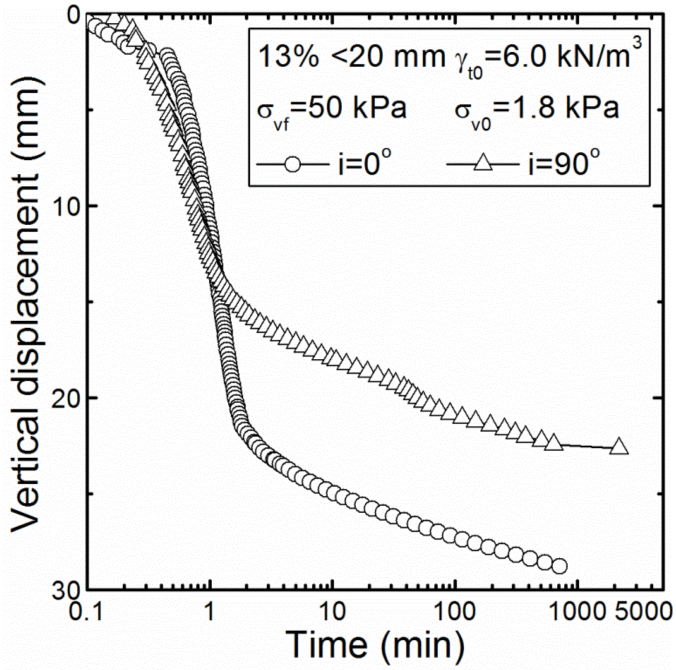

Figure 6. Effect of fibrous waste orientation on the compressibility of practically identical MSW from Tri-Cities landfill.

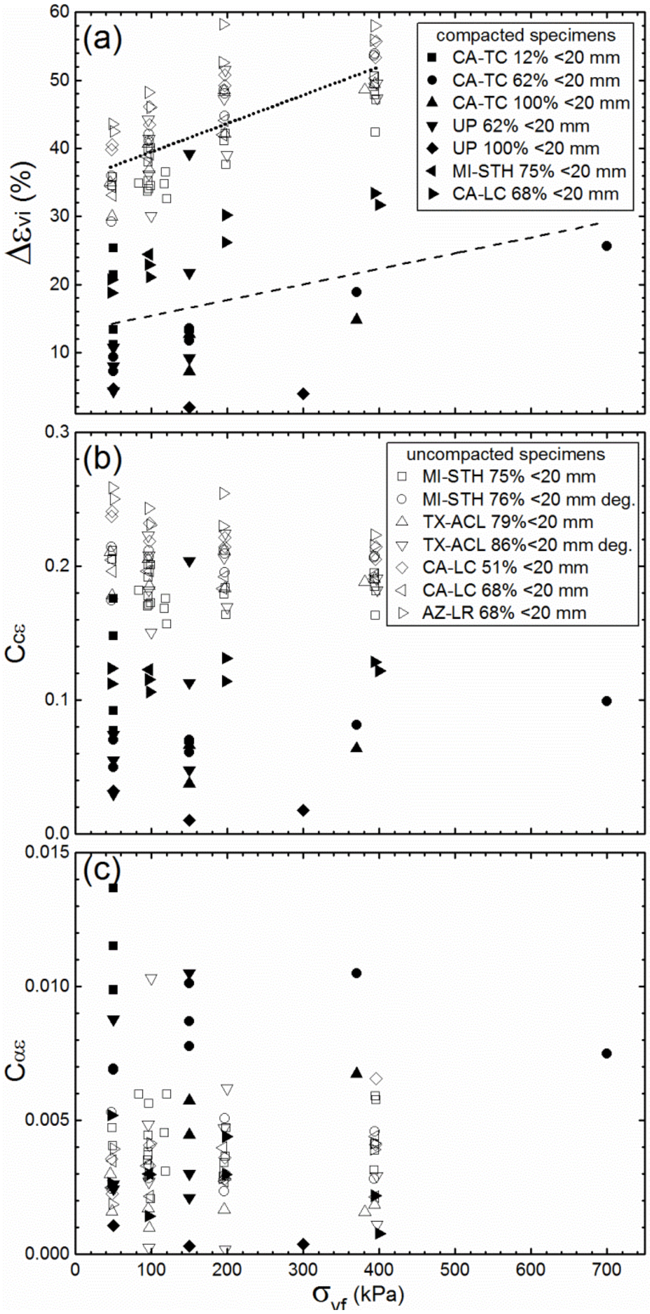

Figure 7: Experimental results for compacted and nearly uncompacted specimens in terms of (a) immediate strain; (b) $C_{c\varepsilon}$, and (c) $C_{\alpha\varepsilon}$. (The legend is split in two figures for illustration purposes only.)

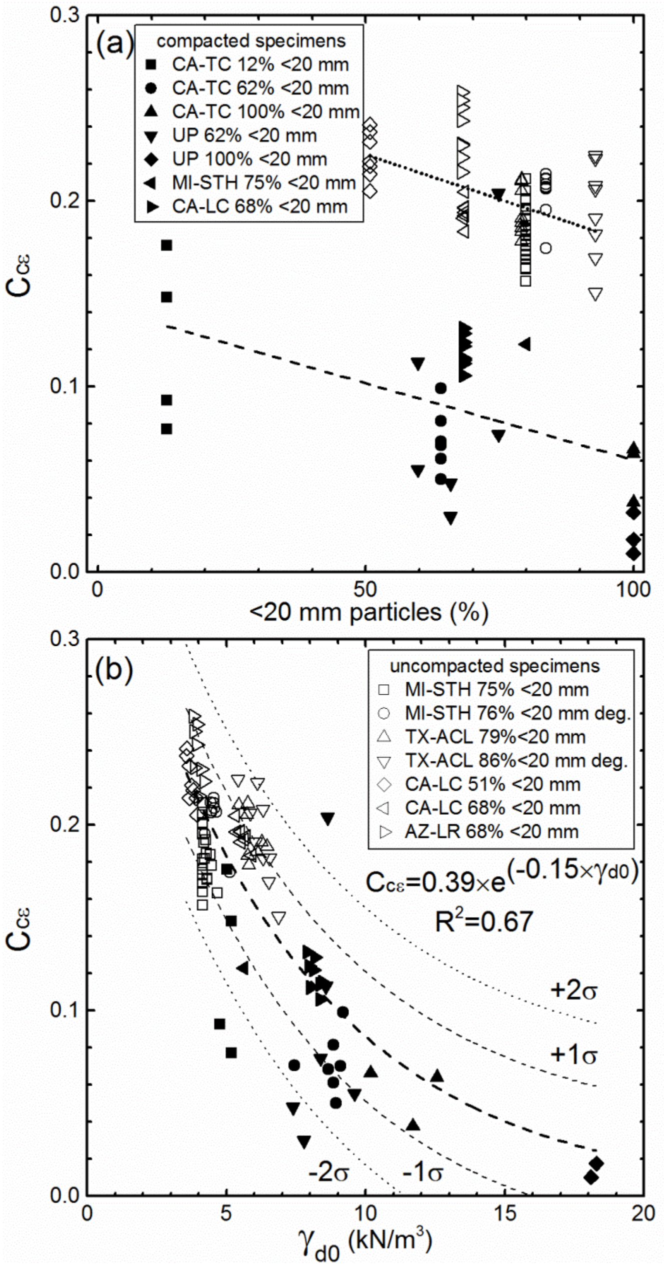

Figure 8: Relationship between $C_{c\varepsilon}$ and (a) percentage of <20 mm material, and (b) dry unit weight prior to compression (γ_{d0}). (The legend is split in two figures for illustration purposes only.)

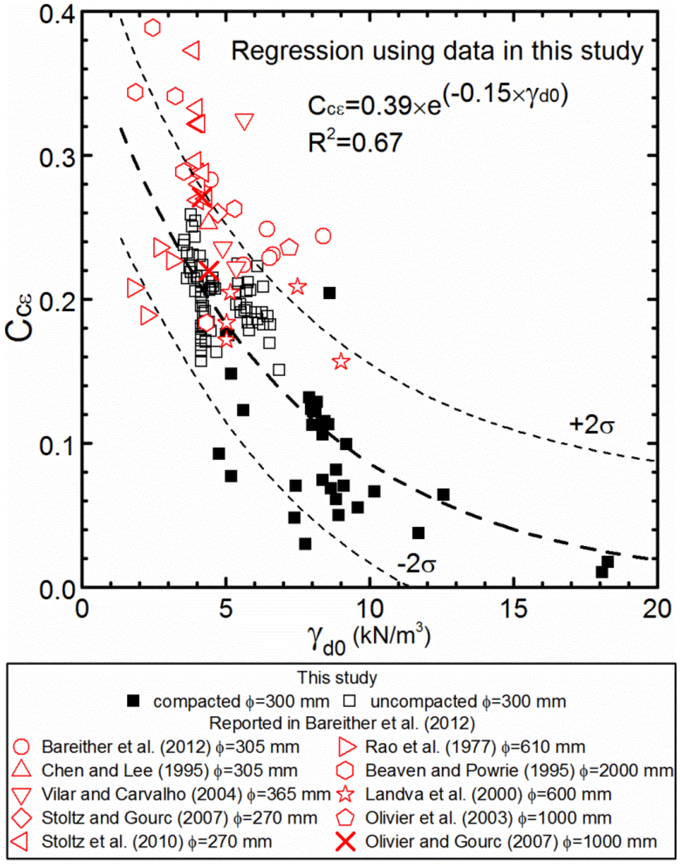

Figure 9: Relationship between $C_{c\varepsilon}$ and dry unit weight prior to compression (γ_{d0}) based on this study and the literature.

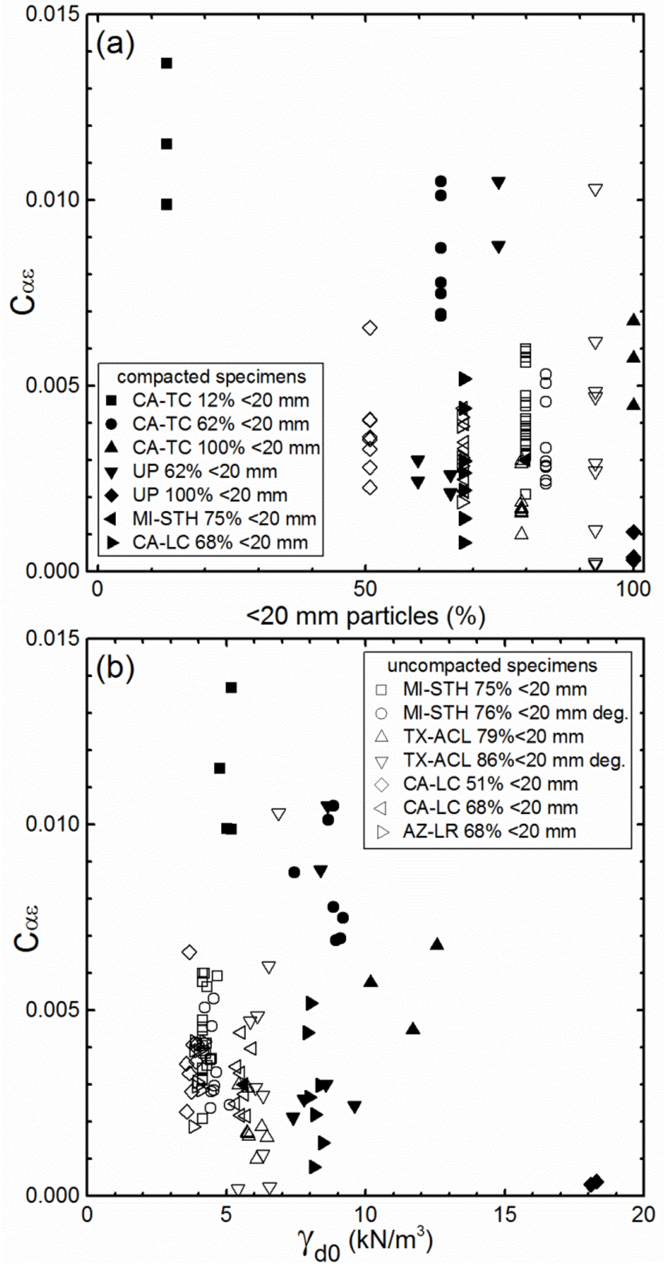

Figure 10: Relationship between $C_{\alpha\varepsilon}$ and (a) percentage of <20 mm material, and (b) dry unit weight prior to compression (γ_{d0}). The legend is split in two figures for illustration purposes only.

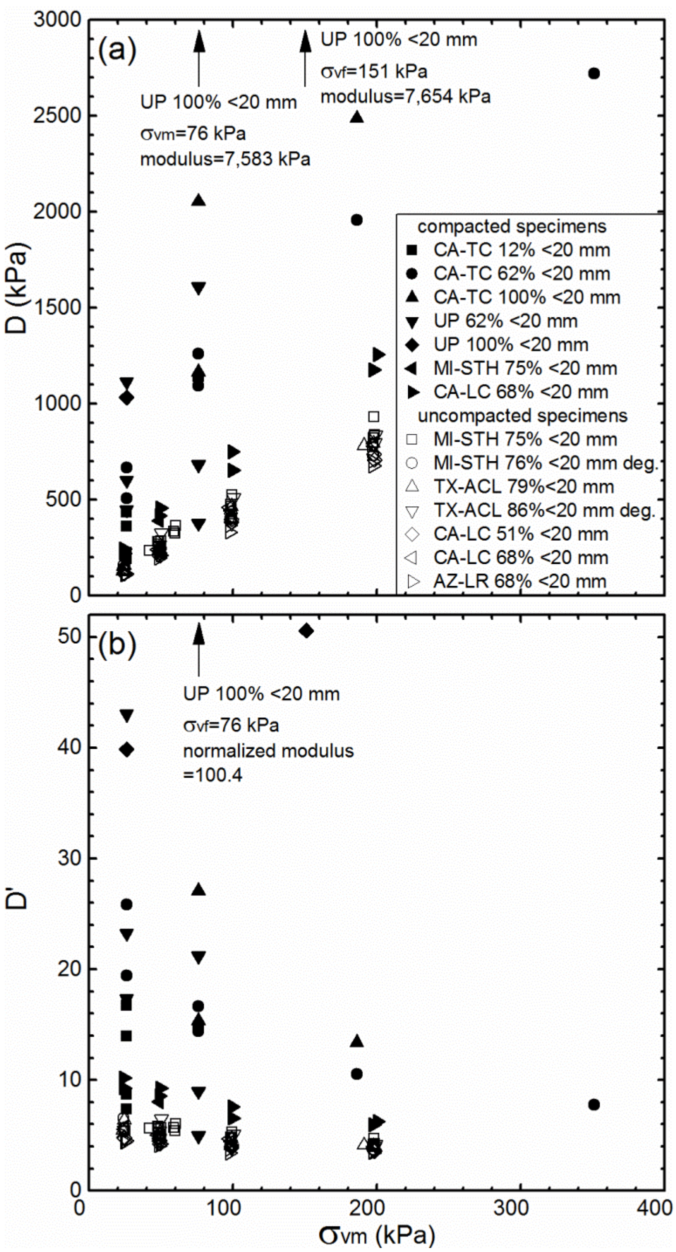

Fig. 11. Relationship between mean vertical stress (σ_{vm}) and (a) constrained modulus (D), and (b) normalized constrained modulus (D').

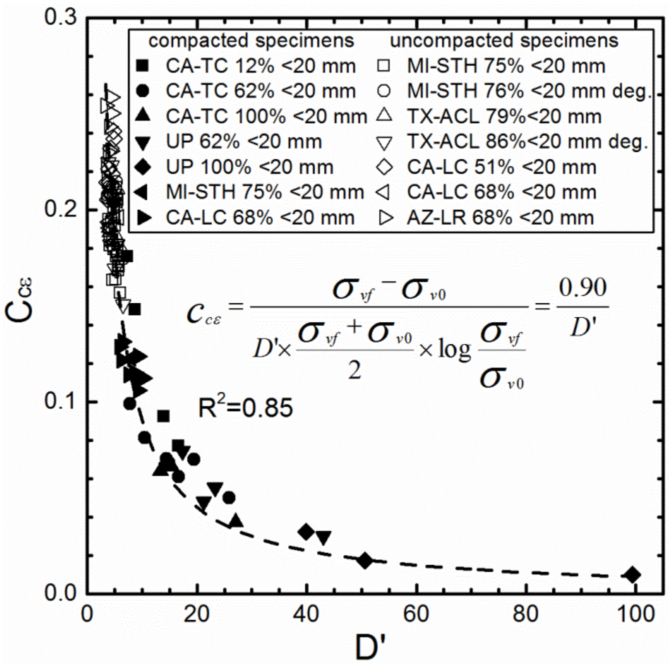

Fig. 12. Correlation between $C_{c\varepsilon}$ and D'.