Geotechnical properties of municipal solid waste at different phases of biodegradation

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ABSTRACT

This paper presents the results of laboratory investigation conducted to determine the variation of geotechnical properties of synthetic municipal solid waste (MSW) at different phases of degradation. Synthetic MSW samples were prepared based on the composition of MSW generated in the United States and were degraded in bioreactors with leachate recirculation. Degradation of the synthetic MSW was quantified based on the gas composition and organic content, and the samples exhumed from the bioreactor cells at different phases of degradation were tested for the geotechnical properties. Hydraulic conductivity, compressibility and shear strength of initial and degraded synthetic MSW were all determined at constant initial moisture content of 50% on wet weight basis. Hydraulic conductivity of synthetic MSW was reduced by two orders of magnitude due to degradation. Compression ratio was reduced from 0.34 for initial fresh waste to 0.15 for the mostly degraded waste. Direct shear tests showed that the fresh and degraded synthetic MSW exhibited continuous strength gain with increase in horizontal deformation, with the cohesion increased from 1 kPa for fresh MSW to 16 to 40 kPa for

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degraded MSW and the friction angle decreased from 35° for fresh MSW to 28° for degraded MSW. During the triaxial tests under CU condition, the total strength parameters, cohesion and friction angle, were found to vary from 21 to 57 kPa and 1 to 9°, respectively, while the effective strength parameters, cohesion and friction angle varied from 18 to 56 kPa and from 1° to 11°, respectively. Similar to direct shear test results, as the waste degrades an increase in cohesion and slight decrease in friction angle was observed. Decreased friction angle and increased cohesion with increased degradation is believed to be due to the highly cohesive nature of the synthetic MSW. Variation of synthetic MSW properties from this study also suggests that significant changes in geotechnical properties of MSW can occur due to enhanced degradation induced by leachate recirculation.

Keywords: Synthetic municipal solid waste; bioreactor landfills; leachate recirculation; biodegradation; geotechnical properties; moisture content; degree of decomposition; hydraulic conductivity; compressibility; shear strength.

1. Introduction

Bioreactor landfill technology involves injecting leachate and other supplemental liquids into the waste to accelerate or enhance the anaerobic biodegradation of MSW. Bioreactor landfills offer a sustainable way to achieve higher rates of MSW degradation, faster reduction of leachate and landfill gas pollution potential, and an increase in landfill volumetric capacity. They also offer significant reductions in post-closure management as a result of the reduced period for leachate and gas generation (Sharma and Reddy, 2004; ITRC, 2006).

Under the U.S. Environmental Protection Agency (USEPA) Research Development & Demonstration Rule (40 CFR 258.4), several field demonstration projects have been initiated in the United States to assess the performance of bioreactor landfills as compared to the conventional landfills. Some of the well-designed demonstration projects showed accelerated stabilization of MSW based on the quantity and quality of landfill gas produced and the amount of landfill settlement (Reddy and Bogner, 2003; ITRC, 2006; Benson et al., 2007). Several landfill failures have been attributed to accumulation of leachate within the landfills or uncontrolled leachate injection (Koerner and Soong, 2000; Blight, 2008). Therefore, controlled leachate recirculation operations are essential to prevent built-up of pore water pressures in the landfill and prevent any failures.

It is also believed that the degradation of organic matter in the waste changes the composition of solids matrix of the MSW; most degraded MSW is sometimes described as “muck-like” material. With the drastic changes in solids composition and increased moisture content, the mechanical behavior of MSW is expected to be quite different than that of fresh MSW (undegraded condition). It is critical to perform geotechnical stability analyses based on the properties that accurately describe the MSW under different phases of degradation. Several studies have been reported on geotechnical properties of MSW (Landva and Clark, 1990; Gabr and Valero, 1995; Kavazanjian, 2001; Zekkos, 2005; Grisolia and Napoleoni, 1996; Jones et al. 1997; Vilar and Carvalho, 2004; Reddy et al., 2009a,b); however, very few studies focused on determining the change in properties of MSW due to degradation under bioreactor landfill conditions (Wall and Zeiss, 1995; Van Impe and Bouazza, 1998; Pelkey et al. 2001; Hossain, 2002; Machado et al. 2006; Reddy et al., 2009a). In general, these studies did not systematically quantify the effects of leachate recirculation and enhanced degradation on the engineering properties of MSW.

Hossain (2002) reported controlled laboratory studies on shredded MSW from a transfer station in which the MSW was anaerobically degraded in reactors with leachate recirculation. Based on the methane (CH_4) production, reactors were destructively sampled to obtain MSW samples degraded to different levels. Cellulose (C), hemicellulose (H) and lignin (L) concentrations of the samples were measured to better characterize the extent of degradation. A general trend of increased compressibility (compression index) and decreased shear strength (friction angle with zero cohesion) with level of degradation (represented by (C+H)/L) was reported. Additional studies performed following a similar approach, but using MSW from another landfill site, showed that both shear strength properties (cohesion and friction angle) and hydraulic conductivity decreased with increased decomposition of MSW (Hossain et al., 2009; Hossain and Haque, 2009).

Reddy et al. (2009a) determined the changes in geotechnical properties of landfilled MSW which was subjected to leachate recirculation for about 1.5 years. Because of the low amount of leachate recirculation, the extent of MSW degradation was minimal, leading to only minor differences between the properties of fresh and landfilled MSW. Because of heterogeneous composition of field MSW, quantifying the changes in properties solely due to biodegradation is often complicated. To overcome this problem, synthetic MSW can be used in laboratory investigations to determine the parameters affecting the behavior of MSW under controlled laboratory conditions. Synthetic MSW allows simulation of MSW with the desired composition and it is prepared by mixing specific proportions of selected fresh products (paper, grass, etc.).

This paper presents the results of a comprehensive laboratory study to systematically quantify changes in geotechnical properties at various phases of biodegradation under highly controlled conditions in customized test reactors. The degradation process was monitored by measuring gas production rates and gas composition. Based on the testing of synthetic MSW exhumed at different phases of degradation, the changes in geotechnical properties are quantified as a function of degree of degradation.

2. Materials and methods

2.1. Fresh and Biodegraded Synthetic MSW Preparation

Fresh synthetic MSW was prepared in the laboratory to be representive of the typical composition of MSW generated in the United States. Typical MSW disposed in the landfills of the United States consists of 59% biodegradable fractions and 41% non-biodegradable fractions on wet mass basis (USEPA, 2006). Biodegradable fractions include paper and paper products, food waste, and garden waste while nonbiodegradable fractions include metals, plastics, textiles, rubble, glass, miscellaneous inorganic waste, and recalcitrant (lignin) fractions of wood wastes. The biodegradable fraction (60%) was represented by selected fresh materials: paper and paper board (25.2%) in MSW were represented by 20% shredded paper; yard trimmings and wood (14.9%) was represented by 20% grass; food scraps and other biodegradable fractions (19.1%) were represented by 10% vegetable waste, 5% meat (ground beef) and 5% cellulose non-paper material. The non-biodegradable fraction (40%) of synthetic MSW was represented by an equal mixture of local glacial till (CL) and fine sand (SP). Clayey local glacial till is often used for daily cover at landfills in the midwestern United States, except where alternate daily cover materials (non-soil) are used (Bogner, 1990). Exhumed landfill samples from Midwestern U.S. landfills has indicated that substantial percentages of local soils can be mixed with solid waste, due to repetitive applications of daily cover and periodic placement of thicker intermediate soil covers (Bogner, 1990).

The preparation of synthetic MSW involved weighing required amounts of fresh individual components and then placing them all together in a large plastic container. Leachate (with pH 7.5) from a landfill (Orchard Hills landfill, IL) was added. To expedite the degradation of synthetic MSW, anaerobic digester sludge obtained from a wastewater treatment plant (Lisle, IL) was also added. Synthetic MSW components, sludge and leachate were mixed by hand until the sludge and leachate distributed uniformly and the material appeared homogeneous. The synthetic MSW was then placed in the specially designed bioreactor landfill reactors.

2.2. Bioreactor assembly and operation

Figure 1 is a schematic of the bioreactor used for enhanced anaerobic degradation of synthetic MSW. The bioreactor consisted of a cylindrical cell fitted with metal plates at the top and the bottom. The tubing was made of acrylic and had an inside diameter of 127 mm and a length of 508 mm. The metal plates made of aluminum were fixed at the top and bottom of the cylindrical cell using bolts. Top plate had three ports: one for leachate recirculation, one for gas sampling and volume measurement, and another to measure gas pressure. Leachate was collected through the port provided at the bottom. All connections to the reactors were properly sealed with anaerobic sealant to prevent any leak or air intrusion. The reactor was accompanied by a recirculation cell of diameter 102 mm and a height of 254 mm. Sludge-amended leachate was re-circulated to the bioreactor through the recirculation cell.

Four identical reactors R1, R2, R3 and R4 were prepared by placing 3 kg of synthetic MSW in each reactor. To ensure efficient leachate recirculation, a filter paper, geotextile and a steel wire mesh were placed at the bottom prior to the loading of synthetic MSW into the reactor. Synthetic MSW was placed in three compacted layers and the bulk unit weight of compacted synthetic MSW ranged from 10 - 15 kN/m^3. All connection ports were properly sealed using anaerobic sealant. Gas tightness of the reactors was checked by immersing nitrogen-filled reactors in a water bath. After the leak check, each reactor was once again purged with nitrogen to displace the air if present in it, resulting in the onset of anaerobic degradation phase. After ensuring the complete anaerobic condition, all reactors were placed in a chamber maintained at a temperature of 35°C – 38°C which provided a favorable environment for the growth of microbes.

To enhance the biodegradation process, leachate recirculation was carried out in all four reactors. Leachate volume of 10% total weight of synthetic MSW was recirculated through the waste samples. On the first day, leachate collected from a landfill (pH 7.5) was used for recirculation, since the amount of leachate generated from the reactors was less than required. From the second day, leachate collected from the reactors R1, R3 and R4 was neutralized (to pH 7.0) using sodium bicarbonate and mixed with leachate obtained from the landfill to recirculate the desired volume. This procedure was continued for first 50 days. Thereafter, reactors were recirculated with the amended bioaugmented leachate (4 liters of leachate from the landfill amended with 500 g of anaerobic digestor sludge, 100 g of potassium phosphate, and 100 g of sodium bicarbonate). In the case of reactor R2, amended leachate was recirculated from the beginning. Leachate was recycled thrice a week for the first 150 days.

Biodegradation process was monitored by measuring the volume and composition of gas and pH of leachate generated by synthetic MSW in each reactor. Gas volume was measured by water displacement method. Gas composition was measured using SRI 9300B gas chromatograph (GC) equipped with a thermal conductivity detector**.** The pH of leachate was measured in accordance with the procedure of EPA 9040C (USEPA, 1996).

Different phases of biodegradation were demarcated based on the composition of gas and pH of leachate generated, and synthetic MSW samples were exhumed at different phases of biodegradation. Samples from each phase of biodegradation were characterized by testing for moisture content, organic content, specific gravity, and gradation based on the standard ASTM testing procedures (ASTM, 2008). Moisture content was determined in accordance with the standard procedure ASTM D2216, but the samples were dried at a lower constant temperature of 60°C (to avoid possible burning of any organic constituents) until the mass remained constant. Wet gravimetric moisture content, defined as the ratio of mass of moisture to the mass of wet synthetic MSW, is used throughout this paper as it is commonly used in landfill practice. The organic content, which is a representation of volatile solids in the synthetic MSW, was measured as per ASTM D2974 (heated at 750°C for 12 hours to achieve constant mass). Specific gravity was determined primarily in accordance with ASTM D854, with the exception that the entire synthetic MSW sample was used for testing instead of screening through #4 sieve. Particle size distribution was determined as per ASTM D422. Degree of decomposition (*DOD*) was defined as follows to express the extent of biodegradation (Andersland et al., 1984):

$$DOD = \left(1 - \frac{X_{fi}}{X_{fo}}\right)\frac{1}{\left(1 - X_{fi}\right)} \times 100 \qquad (1)$$

Where X_{fo} is the initial organic fraction and X_{fi} is the organic fraction after partial decomposition. In other words, X_{fo} and X_{fi} are the initial organic content and the organic content at any degradation stage under consideration given in fractional form, respectively. Equation 1 relates the percent organic fraction degraded with respect to the inorganic fraction present, and it can be seen that *DOD* varies from 0% for undegraded or initial waste condition to 100% for complete degradation of organic fraction in the waste. It should be noted that the MSW samples R1, R2, R3 and R4 represented different phases of degradation, namely anaerobic acid phase, accelerated methane phase, decelerated methane phase, and methane stabilization phase, respectively, based on the gas composition data.

2.3. Geotechnical testing

The synthetic MSW samples retrieved from the reactors were air-dried for several days and then their moisture was adjusted to 50% on a wet weight basis (100% on dry weight basis). The synthetic MSW was then used to prepare specimens for hydraulic conductivity, compressibility, and shear strength testing as described below.

2.3.1. Hydraulic Conductivity

To measure the hydraulic conductivity, rigid-wall as well as flexi-wall (triaxial) permeameters were used in general accordance with ASTM standard procedures ASTM D2434 and D5084 (ASTM, 2007). Rigid-wall constant and falling head hydraulic conductivity tests were conducted at zero confining pressure. For the fresh and R1 (anaerobic acid phase) samples, a rigid-wall constant head method was used. Synthetic MSW from R2 (accelerated methane), R3 (decelerated methane) and R4 (methane stabilization) samples were only subjected to falling head test due to the less permeable nature of these degraded samples.

Flexi-wall permeability tests were conducted at different confining pressures to study the variation in hydraulic conductivity with respect to density at different phases of degradation. Specimens compacted in a cylindrical mould (diameter 50 mm and height 100 mm) using a tamper were extruded and placed in latex membranes and then in the triaxial cells. The samples were first saturated by applying 35 kPa initial confining pressure and flushing deionized water under a constant hydraulic gradient. Once the sample was saturated, flow volume in a predetermined elapsed time was measured, and the results were then used to calculate the hydraulic conductivity. Following the saturation under 35 kPa confining pressure, the specimens were consolidated under 69 kPa, 138 or 276 kPa sequentially, and hydraulic conductivity was measured under each confining pressure based on the flow volume in given time under constant hydraulic gradient across the sample.

2.3.2. Compressibility

Confined compressibility tests were performed in a floating ring oedometer in general accordance with ASTM D2435 (ASTM, 2007). Fresh and degraded synthetic MSW samples were mixed with water to yield initial wet moisture content of 50%. The samples were then placed into the ring (63 mm diameter and 25 mm thick) in two layers, and each layer was compacted 15 times using Harvard Miniature compaction tamper equipped with 9 kg spring. The compacted samples had initial wet unit weight of 8.6 – 16.9 kN/m^3 with target moisture content of 50% on a wet weight basis. The testing procedure involved first subjecting the specimen to a constant vertical stress of 48 kPa and observing compression for 24 hours. Subsequently, the vertical stress was increased to 96, 192, 383 and 766 kPa, and compression was monitored for 24 hours under each vertical stress. Long term compressibility was also tested for the same unit weight and moisture content conditions of synthetic MSW by following the above procedure until 383 kPa and then the vertical pressure was maintained constant and compression was measured with time for 15 days.

2.3.3. Drained Shear Strength

Drained shear strength properties of the synthetic MSW were determined by direct shear tests as per ASTM D3080 (ASTM, 2007). Specimens were compacted into a circular shear box with inside diameter 63 mm and thickness 34 mm in layers. Initial wet unit weight of the samples ranged from 11.2 to16.2 kN/m^3, with moisture content of 50% on wet basis. Porous stones were placed on the top and the bottom of the specimen. The specimen was subjected a constant normal stress of 87 kPa and then sheared at a constant strain rate of 0.035 mm/min. The horizontal deformation and shear stress were recorded periodically. The testing was continued until the horizontal displacement reached 15% or more of the specimen diameter (none exhibited peak shear response). The same procedure was followed to test different samples under two other normal stresses of 179 kPa and 271 kPa. The fresh synthetic MSW was tested under normal stresses of 32, 179, 271 and 364 kPa.

2.3.4. Consolidated Undrained (CU) Shear Strength

Consolidated undrained triaxial testing was conducted in accordance with ASTM D4767 (ASTM, 2007). Synthetic MSW was compacted into cylindrical molds in layers. The compacted samples had a diameter of 50 mm and height 100 mm with initial wet unit weight ranging from 11.1 to 17.1 kN/m^3. Each specimen was extruded from the mold and transferred to a latex membrane and placed in the triaxial chamber. Specimen was initially subjected to confining pressure of 35 kPa and back pressure of 21 kPa and was fully saturated. For each waste condition, three specimens were consolidated under 69, 138, and 276 kPa confining pressures and then sheared at a constant strain rate of 2.1 mm/min. During shearing, pore water pressure was also measured. In the absence of a peak shear response, the tests were continued until they reached 30% axial strain. Based on the Mohr-Coulomb failure criteria, total and effective shear strength parameters (cohesion and friction angle) were determined. In geotechnical testing, it is common to assume 15 to 20% strain level as a failure condition and to use the corresponding stresses to calculate shear strength parameters. To allow comparison of the results with direct shear test, shear strength parameters for triaxial tests were also calculated at 15% strain.

3. Results and discussion

The moisture content, organic content (loss-on-ignition, LOI), specific gravity, and grain size distribution of the exhumed synthetic MSW samples from the bioreactors at different phases of degradation are summarized in Table 1 and Figure 2. These samples were air-dried and then their moisture was adjusted to the same 50% on a wet weight basis (100% on dry weight basis) prior to testing for hydraulic conductivity, compressibility, and shear strength testing.

3.1. Hydraulic Conductivity

Hydraulic conductivity of fresh and degraded synthetic MSW samples ranged from 10^{-3} to 10^{-8} cm/s (Figure 3a and 3b). The rigid wall permeameter test results provide hydraulic conductivity under zero confining pressure. The hydraulic conductivity of the degraded synthetic MSW was two orders of magnitude less than the fresh synthetic MSW. This decrease in hydraulic conductivity can be attributed to the degradation and the increase in density of the samples; bulk unit weight of fresh synthetic MSW was 8.83 kN/m^3 which increased to 16.87 kN/m^3 for degraded samples. Synthetic MSW with the highest degradation yielded hydraulic conductivity in the clay range due to their reduction in particle size.

In the flexi-wall permeameter tests, as confining pressure increased, hydraulic conductivity decreased, indicating a trend similar to soils (Figure 3b). At any particular confining stress, the hydraulic conductivity of fresh synthetic MSW was higher than the degraded synthetic MSW. In the stabilized methanogenic phase with 70% decomposition, the hydraulic conductivity was reduced by three orders of magnitude. This decrease can be attributed to the reduction in particle size with degradation, the increased percentage of fines, and the resulting higher density. Test results clearly show that the degradation of synthetic MSW will result in lower hydraulic conductivity, which has to be considered in the design of leachate recirculation systems, if used for accelerated degradation of MSW under field conditions. Accordingly, the injection rate for recirculating leachate has to be adjusted to avoid development of excessive pore water pressures leading to slope instability problems.

Figure 4 shows how hydraulic conductivity of synthetic MSW varies with the degree of decomposition. Figure 5 shows the variation of hydraulic conductivity of the synthetic MSW and other reported values of field MSW with respect to dry unit weight. At a lower confining pressure, fresh synthetic MSW tested at dry density of 650 kg/m^3, yielded hydraulic conductivity in the same range as fresh field MSW (Reddy et al., 2009b; Reddy et al. 2009c). For the higher confining pressure of 276 kPa, the hydraulic conductivity of fresh synthetic MSW was two orders of magnitude higher than that of degraded MSW. The presence of 40% fines to represent nonbiodegradable material resulted in a clay-like behavior at higher confining pressures. Korman et al. (1987) also reported that hydraulic conductivity of fresh field MSW ranged from 2×10^{-5} to 3×10^{-7} cm/s in the range similar to fresh synthetic MSW. Bleiker et al. (1995) reported similar trends to the synthetic MSW results, namely increasing waste density, resulting in lower hydraulic conductivity.

3.2. Compressibility Characteristics

Normal pressure versus maximum axial strain for synthetic MSW at different stages of degradation is shown in Figure 6. Compression ratio ($C_{c\varepsilon}$), which is the slope of these curves, was calculated for each case and shown on this figure. It should be noted that compression ratio is used commonly in MSW settlement calculations and it is related compression index (C_c), which is used commonly for soils, by: $C_c=C_{c\varepsilon}/(1+e_0)$; where e_0=initial void ratio. As shown in Figure 6, the compression ratio of the synthetic MSW varied in the range of 0.34 to 0.15. As the waste degraded, the compression ratio decreased. Figure 7 shows the variation of compression ratio with the degree of decomposition.

For the normal pressure of 48 kPa, fresh synthetic MSW and R1 representing acid production phase shows higher strain compared to other samples. In the fresh synthetic MSW, larger particle size and lower density of 8.53 kN/m^3 resulted in greater compression due to particle raveling, interaction and fiber effect. Similarly R1 sample had volumetric strain of 29% which may be attributed to the difference in initial density of the sample prepared. R2 and R3 samples resulted in lower strain varying from 18 to 22% due to increase in density resulted from smaller particle size. R4 sample resulted only in 11% strain due to higher density attributed by 86% degree of decomposition and 73% reduction in organic content. Increase in the normal pressure from 48 kPa to 96 kPa and subsequently to 192, 383 and 766 kPa resulted in compression behavior similar to previous loading. Synthetic MSW at different stages of degradation has similar rate of change in the strain for the normal pressure greater than 383 kPa.

Irrespective of the size of the oedometer cell or the maximum particle size, the compression ratio of synthetic MSW in published studies ranged from 0.16 to 0.28 (Reddy et al. 2009d, Dixon et al. 2008; Hettiarachchi, 2005; Langer, 2005), and these are compared in Table 2. Table 2 also provides compressibility values found in the literature for fresh to degraded MSW. In a recent study by the authors, the compression ratio of fresh shredded MSW varied from 0.24 to 0.33 with total compression between 46% and 58% under a maximum pressure of

766 kPa (Reddy et al., 2009b). For the aged MSW (exhumed landfill samples), the compression ratio varied from 0.15 to 0.36 (Durmusoglu et al., 2006; Hossain 2002; Wall and Zeiss 1995; Gabr and Valero 1995; Landva and Clark 1990; Reddy et al., 2009a). From the reported values, it can be observed that there is no significant difference or any particular trend in the compression ratio in spite of different size specimen, age of the waste and increase in moisture content (Reddy et al. 2009a; Gabr et al., 2007; Durmusoglu et al., 2006; Hettiarachchi, 2005). In the current study, compression ratio decreased with aging. However, few researchers have reported aged MSW yielding higher compression ratios than fresh MSW (Wall and Zeiss 1995; Landva and Clark 1990). Compression ratio of synthetic MSW are approximately within the range of values reported in the published literatures. Total compression of the synthetic MSW was in range of fresh field MSW.

Creep behavior of the fresh and degraded synthetic MSW was studied through the long-term compressibility tests under a constant vertical stress of 383 kPa. Based on the measured compression with time, secondary compression ratio ($C_{\alpha\varepsilon}$) was calculated. $C_{\alpha\varepsilon}$ is defined as $\Delta\varepsilon/log(t_2/t_1)$, and it should be noted that the secondary compression ratio and the secondary compression index (C_α) are related by: $C_{\alpha\varepsilon}=C_\alpha/(1+e_p)$, where e_p=void ratio at the end of primary compression. The calculated secondary compression ratio of the synthetic MSW varied in the range of 0.011 to 0.015. A decrease in secondary compression ratio with increase in degradation of synthetic MSW was observed. Figure 8 shows the variation of secondary compression ratio with the degree of decomposition, showing similar behavior to primary compression ratio.

3.3. Shear strength based on direct shear tests

Figures 9(a) and 9(b) show the typical horizontal displacement versus shear stress response under different normal stresses for fresh and the mostly degraded (R4) synthetic MSW, respectively. Similar behavior was found for the samples tested under other intermediate phases (R1, R2 and R3). All of the tests were conducted on samples at an initial moisture content of 50% on wet weight basis and with bulk unit weight ranging from 11.2 to 16.2 kN/m^3. The fresh and degraded synthetic MSW samples exhibited continuous strength gain with increase in horizontal deformation. In the absence of samples reaching any peak strength, shear stress at 15% horizontal deformation was selected to determine the shear strength parameters. Normal stress versus shear stress at 15% deformation was plotted, and the shear strength parameters were calculated based on the Mohr-Coulomb failure criteria (Figure 10). Based on the analysis of the data from each set, cohesion of fresh synthetic MSW was 1 kPa and degraded synthetic MSW was increased in the range from 16 to 40 kPa and the friction angle decreased in the range from 35° to 28°.

From the composition of synthetic MSW, it is likely that grass, paper and fines contributed to the higher friction angle and lower cohesion under freshly prepared condition. As the MSW degrades particle size reduces and a more cohesive nature results. The stabilized methanogenic phase where 70% decomposition has taken place resulted in cohesion of 34 kPa and friction angle of 29°.

In this study, overall composite behavior of fresh synthetic MSW was frictional. However, with biodegradation, an increase in cohesion and decrease in friction angle was clearly observed through the testing and was confirmed by Figure 11. This observation is rather contrary to the current understanding established by data published in the literature concluding that the behavior of MSW is mainly frictional in nature (Langer 2005; Hossain 2002; Howland

and Landva 1992). Typically biodegradation of organic material such as food waste and garden waste makes the remaining MSW more frictional with time. That means in typical MSW cohesion diminishes and friction angle improves with the progression of biodegradation. The main reason for observing the opposite trends during this research is the selection of the substitute material to generate the non-biodegradable portion of synthetic MSW: 20% glacial till and 20% sand. Glacial till can have a considerable fraction of clay that contributes to the cohesive property. Lack of material such as metals, plastics and textiles must have caused the selected material less frictional than assumed. Though sand is a frictional material, waste components such as metals and plastics are known for their interlocking contribution towards frictional properties. Some slowly-biodegradable material within garden waste can also contribute to frictional properties early in the biodegradation process; but these were not represented in the grass mixture used for this study.

Table 3 presents a comparison of drained direct shear strength properties of synthetic MSW and field MSW found in published literature. Similar to compression ratio, irrespective of the size of the shear box or the maximum particle size, friction angle for synthetic MSW varied in a range of 26-35° and this range for field MSW is reported to be 24 - 39° (Table 3). Cohesion varied in a wide range of 1 – 64 kPa for synthetic MSW and 0 – 78 kPa for field MSW. Shear strength parameters for the field fresh MSW conducted in large scale direct shear testing apparatus yielded friction angle between 23 and 35° and cohesion between 23 and 78 kPa (Pelky et al. 2001; Caicedo et al. 2002; Gabr and Valero 1995; Landva and Clark 1990; Johnes et al. 1997).

3.4. Shear strength based on triaxial CU tests

The axial strain versus deviator stress and pore water pressure results from triaxial CU tests conducted using fresh and mostly degraded synthetic MSW are shown in Figures 12 and 13, respectively. Other degraded samples showed similar stress-strain and pore water pressure response. During the testing, deviator stress increased continuously with increase in axial strain, without exhibiting any peak or ultimate response. Therefore, the shear strength properties of MSW are strain dependent. Figure 14 shows the calculated shear strength parameters obtained from all triaxial tests. With pore water pressure measurements, it was possible to calculate both total stress parameters and effective stress parameters. Several previous studies reported stress-strain curves to be concave upward (Jessenberger and Kockel, 1993; Gabr and Valero, 1995; Grisolia et al., 1995; Kavazanjian 2001; Caicedo et al. 2002; Vilar and Carvalho, 2002), but such behavior was not observed in this study, perhaps due to shredding and absence of reinforcing components such as fibers in the synthetic MSW used in this study.

Figure 15 presents the variation of total stress parameters with the degree of decomposition and Figure 16 presents the variation of effective stress parameters with degree of decomposition. The cohesion varied between 21 and 57 kPa and friction angle varied from 1° to 9°. Similar to direct shear test results, as the waste degrades an increase in cohesion and slight decrease in friction angle was observed. One can logically conclude that the lack of frictional material and inclusion of cohesive soils resulted in a declining friction angle and an improving cohesion with the progression of biodegradation.

Shear strength properties from this study were compared with published triaxial test results for MSW (Tables 4 and 5). During a previous study by Reddy et al. (2009a), shredded fresh field MSW was tested using the same testing procedures and same sample dimensions yielded the average total strength parameters: cohesion of 32 kPa and friction angle of 12°. Values obtained for the fresh synthetic MSW through CU testing were lower than that of fresh field MSW. The effective angle of friction (14°) and effective cohesion (45 kPa) reported by Caicedo et al. (2002) for relatively fresh MSW from Dona Juana landfill are slightly higher than what was found for synthetic MSW, which may be due to the presence of higher percent of organic matter in the MSW from Don Juana landfill. Sample R3 with 50% decomposition had shear strength parameters with higher cohesion similar to values reported by Caicedo et al. (2002). Gabr and Valero (1995) conducted triaxial CU tests (without pore water pressure measurement) on 15 year old MSW and reported a friction angle of 34° and cohesion of 18 kPa, which show that friction angle increased and cohesion decreased, possibly due to degradation, the reverse of trends from the synthetic MSW. Based on the triaxial CU tests with pore water measurements, Vilar and Carvalho (2005) reported friction angles of 22 -33° and cohesion 20-71 kPa, with such high cohesion possibly due to presence of 55% organic material. In general, using MSW from field samples, an increase in friction angle and a decrease in cohesion has been reported during biodegradation. On the other hand, the synthetic MSW became highly cohesive with degradation due to the presence of easily biodegradable components and the inclusion of clay soil. Recently, Terzaghi effective stress in modified form was used by Shariatmadari et al. (2009) to interpret the CU test results on MSW, and such analysis may be required to properly analyze the results of CU tests conducted in this study.

4. Conclusions

Geotechnical properties of synthetic MSW at different phases of biodegradation were determined through laboratory-scale testing. In particular, hydraulic conductivity, compression characteristics, and shear strength parameters (friction angle and cohesion) of synthetic MSW were studied at various stages of degradation. The test results were compared with the relevant published studies. The following conclusions can be drawn based on the results of this study:

Hydraulic conductivity of synthetic MSW samples ranged from 1.4×10^{-5} to 8.3×10^{-9} cm/s. Degradation produced more fines and higher unit weight, which resulted in lower hydraulic conductivity of the degraded synthetic MSW.

The compression ratio of the synthetic MSW varied from 0.34 to 0.15, and degradation resulted in lower settlement compared to fresh samples. Decreases in primary and secondary compression ratios were observed with increased degradation.

Drained cohesion of synthetic MSW varied from 1-40 kPa and the drained friction angle ranged from 35-28°. The decrease in the friction angle 35° to 28° may be attributed to the lack of materials such as metals, plastics and textiles in the samples. As the sample degrades, there is an increase in the cohesion and decrease in frictional angle. For fresh as well as all the stages of degraded synthetic MSW, both the friction angle and cohesion increased as a function of increasing horizontal displacement.

Triaxial CU tests with porewater pressure measurements provided total and effective shear strength parameters. Based on the total stresses, the cohesion varied between 21 and 57 kPa and friction angle varied from 1° to 9°. Based on the effective stresses, cohesion ranged from 18 to 56 and friction angle varied from 1° to 11°. The synthetic MSW used in this research exhibited more cohesive behavior as the biodegradation progressed, which is contrary to some reported studies (Gabr et al., 1997; Hossain et al., 2009).

Overall, this study utilized synthetic MSW with controlled composition to systematically quantify the variation of geotechnical properties at different phases of degradation. The variation in properties can be significant and should be properly accounted in the analysis and design of landfills, particularly bioreactor landfills. However, the synthetic MSW used in this study lacks components such as fibers with frictional and interlocking properties; therefore, the effects of such components on geotechnical properties of MSW at different phases of degradation should be properly assessed and incorporated.

Acknowledgements

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Table 1. Characteristics of fresh and degraded synthetic MSW

Bioreactor	Terminal Degradation Phase	Gravimetric Moisture Content (wet weight basis) at Termination* (%)	Organic Content or LOI (%)	Degree of Decomposition (%)	Specific Gravity
-	Fresh	83.0	57.5	0	1.09
R1	Anaerobic Acid	68.8	40.2	50	2.05
R2	Accelerated Methane	77.9	38.9	53	2.26
R3	Decelerated Methane	84.3	28.6	70	2.30
R4	Methane Stabilization	53.9	15.5	86	2.47

*All samples had initial moisture content of 83% (wet weight basis) prior to placing in the reactors; final moisture content influenced by leachate recirculation just before removal from the reactor. Geotechnical testing on all samples was performed at moisture content of 50% (wet weight basis)

Table 2. Compressibility of synthetic MSW and field MSW based on laboratory experiments

	Source	Compression Ratio
Synthetic MSW	*Current Research:* 63 mm diameter oedometer test, **fresh to degraded synthetic MSW** particles were of average size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm	0.15 – 0.34
	Reddy et al. (2009d) 63 mm diameter oedometer test, **fresh synthetic MSW** particles were of average size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm	0.16 - 0.31
	Dixon et al. (2008) Large scale test of size 500x500x0750mm, **fresh synthetic MSW**, maximum particle size 120–500mm	0.30
	Hettiarachchi (2005) 63 mm Teflon cell, **fresh synthetic MSW**, maximum particle size 5mm	0.18 - 0.21
	Langer (2005) 0.5 x 0.5 x 0.75 m compression box, shredded **fresh synthetic MSW** control samples, maximum particle size 10 mm×40 mm	0.30
Field MSW	*Reddy et al. (2009b)* 63 mm diameter oedometer test, shredded **fresh MSW**, maximum particle size 40 mm	0.24-0.33
	Dermusoglu et al. (2006) 63mm oedometer, 10 years old **degraded MSW** 711 mm diameter oedometer, 10 years old **degraded MSW**	0.13 – 0.23 0.19 – 0.26
	Vilar and Carvalho (2005) 385mm diameter, 365mm high oedometer test, 15 years old **degraded MSW**	0.21
	Hossain (2002) 63.5 mm diameter oedometer tests, shredded **relatively fresh MSW** in control samples, maximum particle size 120 - 500 mm, majority was 40 – 120 mm	0.16 - 0.25
	Gabrand Valero (1995) 63 mm diameter oedometer test, 15 – 30 years old **degraded MSW**, maximum particle size 6.3 mm	0.15 – 0.22
	Wall and Zeiss (1995) 570mm diameter cell, shredded **fresh MSW**, maximum size 4.7 cm	0.21- 0.25
	Landva and Clark (1990) 470 mm diameter consolidometer, shredded **fresh MSW** samples from Edmonton, Canada	0.35

Table 3. Drained shear strength properties of synthetic MSW and field MSW based on direct shear tests

	Source	Friction Angle (degrees)	Cohesion (kPa)
Synthetic MSW	*Current Research* 63.5 mm diameter shear box, **fresh to degraded synthetic MSW**, strength defined at 15% strain	35 (fresh) 34 (R1) 29 (R2) 29 (R3) 28 (R4)	1 (fresh) 16 (R1) 18 (R2) 34 (R3) 40 (R4)
	Reddy et al. (2009d) 63.5 mm diameter shear box, **fresh synthetic MSW** particles were of average size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm, shear strength defined at 15% strain	27-29	16 – 19
	Dixon et al. (2008) 1.0 x 1.0 m shear box, **synthetic MSW**, maximum particle size 120–500mm, shear strength defined at 240 -260 mm	34	0
Field MSW	*Reddy et al. (2009b)* 63.5 mm diameter shear box, **shredded fresh MSW**, maximum particle size 40 mm, shear strength defined at 15% strain	26-30	31-64
	Hossain (2002) 100 mm diameter shear box, **Shredded field MSW**, maximum particle size 50 mm	24 - 32	-
	Caicedo et al. (2002) 900 mm diameter sample, **1 year old unshredded MSW**, shear strength defined at 6.7% strain	23	78
	Pelky et al. (2001) 450mm×305mm shear box, **fresh MSW**	29	0
	Jones et al. (1997) Wykeham 300mm×300mm shear box, disturbed bulk sample, large particles were removed, **3 months old MSW**, shear strength defined at 10% stress	31	10.5
	Gabr and Valero (1995) 63.5 mm diameter shear box, **15 – 30 years old MSW**, shear strength defined at 5 – 10% strain	20 - 39	0 – 28
	Landva and Clark (1990) 434mm×287mm sample dimensions, shredded fresh **MSW** from Edmonton, Canada, shear strength defined at peak stress	24	23

Table 4. Total stress parameters for synthetic MSW and field MSW based on triaxial shear tests

Source	Friction Angle (degrees)	Cohesion (kPa)
Current Research CU tests, 50 mm diameter 100 mm long sample, **fresh to degraded synthetic MSW**, shear strength defined at 15% strain	8 (fresh) 6 (R1) 1 (R2) 9 (R3) 5 (R4)	21 (fresh) 48(R1) 37 (R2) 41(R3) 57 (R4)
Reddy et al (2009d) CU tests, 50 mm diameter 100 mm long sample, **fresh synthetic MSW** particles were of average size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm shear strength defined at 15% strain	6 - 8	19 - 23
Reddy et al. (2009b) CU tests, 50 mm diameter 100 mm long sample, **Shredded field fresh MSW**, maximum particle size 15 -20 mm, shear strength defined at 15% strain	12	32
Gabr and Valero (1995) CU tests, 70.6 mm diameter 152 mm long sample, **15 – 30 years old degraded MSW**, shear strength defined at 15% strain	34	17

Table 5. Effective stress parameters for synthetic MSW and field MSW based on triaxial shear tests

Source	Friction Angle (degrees)	Cohesion (kPa)
Current Research CU tests, 50 mm diameter 100 mm long sample, **fresh to degraded synthetic MSW**, shear strength defined at 15% strain	11 (fresh) 7 (R1) 1 (R2) 10 (R3) 6 (R4)	18 (fresh) 51 (R1) 37 (R2) 43 (R3) 56 (R4)
Reddy et al. (2009b) CU tests, 50 mm diameter 100 mm long sample, **Shredded field fresh MSW**, maximum particle size 15 -20 mm, shear strength defined at 15% strain	16	38
Caicedo et al. (2002) CD tests, 300mm diameter 600mm long, **1 year old unshredded MSW**, shear strength defined at 15% strain	45	14
Vilar and Carvalho (2005) CD tests, 150 – 200 mm diameter 300 – 400 mm long, **15 year old degraded MSW**, shear strength defined at 10% strain	22	20

Figure Captions

Figure 1. Schematic diagram of bioreactor cell

Figure 2. Particle size distribution of synthetic MSW at various phases of biodegradation

Figure 3. Variation of synthetic MSW hydraulic conductivity: (a) with dry unit weight (results from rigid-wall permeameter tests) and (b) with confining pressure (results from flexi wall permeameter tests)

Figure 4. Variation of synthetic MSW hydraulic conductivity with degree of decomposition

Figure 5. Comparison of synthetic MSW hydraulic conductivity with reported field MSW hydraulic conductivity

Figure 6. Compressibility of synthetic MSW

Figure 7. Variation of synthetic MSW compression ratio with degree of decomposition

Figure 8. Variation of synthetic MSW secondary compression ratio with degree of decomposition

Figure 9. Horizontal displacement versus shear stress for (a) fresh synthetic MSW (DOD=0%) and (b) degraded synthetic MSW from R4 Reactor (DOD=86%)

Figure 10. Direct shear test results for synthetic MSW in different degradation phases

Figure 11. Variation of synthetic MSW direct shear strength properties with degree of decomposition

Figure 12. Triaxial CU test results for fresh synthetic MSW (DOD=0%)

Figure 13. Triaxial CU test results for the degraded synthetic MSW from Reactor R4 (DOD=86%)

Figure 14. Total and effective shear strength parameters for fresh and degraded synthetic MSW

Figure 15. Variation of synthetic MSW total shear strength parameters with degree of decomposition
Figure 16. Variation of synthetic MSW effective shear strength parameters with degree of decomposition

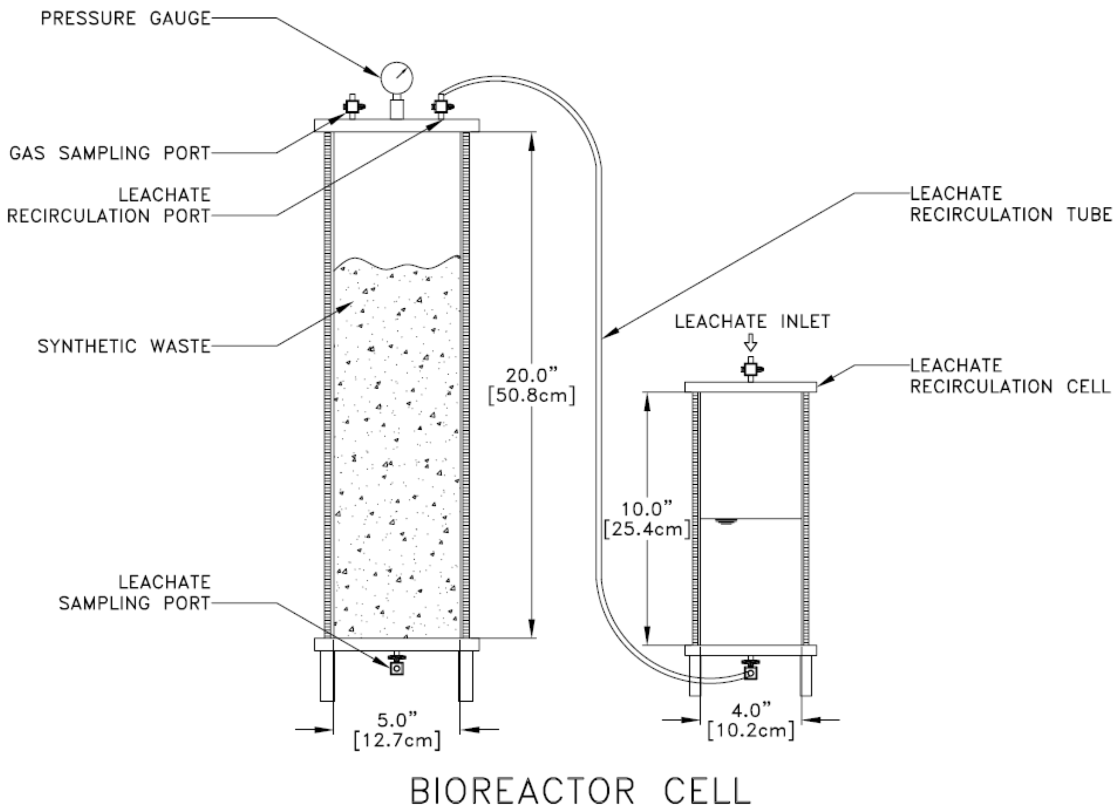


Figure 1. Schematic diagram of bioreactor cell

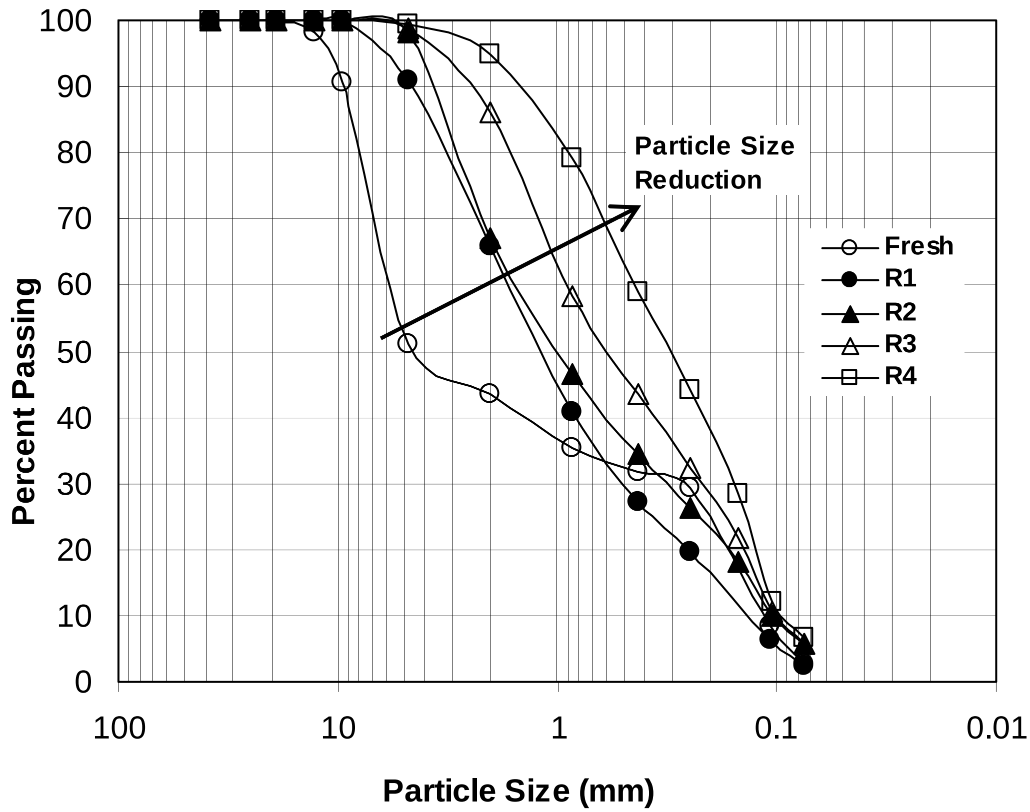
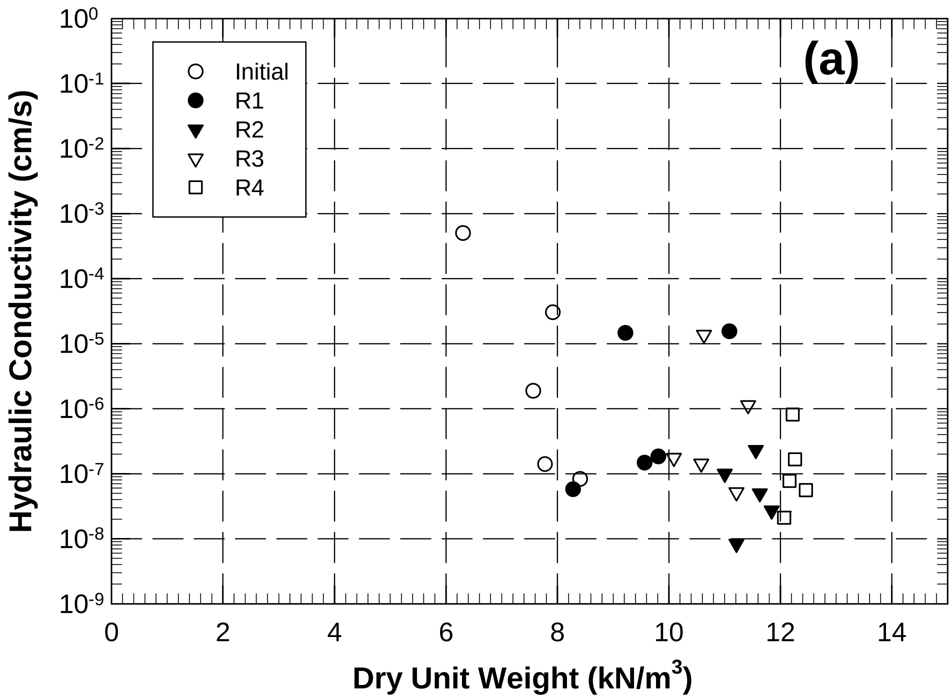


Figure 2. Particle size distribution of synthetic MSW at different phases of biodegradation



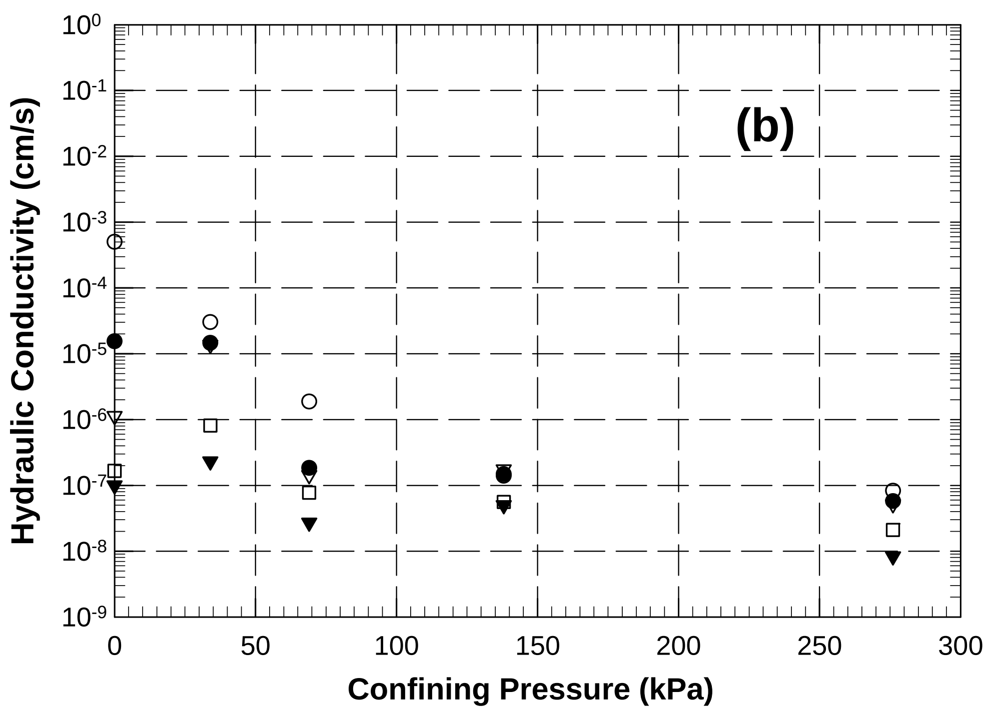


Figure 3. Variation of synthetic MSW hydraulic conductivity (a) with dry unit weight (results from rigid-wall permeameter tests) and (b) with confining pressure (results from flexi-wall permeameter tests)

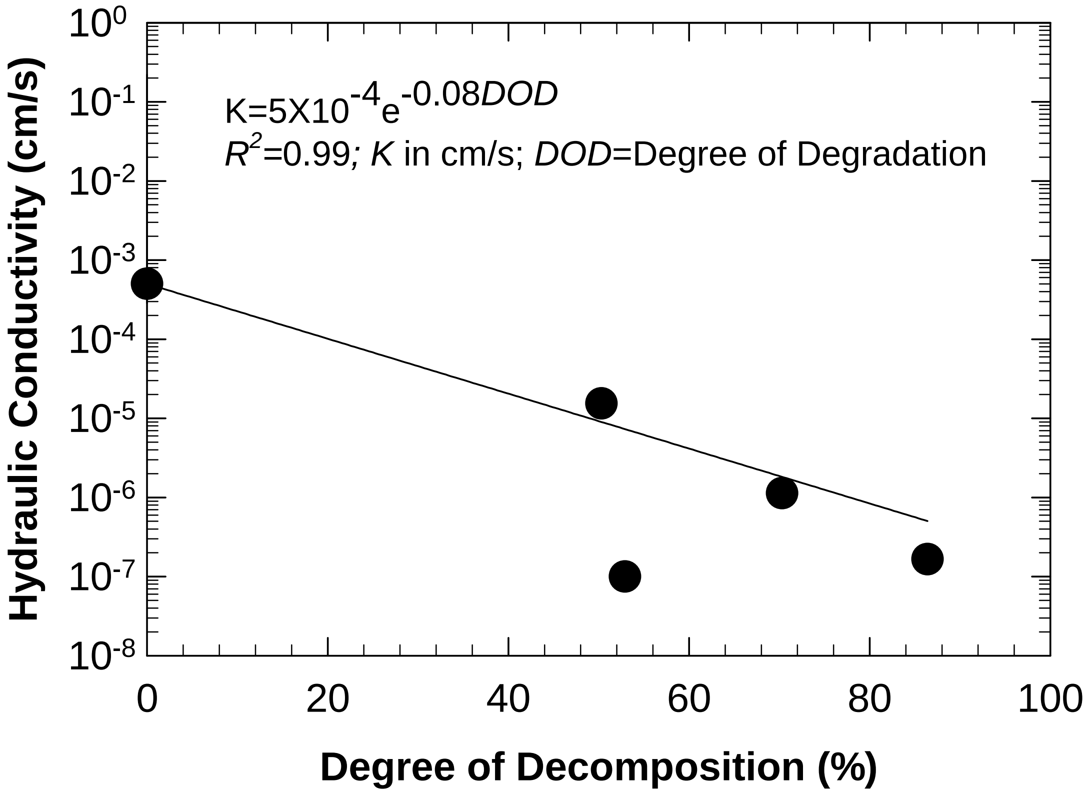


Figure 4. Variation of synthetic MSW hydraulic conductivity with degree of decomposition

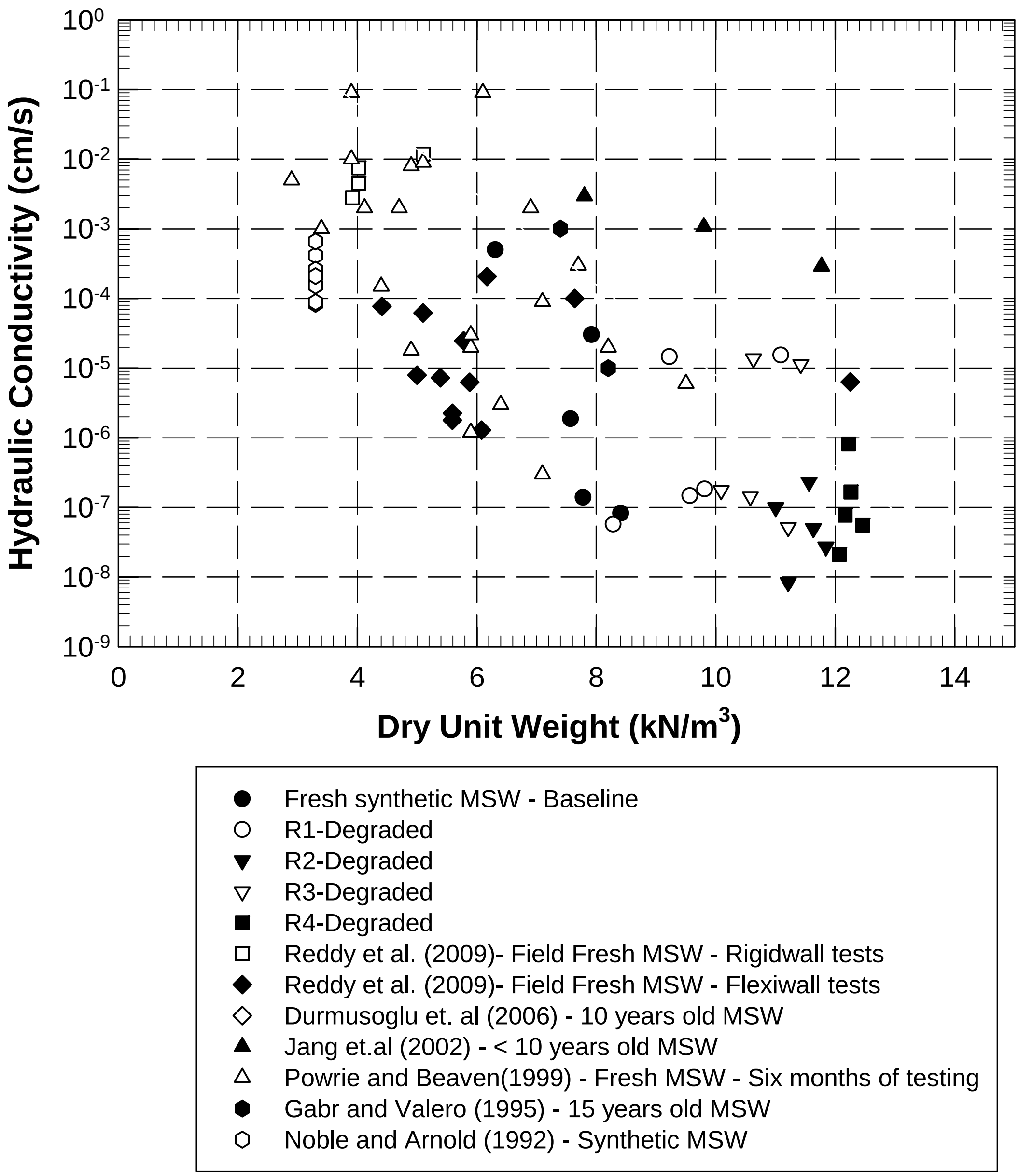


Figure 5. Comparison of synthetic MSW hydraulic conductivity with reported field MSW hydraulic conductivity

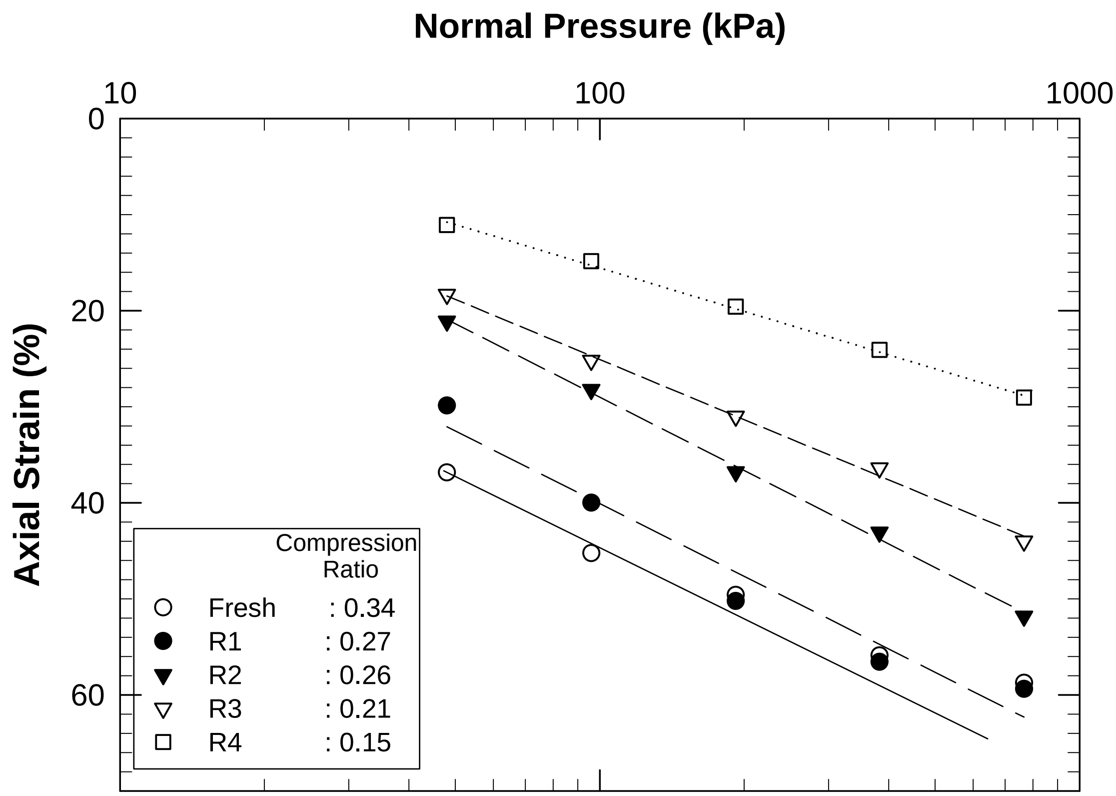


Figure 6. Compressibility of synthetic MSW

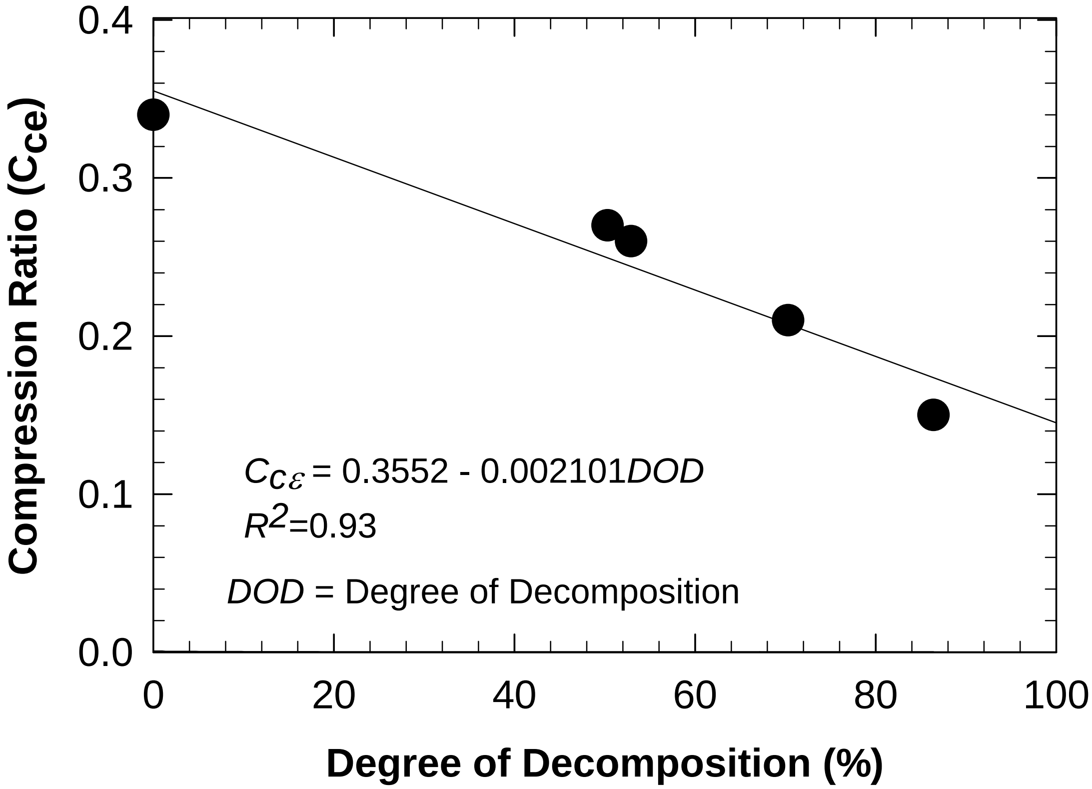


Figure 7. Variation of synthetic MSW compression ratio with degree of decomposition

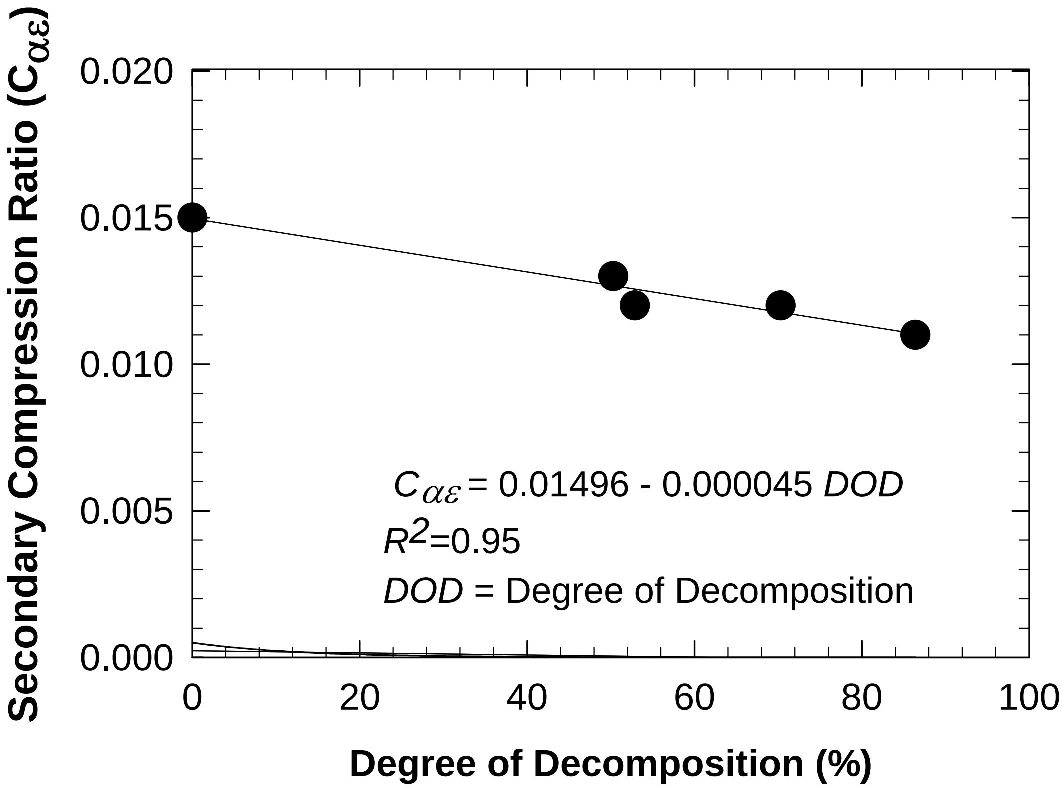


Figure 8. Variation of synthetic MSW secondary compression ratio with degree of decomposition

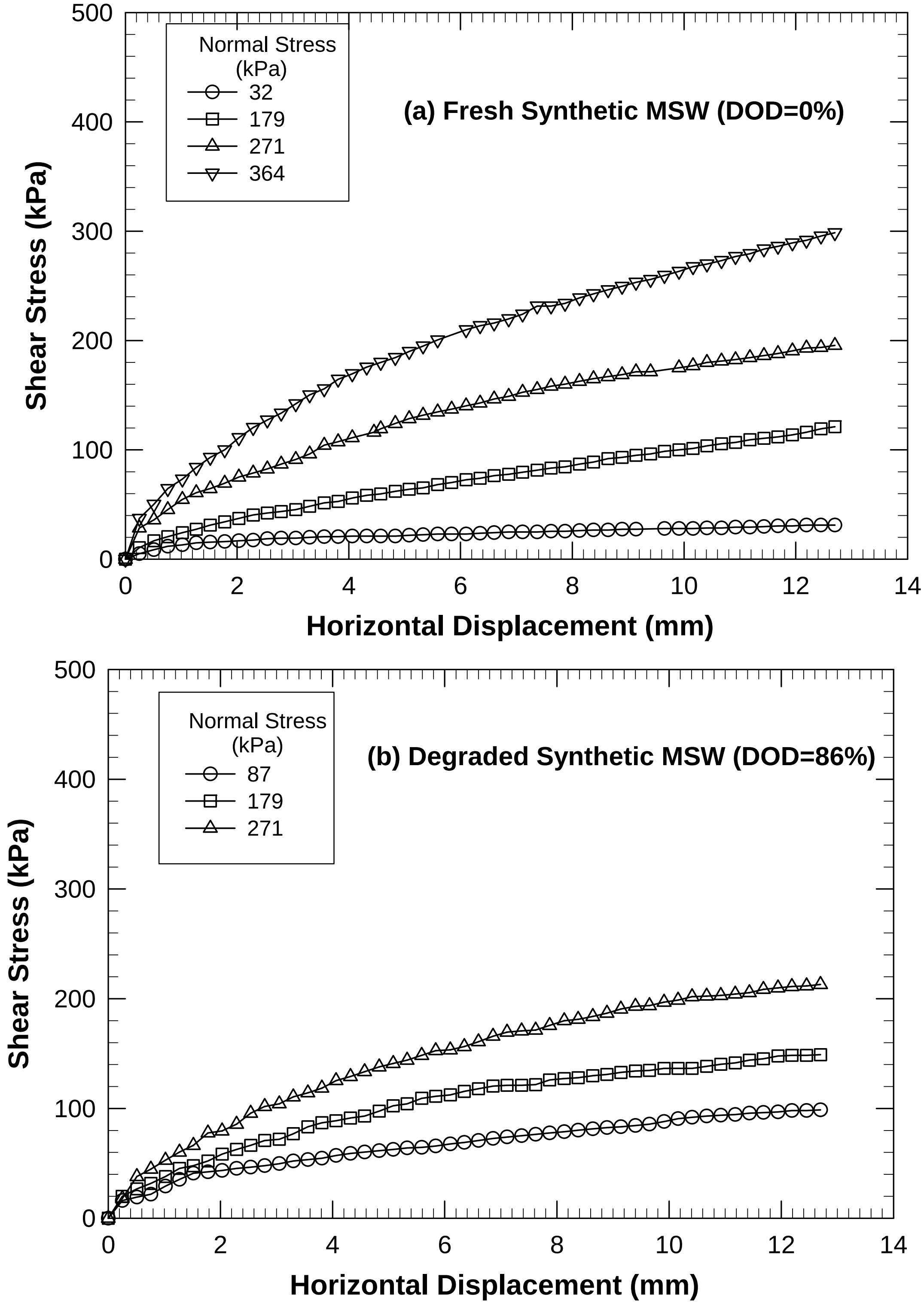


Figure 9. Horizontal displacement versus shear stress for (a) fresh synthetic MSW (DOD=0%) and (b) degraded synthetic MSW from R4 Reactor (DOD=86%)

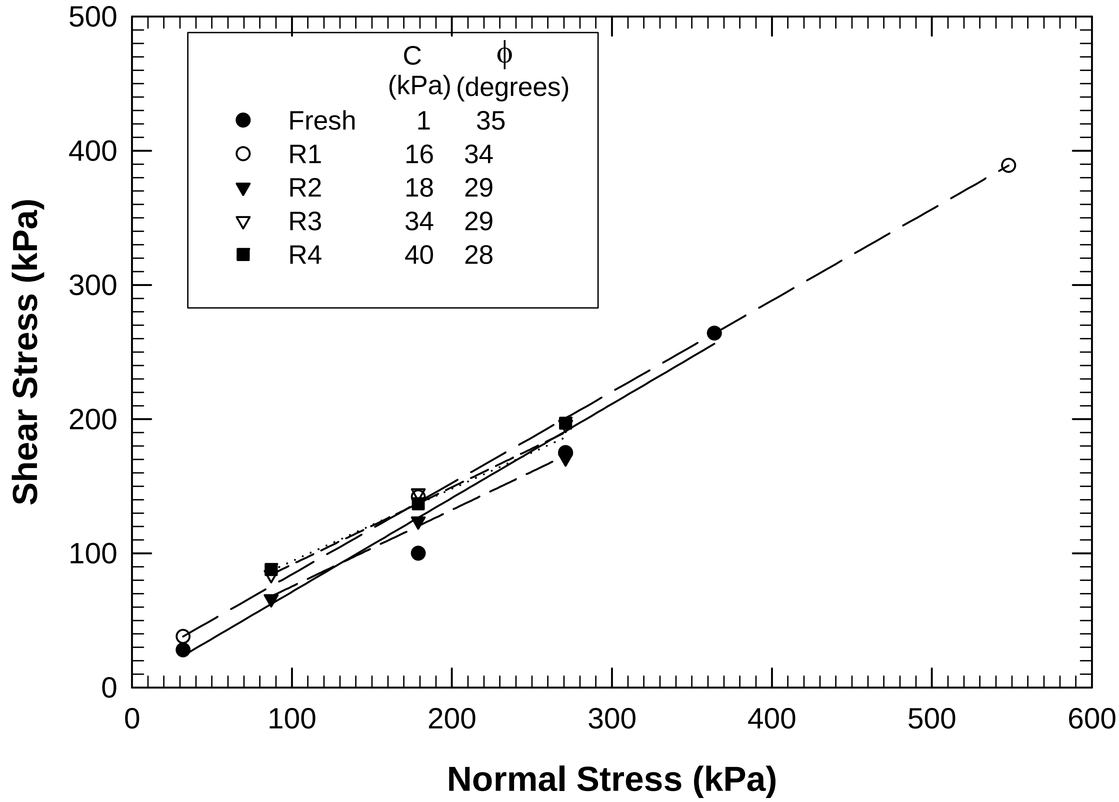


Figure 10. Direct shear test results for synthetic MSW in different degradation phases

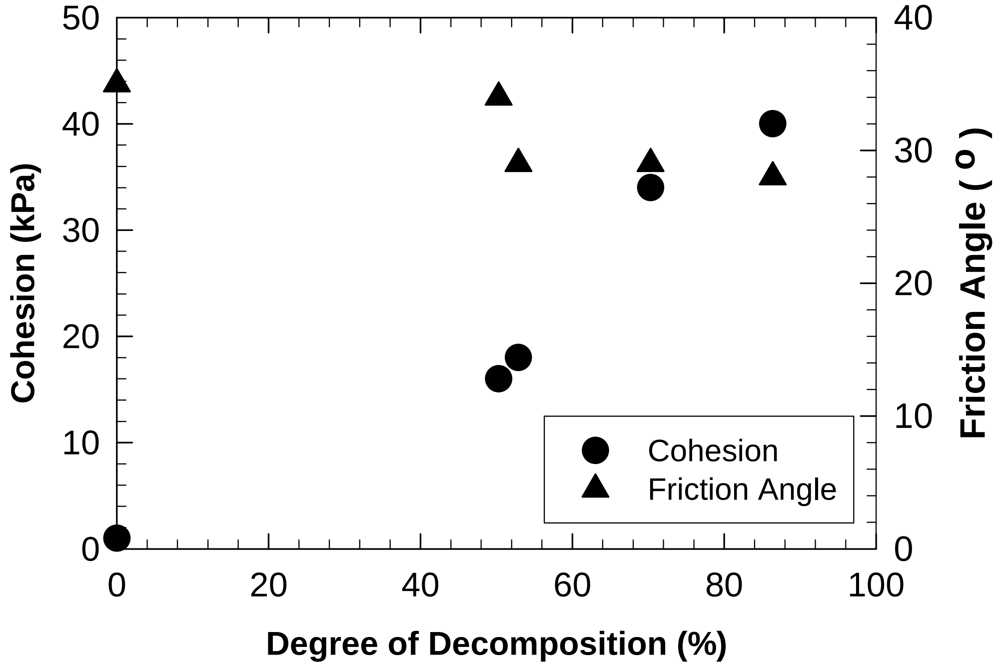


Figure 11. Variation of synthetic MSW direct shear strength properties with degree of decomposition

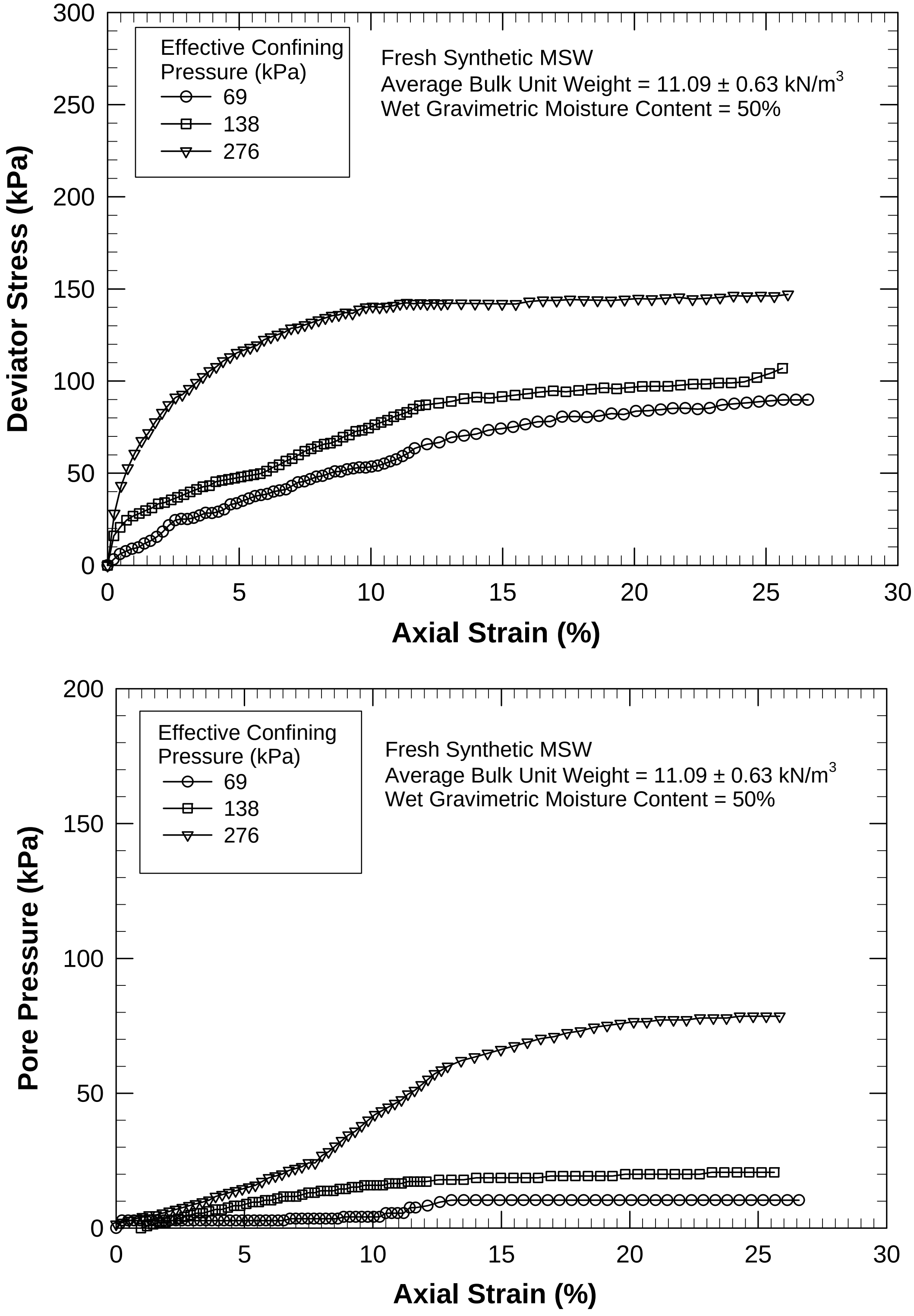
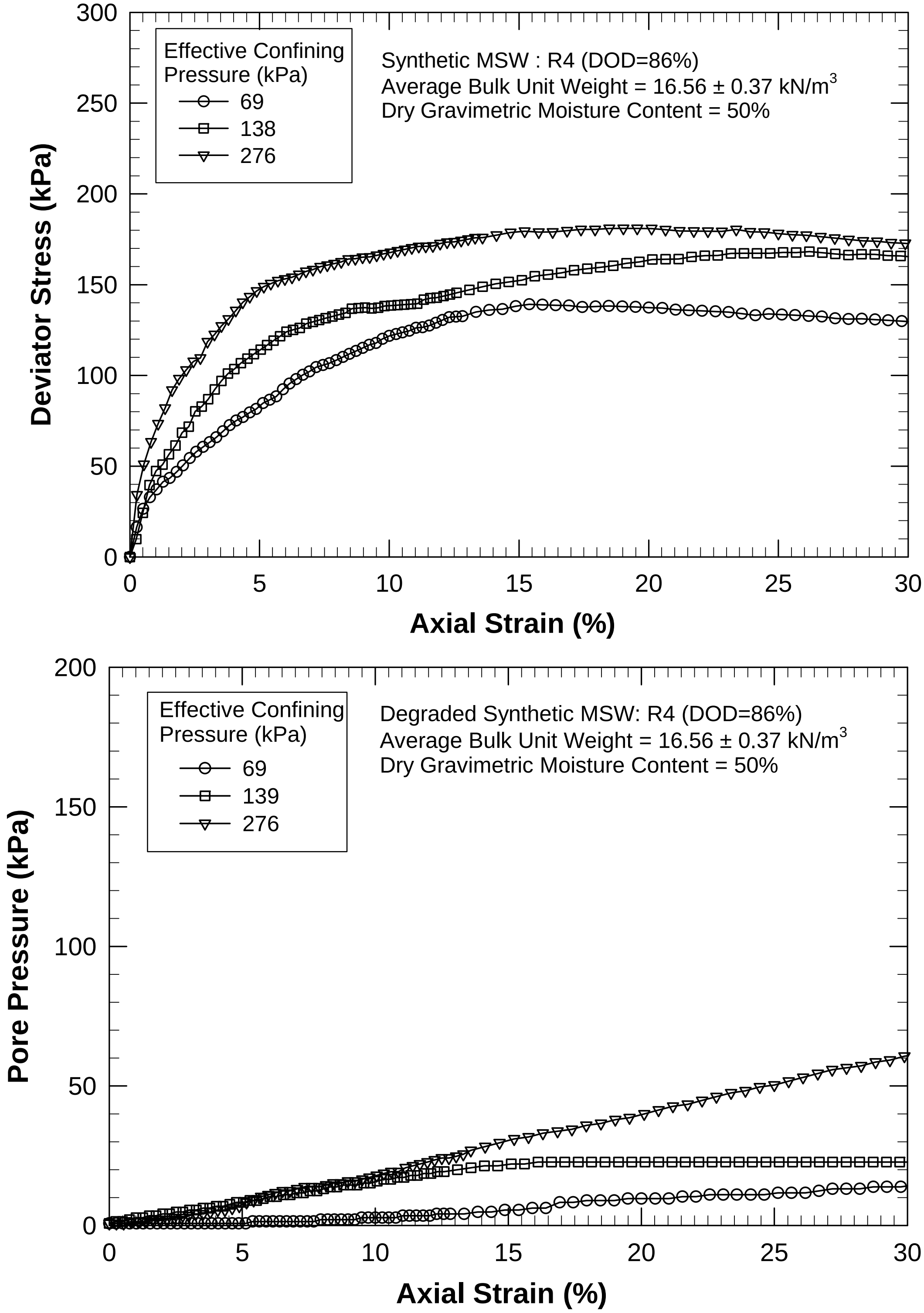
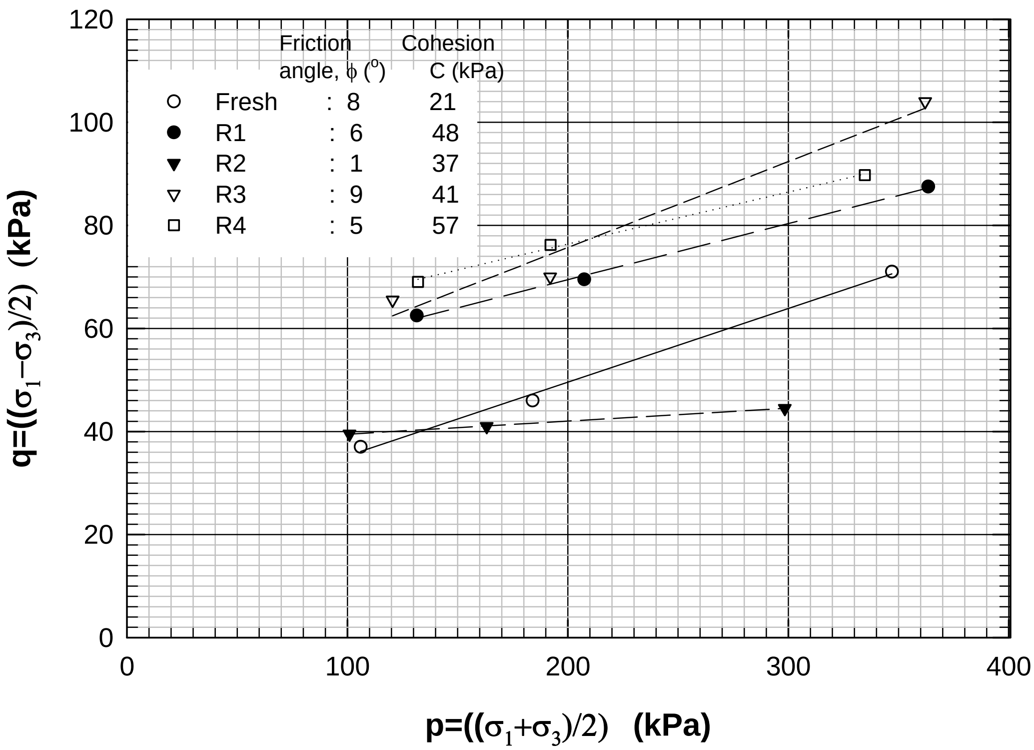


Figure 12. Triaxial CU test results for fresh synthetic MSW (DOD=0%)

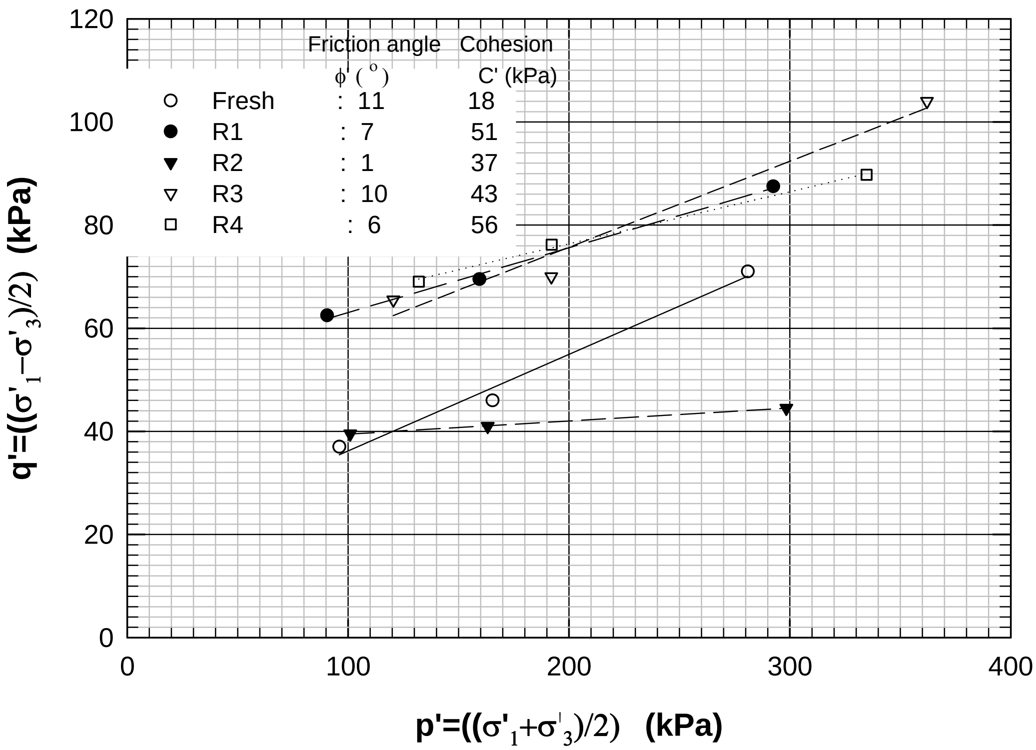


(b)

Figure 13. Triaxial CU test results for the degraded synthetic MSW from Reactor R4 (DOD=86%)



(a) Total Strength Parameters



(b) Effective Strength Parameters

Figure 14. Total and effective shear strength parameters for fresh and degraded synthetic MSW

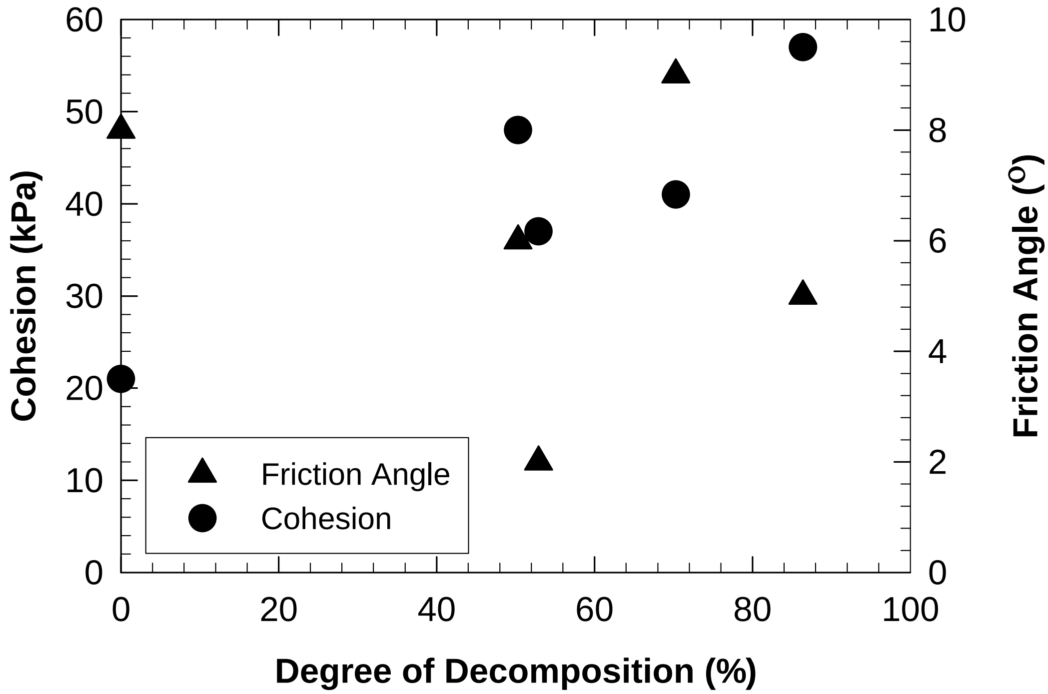


Figure 15. Variation of synthetic MSW total shear strength parameters with degree of decomposition

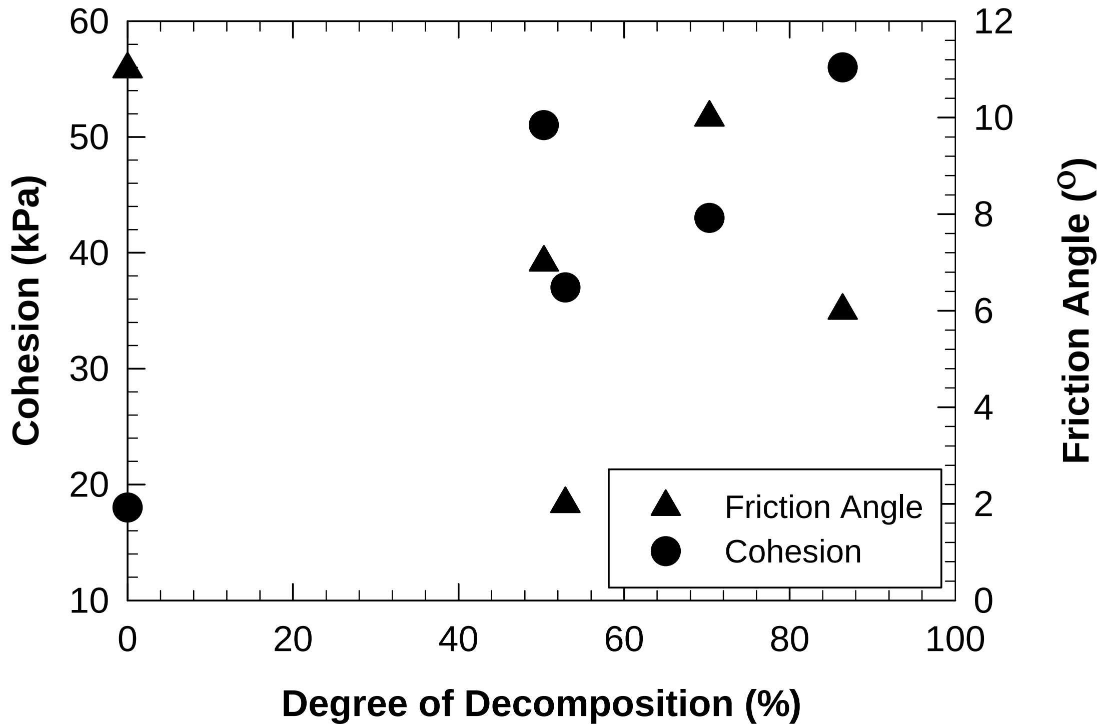


Figure 16. Variation of synthetic MSW effective shear strength parameters with degree of decomposition