# Short-Time Effects on Compressive Strength of Residual Soils Due to Rainwater

Vivi Anggraini[1,2,*], Iskandar Isdaryanto[3], Muhammad Imran Mohamad Illiayas[1] and Emmanuella Stephanie[1]

[1]*Civil Engineering Discipline, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, Bandar Sunway 47500, Selangor Darul Ehsan, Malaysia*

[2]*Engineer Profession Program, Atma Jaya Catholic University, Jakarta, Indonesia. Jl. Jenderal Sudirman No.51, Daerah Khusus Ibukota Jakarta 12930, Indonesia*

[3]*Engineering Faculty, Atma Jaya Catholic University of Indonesia, Jl. Jenderal Sudirman No.51, Daerah Khusus Ibukota Jakarta 12930, Indonesia*

**Abstract:** The short-term effects of acid rain on the geotechnical properties of residual soil were investigated. Artificial acid rain (AAR) of pH values 2, 4 and 6 was created with an infiltration setup to replicate the interaction between acid rain and soil. The soil specimens were infiltrated with AAR for durations of 30mins and 60mins for each pH level of 2, 4 and 6 and a control sample using deionised water of pH 7.5. Unconfined compression test (UCS) and Atterberg limits test were performed on the treated samples to study the mechanical behaviour and the characteristics of the soil once contaminated with AAR. The results revealed that reducing the pH value of AAR led to a reduction in compressive strength and Young's modulus and an increment in liquid limit while the plastic limit remained unchanged. The reduction in compressive strength due to acid rain was observed to be almost halved when the bulk unit weight of the soil was increased for the same infiltration period.

**Keywords:** Residual soils, Rainwater, Acid rain.

## 1. INTRODUCTION

Rapid urbanisation and industrialisation in developing countries have given rise to the occurrence of acid rain, with Malaysia beginning to experience its adverse effects [1]. The effects of acid rain have increased dramatically, particularly in industrialised countries, with it being a major local ecological issue, thus stimulating a global concern [2]. The occurrence of acid rain can be attributed mainly to human activities such as the combustion of fossil fuels in power plants, waste burning, and exhaust fumes from automobile usage [3]. It could also originate from natural sources such as volcano emissions, forest fires, and microbial processes [4]. Acidic deposition stems from air pollution, with its major sources being sulphur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) [5]. These oxides react with rainwater to form precipitations of low pH values.

With the increasing pattern of acidic deposition globally, research studies have been conducted to study the ramifications of acid rain on the engineering properties of soil. Physical and chemical changes to the soil were reported, notably concerning the compressive strength and Atterberg limits. A study [6] reported that the chemical properties of the medium affect the mechanical performance of the soil significantly. The dissolution of calcium carbonates caused by acidic fluids also produced "loose" structures with increased voids and greater compressibility due to the destruction of carbonate bonds between clay particles/aggregates [7]. A study [8] showed that the structural composition of organic matter was altered due to soil acidification.

The physicochemical properties of the soil need to be understood to understand how the compressive strength of the soil is altered after acid rain infiltration. Iron oxide holds the soil particles together in natural conditions [9]. Significant changes in mineral structure might also occur due to the dissolution of alumina and silica from soil [7, 10] reported that acidic solutions solved calcium carbonate and broke carbonatic bonds between clay particles in a study that infiltrated hydrogen chloride into the clay from the Osaka Bay. The results from a study [11] showed that a low pH reduced the strength of residual sedimentary soil (SRS) and residual igneous soil (IRS) specimens and also that the strength loss continued as the fluxes of the AAR increased from 1 year to 20 years. Similar findings were also found when primary and secondary kaolinite clays were used instead (PK and SK) [12].

*Address correspondence to this author at the Civil Engineering Discipline, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, Bandar Sunway 47500, Selangor Darul Ehsan, Malaysia;
Tel: +603 55159697; E-mail: vivi.anggraini@monash.edu

E-ISSN: 2410-4701/22 

A study [13] reported that the compressive strength of laterite was reduced when soaked in an acidic medium, with the iron content showing a significant decrement of 11.52% at the end of the soaking period. The reduction in iron content may suggest the destruction of the aggregate structure, contributing to the loss in compressive strength. Another study [11] reported that the SRS samples became more brittle with a lower compressive strength due to decreased pH levels and increased AAR infiltration periods. Similar stress-strain relationships were reported in IRS samples and primary and secondary kaolinite clays. The soil fabric was said to be destroyed due to the decrease in the aluminium and iron contents, thus reducing the shear strength. The reduction in the concentration of elements and the loose structure for both soils due to the influence of AAR was confirmed through a scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX) analysis [11].

Similar factors that caused a reduction in compressive strength were believed to cause an increase in the Atterberg limits. A study [14] reported that due to the dissolution of calcium carbonate, a correlation was evident between the decrease in pH with the increases in compression indices, the liquid limit (LL), and the plasticity index (PI) of soil. Another study [15] also showed that the Atterberg limits and soil permeability increased as the acidity and alkalinity of artificial rain increased. Black cotton soil followed by kaolin clay and bentonite, exhibited severe morphological changes when polluted with acids [16]. Another study [17] also stated that 'an increase in the sensitivity ratio and in the liquid limit (LL) was detected when alluvial clay was soaked in the higher acid rain'. An article [12] reported that the Atterberg limits of PK and SK soils decreased as the pH value reduced and the infiltration period increased. Similar patterns were also observed in the Atterberg limits when SRS and IRS soils were used [11]. A reduction in the zeta potential of both minerals was observed as a result of the simulated acid rain, causing changes to the Atterberg limits [12].

A study [18] on the effect of pore water pH on the mechanical properties of clay soil concluded that the presence of acid would break cementing agents between the clay particles and enlarge the size of voids within the soil, therefore, increasing the LL of clay. Another study [19] reported that the addition of acid into kaolinite increases the liquid limit but leaves the plastic limit markedly unchanged, thus increasing the plasticity index of the soil. Soaking laterite in an acidic solution also increased the liquid limit and a small change in the plastic limit, causing the plasticity index to increase [13]. A study [20] to investigate the effect of pH on the Atterberg limits of kaolinitic and montmorillonite clay showed that the liquid limit increased when the pH decreased as well as with an increase in the curing period citing that the soil particles experienced flocculation in the acidic range.

In Malaysia, most of the acidic chemicals in the air fall to the ground in the form of wet deposition [11]. The average annual rainfall is within the range of 1500 mm to over 2400 mm, whereas in inland areas and coastal areas, it is 2750 mm and 1750 mm respectively [21]. A rising trend in rain acidity was also shown by a study by Zabawi *et al*. in 2008 [22], particularly in areas such as Kuala Lumpur, Klang Valley, Pulau Pinang, Perai, Johor Bahru, and Senai. Compared to 1990, there is an increasing risk of acidification in 2050 in extended regions of southern and eastern Asia as well as parts of southern Africa [23]. Studies by Ayers *et al*. in 2002 [1] using rainwater samples from five major sites in Malaysia confirmed that potentially noteworthy levels of acid rain occur in Malaysia due to urban and industrial activities. This study [1] also stated that annual pH values in the range 4.16-4.40 and estimated total deposition fluxes of acidic sulphur and nitrogen species in the range 120-350 meq m-2yr-1 show all sites to be impacted significantly by acidic deposition. Another study [24] reported that the total acid deposition fluxes obtained from Petaling Jaya, Malaysia, from March 1993 to March 1998 were at levels that would have prompted emissions reduction programs in Europe and North America. An analysis of the status of acid deposition in Malaysia based on Malaysian Meteorological Department (MMD) data conducted by Mohamad *et al*. in 2010 [25] showed that in the year 2008, most states in Malaysia recorded unhealthy levels of rain acidity particularly in Selangor and its neighbouring states. Ibrahim *et al*. in 2019 conducted a study [26] using Inverse Weight Distance (IDW) to analyse acid rain data in accordance with standards set by the Malaysian Meteorological Department. The pattern of acid rain distribution for three days during working and non-working days was analysed in Rawang and it was found that the lowest pH value of 3.98 was recorded on a working day and at the station where many chemical-based industries are located, reaffirming the statement that industrialisation is a major driver of acid rain.

Based on the literature above, it is evident that there is an increasing concern about the effects of acid rain on the engineering properties of soil. Due to the unique properties of the host soil and pore fluid, further research is needed to explore the extent to which acid rain can adversely influence the geotechnical properties of natural soils and how it may contribute towards slope failure. Therefore, this study aims to investigate the short-term effects of acid rain on the compressive strength of residual soil. The effects of a change in the bulk density on the compressibility of acid rain-infiltrated soil will also be studied to gain a deeper insight into the influence of compaction towards the degree of compressive strength deterioration caused by acid rain for a predetermined infiltration period.

## 2. EXPERIMENTAL

### 2.1. Soil Properties

The soil used in this study was obtained from Bukit Antarabangsa, Selangor, Malaysia (3.1862° North and 101.7704° East). Bukit Antarabangsa sits within the landslide-prone region of Ulu Klang whereby a prominent landslide occurred in 2008 which resulted in casualties and heavy damages [27]. The residual soil from this location was chosen due to the historical records of slope failure incidents that make Bukit Antarabangsa a critical area that is highly susceptible to acid rain-induced slope failure, therefore, warranting urgent remedial and corrective measures if acid rain is a reason for concern to prevent a recurrence of the 2008 fatal landslide. The basic engineering properties of the soil are outlined in Table **1**. According to the unified soil classification system (USCS), the soil is classified as silty clay of low plasticity (CL). The particle size distribution of the residual soil is shown in Figure **1**.

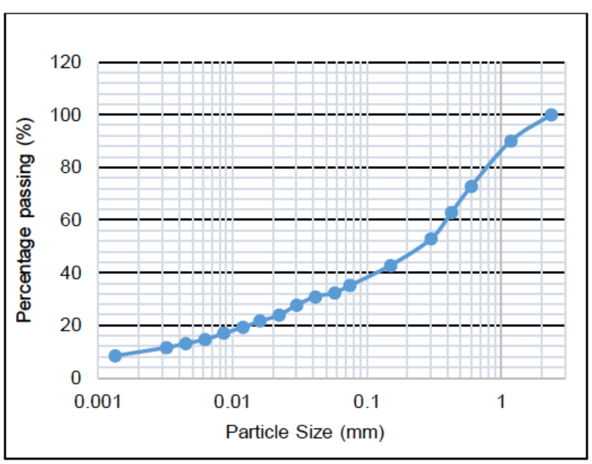


**Figure 1:** Particle size distribution of residual soils.

**Table 1: Physical Properties of Residual Soil**

| Physical Property | Value | Standard |
|---|---|---|
| Natural moisture content (%) | 12.41 | BS 1377-2 |
| Atterberg limits | | BS 1377-2 |
| Liquid limit (LL) (%) | 35.49 | |
| Plastic limit (PL) (%) | 24.40 | |
| Plasticity index (PI) (%) | 11.09 | |
| Specific gracity | 2.69 | BS 1377-2 |
| Particle size distribution | | USCS |
| Gravel (%) | 0 | |
| Sand (%) | 65 | |
| Silt (%) | 10 | |
| Clay (%) | 25 | |

### 2.2. AAR Preparation

Artificial acid rain (AAR) was prepared by adjusting the sulphuric acid concentration of 0.5M with deionised water. AAR with pH values of 2, 4 and 6 were produced to replicate a range of high to mild acidic rain. A pH meter was used to achieve the desired AAR of pH values 2, 4, and 6.

### 2.3. Atterberg Limits Test

Atterberg limits tests were conducted using the prepared AAR of pH values 2, 4 and 6. Oven-dried soil was passed through a 425µm test sieve, and the sieved soil was mixed with the AAR. The Atterberg limits were then determined as per BS 1377-2 of the British Standards.

### 2.4. Soil Sample Preparation

Natural soil was oven-dried and passed through a 4.5mm test sieve. For each test specimen, 500g of sieved soil was mixed to an optimum moisture content of 18%. The soil was then compacted in 3 layers (5 blows per layer from 30cm height) using a 2.5kg rammer in a steel mould to produce a cylindrical soil sample of size 10cm and diameter 5cm to achieve the desired maximum density of the soil as per BS1377-4. The soil sample was subsequently extruded from the mould using a hand-operated hydraulic specimen extruder with its mass measured to determine the bulk unit weight. The bulk unit weight of the soil samples was maintained at approximately 17.5 kN/m$^3$ to ensure that the infiltration of AAR follows a similar rate in each sample. A study [28] stated that the typical bulk unit weight of Malaysian residual soils is within the range of 15 to 23 kN/m$^3$ with another study [29] reporting that the mean value is approximately 17.3 kN/m$^3$, therefore, justifying the usage of 17.5 kN/m$^3$ in this study.

### 2.5. Varying Density of Soil Sample

Another set of soil samples was prepared with a bulk unit weight of 20 kN/m$^3$ to study the effects of soil compaction on the infiltration rate of AAR. To achieve the specified bulk unit weight, the soil was compacted with 25 blows per layer from a height of 30 cm using the same 2.5kg rammer to produce cylindrical soil samples of height 10cm and diameter 5cm.

### 2.6. Infiltration Setup


**Figure 2:** Latex membrane and membrane stretcher.

**Figure 3:** Infiltration setup.

An infiltration setup was produced to replicate the interaction between acid rain and soil. Triaxial test accessories such as latex membranes and a membrane stretcher (Figure **2**) provided a simple yet effective method of encasing the soil samples without damaging their surface. The membrane acts as a waterproof medium where the AAR can percolate through the soil sample. A vacuum pump was connected to the membrane stretcher to expand the latex membrane such that the soil sample could be placed into the membrane undamaged. The pinch valve of the membrane stretcher was then released to enable the membrane to enclose the sample. The enclosed soil sample was removed from the membrane stretcher and placed on a perforated PVC end cap, as shown in Figure **3**.

AAR was poured on the soil column, and a constant ponding depth of 1cm was ensured throughout the infiltration period. The test was performed for infiltration durations of 30mins and 60mins for each pH level of 2, 4 and 6 as well as for a control sample using deionised water of pH 7.5. The infiltration periods were chosen to simulate heavy rainfall events where the rainfall intensity is higher than the infiltration capacity of the soil in which there is ponding of rainwater on top of the soil that lasts for 30mins and 60mins [30]. To ensure sustained percolation of water into the soil column, a ponding depth of 1cm was chosen, as suggested by a study [30]. The soil columns were left to air dry for 24 hours after the infiltration period. Due to time constraints caused by the Covid-19 pandemic, tests were conducted on the samples of bulk density 20 kN/m$^3$ only for the 60min infiltration period for pH 2, 4, 6 and the control sample.

### 2.6. Unconfined Compressive Strength (UCS) Test

After being air-dried for 24 hours, the cured soil samples were removed from the latex membrane using the membrane stretcher. Unconfined compressive strength (UCS) tests were performed on the treated samples for infiltration durations of 30mins and 60mins at varying pH levels of 2, 4, 6 and 7.5. The measurement of UCS for each sample was conducted by BS1377-7 of the British Standards. An Instron 5966 strength testing machine was utilised to perform the UCS tests by applying a strain rate of 1% per minute to each soil specimen until it failed. The stress-strain graph was generated for each sample along with key parameters such as the maximum compressive stress, maximum load and maximum compressive strain.

## 3. RESULTS AND DISCUSSION

### 3.1. Atterberg Limits

Table **2** summarises the Atterberg limits of the soil using AAR of pH values 2, 4, 6 and 7.5. The results demonstrated significant changes with regard to the LL as the pH value was altered. The LL was observed to increase as the pH of AAR became more acidic (Figure **4**). The LL of 35.49% in deionised water rose incrementally to the highest LL value of 49.73% obtained in pH 2. There were, however only small changes in the plastic limit as the pH value decreased, therefore, increasing the plasticity index as the soil is subjected to AAR of higher acidity (Figure **4**). The plasticity index of soil represents the responsiveness of the soil to moisture content changes to gauge its plasticity [31]. The increase in PI of the residual soil indicates that the infiltrated AAR has made the soil more moisture sensitive and that the effects of plasticity are amplified as the pH decreases.

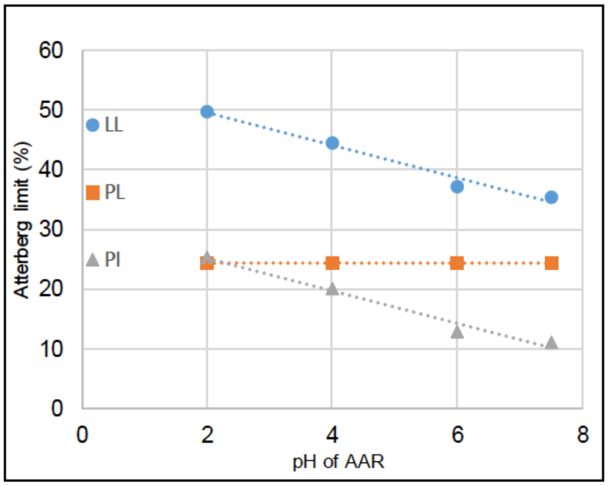


**Figure 4:** Atterberg limits of soil for AAR of different pH values.

**Table 2: Atterberg Limits of Soil for AAR of Different pH Values**

| Atterberg Limits | | | | |
|---|---|---|---|---|
| pH | 2 | 4 | 6 | 7.5 |
| Liquid limit (LL) (%) | 49.73 | 44.52 | 37.24 | 35.49 |
| Plastic limit (PL) (%) | 24.41 | 24.39 | 24.37 | 24.40 |
| Plasticity index (PI) (%) | 25.32 | 20.13 | 12.87 | 11.09 |

The results are consistent with findings from the reviewed literature on acid-induced soil properties that reported similar LL and PL patterns as the pH value decreased. The increase in LL can be attributed to flocculation experienced by the soil particles due to the acidic medium [20, 32], inferred that the breakdown of aggregates caused the increase in the liquid limit as a result of leaching. Soil particles tend to disintegrate with the addition of water or a solution resulting in the specific surface area increasing and further leading to high water adsorption, resulting in increased LL values [13]. The dissolution of calcium carbonates due to the AAR can also be another contributing factor to the results that were obtained. Cemented agents between clay aggregates were found to break down when natural clays were placed in an acidic medium [33]. The enlargement of voids caused by the broken cementing agents, therefore, increases the LL of the soil [18].

### 3.2. Unconfined Compressive Strength

Table **3** shows the UCS test results for all three sets of pH 2, 4, 6 and the control sample (W). The soil samples infiltrated with an AAR of pH 2 demonstrated the lowest UCS in each set of samples, and the UCS was observed to decrease as the pH reduced (Figure **8**). Young's modulus was obtained from the slope of the stress-strain curve in the elastic region to gauge the stiffness of the soil when subjected to compression. The results revealed a decrement in Young's modulus

**Table 3: UCS Test Results**

| 5 blows with 18% OMC for 30mins infiltration period | | | | |
|---|---|---|---|---|
| pH | 2 | 4 | 6 | 7.5 |
| UCS (kPa) | 24.86 | 27.02 | 47.09 | 91.35 |
| Load (N) | 48.82 | 53.05 | 92.45 | 179.37 |
| Strain at UCS (%) | 4.42 | 3.56 | 4.09 | 4.31 |
| Young's Modulus (kPa) | 7.50 | 10.00 | 13.00 | 21.50 |
| **5 blows with 18% OMC for 60mins infiltration period** | | | | |
| pH | 2 | 4 | 6 | 7.5 |
| UCS (kPa) | 24.39 | 25.45 | 32.65 | 87.92 |
| Load (N) | 47.88 | 49.96 | 64.10 | 172.63 |
| Strain at UCS (%) | 5.26 | 5.41 | 4.09 | 5.27 |
| Young's Modulus (kPa) | 5.50 | 6.00 | 6.50 | 13.33 |
| **25 blows with 18% OMC for 60mins infiltration period** | | | | |
| pH | 2 | 4 | 6 | 7.5 |
| UCS (kPa) | 88.07 | 92.05 | 98.62 | 141.58 |
| Load (N) | 173.73 | 180.76 | 193.65 | 277.98 |
| Strain at UCS (%) | 7.53 | 5.89 | 6.81 | 5.30 |
| Young's Modulus (kPa) | 9.09 | 11.50 | 14.55 | 25.00 |

as the pH of the AAR decreased, with all three sets of samples demonstrating a reduction in stiffness of within 60 to 65% from pH 7.5 to pH 2. The increase in the infiltration period from 30mins to 60mins was also observed to further decrease the modulus of elasticity of the samples with a similar bulk unit weight of 17.5 kN/m$^3$. A similar 'yield plateau regime without any significant changes in stress was observed in the samples infiltrated with water and in all the samples compacted with 25 blows per layer [34].

The plateau may indicate that the soil structure is deforming with additional straining, causing the stress to increase and finally reach its peak value. The absence of a plateau in samples of bulk unit weight 17.5 kN/m$^3$ infiltrated with AAR may indicate that the presence of acid destroys the soil structure beyond which there is no increase in stress, and the soil immediately fails.

Figure **5** shows the stress-strain relationship between samples of similar bulk unit weight (17.5 kN/m$^3$) infiltrated with AAR of similar pH but different infiltration periods. A similar stress-strain curve shape was observed despite changes to the infiltration time for each pH value. However, the figures also revealed that the samples infiltrated with the longer period of 60mins reached a lower peak value and that the strain when the curve reached its peak was higher as compared to the same sample infiltrated for 30mins suggesting increased compressibility. This relationship was also apparent for the control sample of deionised water as shown in Figure **5**. When comparing the results of samples of bulk density 17.5 kN/m$^3$ (5 blows), it was observed that the samples infiltrated with AAR for 60mins resulted in a lower UCS for all pH values indicating that the strength of the soil continues to deteriorate as the infiltration duration lengthens.

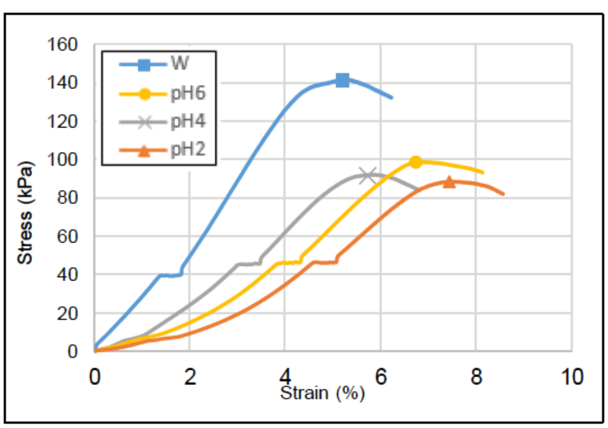


**Figure 5:** Stress-strain graph of soil samples compacted with 25 blows and 60min infiltration time.

These findings are in agreement with the reviewed literature that reported similar results showing a decrease in the strength of soil as the pH decreased and as the period of infiltration increased. The AAR has solved calcium carbonates and broke carbonatic bonds between clay particles making the soil structure more brittle and 'loose' with increased voids [7]. Some studies [11, 12] also suggested that most of the minerals might have leached out due to the effects of AAR and significantly changed the mineral structure, therefore, reducing the mechanical strength of the soil. A reduction in iron content may have occurred as the soil is retained in an acidic medium, causing the aggregate structure within the soil to collapse [13]. The leaching out of iron, specifically $Fe^{3+}$ ions, is due to the strong oxidation nature of sulphuric acid that contains electron donor ions such as $NO_3^-$ and $SO_4^{2-}$ that convert $Fe^{2+}$ to $Fe^{3+}$ [11,12].

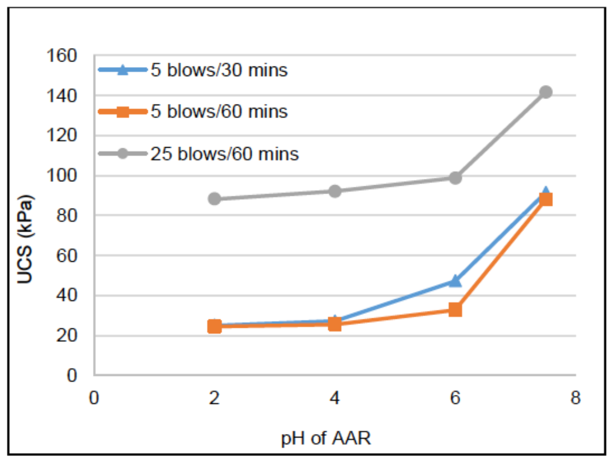


**Figure 6:** UCS values recorded for each AAR pH value in all three sets of samples.

### 3.3. Effects of Change in Bulk Unit Weight

As illustrated in Figure **7a** and **7b**, a significantly higher peak compressive strength value was achieved when the bulk unit weight of the soil increased from 17.5 kN/m$^3$ to 20 kN/m$^3$ for all pH values. When comparing the usage of deionised water with the most acidic AAR of pH 2, the percentage reduction in UCS between the set of samples of bulk density 17.5 kN/m$^3$ and 20 kN/m$^3$ for an infiltration period of 60mins is 72.2% and 37.79% respectively. This can be attributed to the smaller number of voids within the soil structure and the reduction in infiltration rate due to increased compaction. The soil structure is destroyed due to soil compaction resulting in a larger soil structure with lesser natural voids [35]. Macropores, integral for the movement of water and air in the soil, are reduced as the bulk density increases, further impeding the

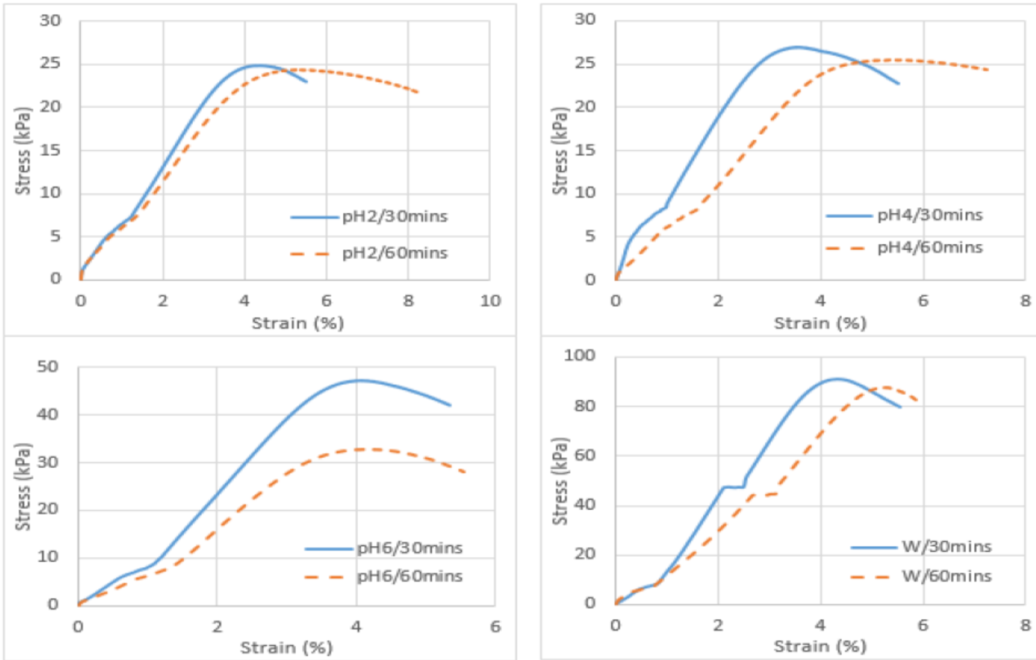


**Figure 7a:** Stress-strain behaviour of soil samples in different infiltration times for each AAR pH value (5 blows).

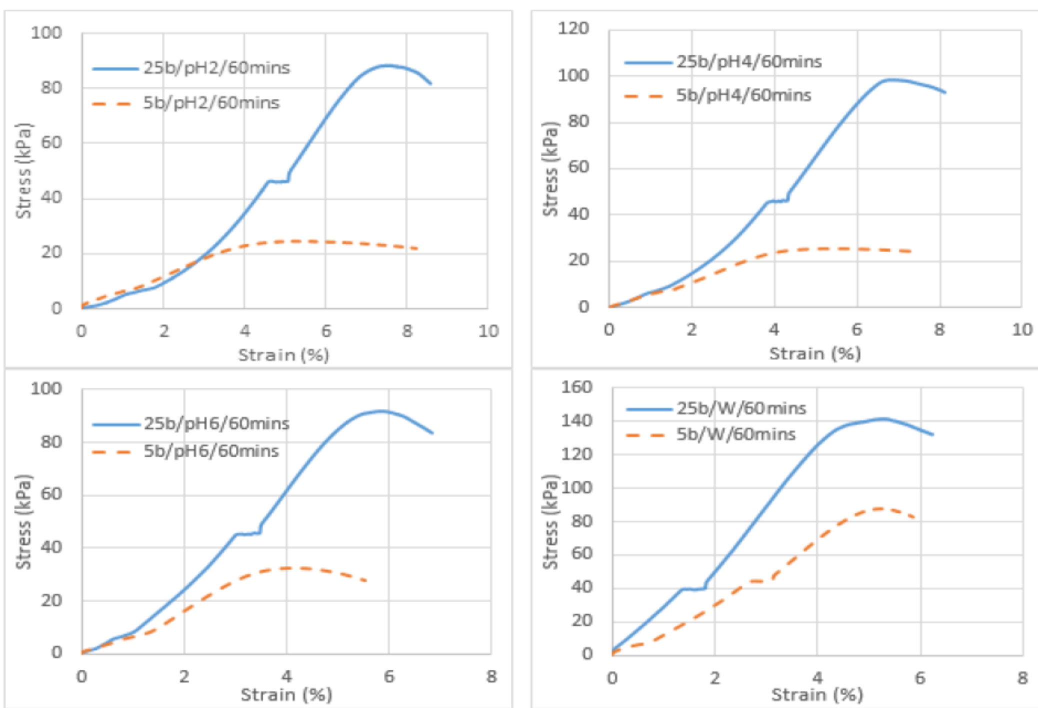


**Figure 7b:** Stress-strain behaviour of soil samples of different bulk unit weight for each AAR pH value (60mins).

penetration of AAR through the soil column. Studies conducted by Gregory *et al*. in 2006 [36] also showed that a low level of compaction could significantly reduce infiltration rates in soils, with decrements of up to 70 to 99% being reported. Additionally, the increase in bulk unit weight resulted in higher modulus of elasticity values indicating that the stiffness of the soil samples improved with increased compaction. As aforementioned, the presence of a plateau regime (Figure **7**) in the stress-strain curve of the samples of bulk unit weight 20 kN/m$^3$ for all pH values also suggests increased mechanical strength due to increased density.

### 3.4. Soil Samples Failure Pattern

Two distinct failure patterns were observed when comparing the set of samples of bulk density 17.5 kN/m$^3$ and 20 kN/m$^3$ after the UCS test (Figure **8**). For the samples that were compacted to a bulk density of 17.5 kN/m$^3$ (5 blows), a “barrelling” failure was observed whereby the samples bulged in the middle of the column [37]. However, distinct inclined failure planes emanating from the top of the soil column were observed in the samples that were compacted to a bulk density of 20 kN/m$^3$ (25 blows). No changes in the failure pattern were observed when the pH of the infiltrated AAR varied for the same bulk density.

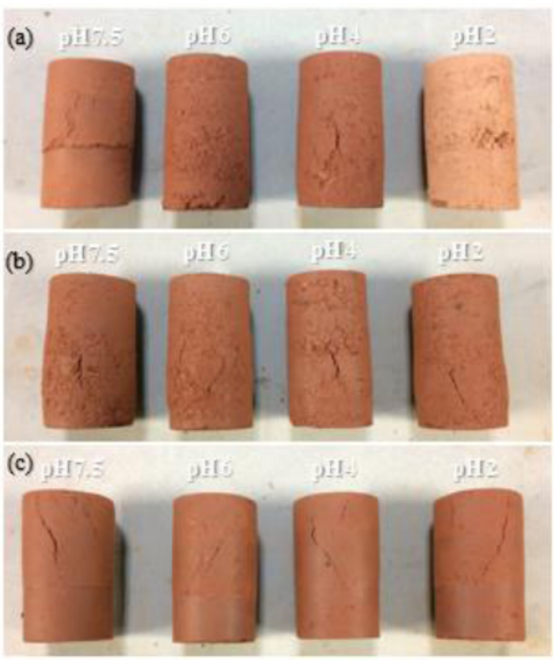


**Figure 8:** Failure pattern of AAR infiltrated soil columns for: (**a**) 5 blows/30mins; (**b**) 5 blows/60mins; and (**c**) 5 blows/60mins for the same bulk density soils.

## 4. CONCLUSION

This research investigated the short-term effects of simulated acid rain on the compressive strength and Atterberg limits of residual soil to assess its possible contribution to slope failure. The influence of bulk unit weight on the compressibility of acid rain-infiltrated soil was also studied for a predetermined infiltration period. The following conclusions were drawn based on the findings of this research:

3. Reducing the pH value of AAR led to the increment of LL, with the PL experiencing little no change, therefore, increasing the PI. The soil may have undergone flocculation due to the presence of acid.

4. The UCS of residual soil deteriorated as the pH value of AAR decreased. The increase in acidity also reduced Young’s modulus of the soil. The deterioration of these physical soil properties intensifies as the infiltration period lengthens. These effects can be attributed to the destruction of bonds between clay particles, leading to increased void sizes.

5. The percentage reduction in UCS due to AAR almost halved as a result of an increase in the bulk unit weight of the soil due to increased compaction. More excellent compaction reduces the number of voids within the soil structure thus impeding the infiltration of AAR through the soil column.

6. The pH level of rain can significantly impact the geotechnical properties of soils and the effects can be amplified as the period of rain intensifies. Adverse effects on the compressibility of residual soil due to acid rain can contribute negatively to the occurrence of slope failure.

## RECOMMENDATIONS FOR FURTHER RESEARCH

Further research is recommended, particularly in studying the long-term influence of acid rain on the compressive strength and Atterberg limits of soil, as only short-term analyses were conducted in this study due to time constraints. A numerical approach, such as using the Hydrus-1D software, is suggested to simulate long-term predictions of the effect of different AAR pH values on the soil. Both experimental and numerical approaches should be taken into account together and in collaboration to enhance the current methods of analysis. Another research aspect that can be explored is the effect of particle size on the penetration of AAR of different pH values to determine whether the usage of finer particles will reduce the infiltration rate of AAR and minimise the acid-induced deterioration of the geotechnical properties of the soil.

## ACKNOWLEDGEMENT

The authors wish to acknowledge Monash University Malaysia for providing the necessary laboratory facilities. Finally, the authors would like to thank Dr Lee Li Yong for her valuable advice for laboratory work.

## REFERENCES


[1] Ayers, G. P., Peng, L. C., Gillett, R. W. *et al.* Rainwater Composition and Acidity at Five Sites in Malaysia, in 1996. Water Air Soil Pollut. 2002; 133: 15-30. https://doi.org/10.1023/A:1012967614759

[2] Mohajan, H. 2019. Acid Rain is a Local Environment Pollution but Global Concern. Sci. J. Anal. Chem. 2019; 3: 47-55.

[3] Singh, A. & Agrawal, M. Acid rain and its ecological consequences. J. Environ. Biol. 2008; 29(1): 15-24.

[4] Omar, M. Z. & Rindam, M. The Impact of Acid Rain on Historical Buildings in Kuala Lumpur, Malaysia. Des. Princ. Pract. 2011; 5(6): 175-192. https://doi.org/10.18848/1833-1874/CGP/v05i06/38233

[5] Menon, S., Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C. & Holland, E. Couplings between changes in the climate system and biogeochemistry. Berkeley: Lawrence Berkeley National Lab.(LBNL); 2007

[6] Santamarina, J., Klein, K., Wang, Y. H. *et al.* Specific surface: Determination and relevance. Can. Geotech. J. 2002; 39: 233-241. https://doi.org/10.1139/t01-077

[7] Imai, G., Komatsu, Y. & Fukue, M. Consolidation Yield Stress of Osaka-Bay Pleistocene Clay with Reference to Calcium Carbonate Contents. J. ASTM Int. 2006; 3(7). https://doi.org/10.1520/JAI13325

[8] Calace, N., Fiorentini, F., Petronio, B. M. *et al.* Effects of acid rain on soil humic compounds. Talanta 2001; 54(5): 837-846. https://doi.org/10.1016/S0039-9140(01)00334-4

[9] Moh, Z.-C. & Mazhar, M. F. Effects of method of preparation on index properties of lateritic soils. In: Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, 1969; Mexico City

[10] Van Olphen, H. & Hsu, P. H. An Introduction to Clay Colloid Chemistry. Soil Sci.1978; 126(1).

[11] Bakhshipour, Z., Asadi, A., Huat, B. B. K. *et al.* Effect of acid rain on geotechnical properties of residual soils. Soils Found. 2016b; 56(6): 1008-1020. https://doi.org/10.1016/j.sandf.2016.11.006

[12] Bakhshipour, Z., Asadi, A., Huat, B. B. K. *et al.* Long-Term Intruding Effects of Acid Rain on Engineering Properties of Primary and Secondary Kaolinite Clays. Int. J. of Geosynth. and Ground Eng. 2016a; 2: 21. https://doi.org/10.1007/s40891-016-0059-1

[13] Sunil, B. M., Nayak, S. & Shrihari, S. Effect of pH on the geotechnical properties of laterite. J. Eng. Geol. 2006; 85(1-2): 197-203. https://doi.org/10.1016/j.enggeo.2005.09.039

[14] Gratchev, I. & Towhata, I. Compressibility of soils containing kaolinite in acidic environments. KSCE J. Civ. Eng. 2016; 20: 623-630. https://doi.org/10.1007/s12205-015-0141-6

[15] Momeni, M., Bayat, M. & Ajalloeian, R. Laboratory investigation on the effects of pH-induced changes on geotechnical characteristics of clay soil. Geomech. Geoengin. 2020; 17(1): 188-196. https://doi.org/10.1080/17486025.2020.1716084

[16] Rama Vara Prasad, C., Hari Prasad Reddy, P., Ramana Murthy, V. *et al.* Swelling characteristics of soils subjected to acid contamination. Soils Found. 2018; 58(1): 110-121. https://doi.org/10.1016/j.sandf.2017.11.005

[17] Kamon, M., Ying, C. & Katsumi, T. Effect of Acid Rain on Physico-Chemical and Engineering Properties of Soils. Soils Found. 1997; 37(4): 23-32 https://doi.org/10.3208/sandf.37.4_23

[18] Koupai, J. A., Fatahizadeh, M. & Mosaddeghi, M. R. Effect of pore water pH on mechanical properties of clay soil. Bull. Eng. Geol. Environ. 2020; 79: 1461-1469. https://doi.org/10.1007/s10064-019-01611-1

[19] Faraghati, S. N., Haji, M. S & Kolaei, A.G. Effect of pH Changes on the Geotechnical Properties of Clay Liners in Landfill. Adv. Res. Civ. Eng. 2019; 1: 49-57. https://doi.org/10.30469/arce.2019.82739

[20] Nivedya, K. Study on the Effect of pH on the Atterberg Limits of Kaolinitic and Montmorillonitic Clay. J. Geotech. Geoenviron. Eng. 2019. Springer. https://doi.org/10.1007/978-981-13-0899-4_31

[21] Yule, C. M. & Gomez, L. N. Leaf litter decomposition in a tropical peat swamp forest in Peninsular Malaysia. Wetl. Ecol. Manag. 2009; 17(3): 231-241. https://doi.org/10.1007/s11273-008-9103-9

[22] Zabawi, A., Esa, S. & Leong, C. P. Effects of simulated acid rain on germination and growth of rice plant. J. Trop. Agric. and Fd. Sc. 2008; 36(2): 281-286.

[23] Kuylenstierna, J., Rodhe, H., Cinderby, S. *et al.* Acidification in Developing Countries: Ecosystem Sensitivity and the Critical Load Approach on a Global Scale. Ambio 2001; 30(1): 20-8. https://doi.org/10.1579/0044-7447-30.1.20

[24] Ayers, G., Peng, L., Fook, L. *et al.* Atmospheric concentrations and deposition of oxidised sulfur and nitrogen species at Petaling Jaya, Malaysia, 1993-1998. Tellus B 2000; 52(1). https://doi.org/10.3402/tellusb.v52i1.16082

[25] Mohamad, Shangarai, Ying. The Status of Acid Deposition in Malaysia Based on Malaysia Meteorological Department (MMD) Data analysis from 1994–2008. Research Publication No.2 2010.

[26] Ibrahim, M. H. *et al.* Investigation of Acid Rain Pattern in Selangor, Malaysia. Int. J. Adv. Sci. 2019; 28(8): 800 - 805.

[27] Kazmi, D., Qasim, S., Harahap, I. S. H. *et al.* Analytical study of the causes of the major landslide of Bukit Antarabangsa in 2008 using fault tree analysis. Innov. Infrastruct. Solut. 2017; 2: 55. https://doi.org/10.1007/s41062-017-0105-4

[28] Huat, B., Gue, S. S. & Ali, F. H. Characterization of tropical soils in the design of material as natural foundation and fill. Tropical Residual Soils Engineering 2004. CRC Press. https://doi.org/10.1201/9780203024621.ch8

[29] Jamalludin, D., Ahmad, A., Zakaria, Z., *et al.* Distribution of bulk unit weight of residual soils from the Northern Malaysia. JPCS 2019; 1349(1): 012025. https://doi.org/10.1088/1742-6596/1349/1/012025

[30] Tan, S. H., Wong, S. W., Lee, M. L., *et al.* Soil column infiltration tests on biomediated capillary barrier systems for mitigating rainfall-induced landslides. Environ. Earth Sci. 2018*;* 77: 1-13. https://doi.org/10.1007/s12665-018-7770-2

[31] Netinger Grubeša, I., Barišić, I., Fucic, A. *et al.* Characteristics and Uses of Steel Slag in Building Construction. Cambridge: Woodhead Publishing; 2016

[32] Ola, S. A. Geotechnical properties and behaviour of some stabilized Nigerian lateritic soils. QJEGH 1978; 11: 145-160. https://doi.org/10.1144/GSL.QJEG.1978.011.02.04

[33] Gratchev, I. & Towhata, I. Compressibility of natural soils subjected to long-term acidic contamination. Environ. Earth. Sci. 2011; 64(1): 193-200. https://doi.org/10.1007/s12665-010-0838-2

[34] Sadowski, A. J., Rotter, J. M., Stafford, P. J. *et al.* On the gradient of the yield plateau in structural carbon steels. J. Constr. Steel Res. 2017; 130: 120-130. https://doi.org/10.1016/j.jcsr.2016.11.024

[35] Duiker, S. W. 2004. Effects of soil compaction. The Pennsylvania State University; 2005: Available from https://extension.psu.edu/effects-of-soil-compaction.

[36] Gregory, J. H., Dukes, M. D., Jones, P. H. *et al.* Effect of urban soil compaction on infiltration rate. JSWC 2006; 61(3):117-124.

[37] Amini, Y. & Hamidi, A. Triaxial Shear Behavior of Cemented Sand-Gravel Mixtures. JRMGE 2014; 6(5): 455-465. https://doi.org/10.1016/j.jrmge.2014.07.006

Received on 09-11-2022 Accepted on 22-12-2022 Published on 28-12-2022

DOI: https://doi.org/10.31875/2410-4701.2022.09.09