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A laboratory investigation of the compaction properties of road sub-base stabilised with cement and latex copolymer.

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Abstract. The quality of road pavements is an important factor to ensure an acceptable level of service and safety to the road users. When flexible road pavements are to be constructed on weak sub-grade soils, it is often necessary to provide a stabilised sub-base to improve their relevant engineering properties. This paper presents the results and observations from a laboratory investigation evaluating the compaction properties of road sub-base stabilised with Type I cement (ordinary Portland cement) and styrene-butadiene latex copolymer. The proposed polymer contents were 0.5%, 0.75%, 1% and 2% and the proposed cement contents were 2%, 3% and 5%. The 2.5kg rammer compaction test was conducted on the gravelly SAND and sandy GRAVEL samples. It was found that the maximum dry densities (MDD) for the untreated soil samples were higher than the cement-polymer-treated soil samples, indicating that the MDD values decrease when cement and polymer are added. The MDD values for gravelly SAND and sandy GRAVEL treated with cement-polymer lied between $2Mg/m^3 \pm 0.03Mg/m^3$ and $2.09Mg/m^3 \pm 0.04Mg/m^3$ respectively. The optimum moisture contents for gravelly SAND and sandy GRAVEL treated with cement-polymer were maintained at 9%±0.5%. The air void lines for gravelly SAND and sandy GRAVEL lied between 7%±1% and 3%±1% respectively.

1. Introduction

It is important to provide road pavements with adequate quality and performance, as they serve several significant functions within a transport system, such providing an acceptable level of service to the road users. Poor quality pavements could compromise the safety of road users. Previous studies, such as reported by Reference [1], had found possible correlations between the pavement quality and the rate of road traffic accidents (RTA). References [2] and [3] proposed how road sections with safety concerns, such as pavement defects, may be identified and ranked for remedial actions. However, rather than adopting a reactive approach, it is often beneficial to ensure that the pavement structural layers are adequately designed and constructed to avoid performance and safety issues during the service life of the road. This is especially crucial when flexible road pavements are to be constructed on weak sub-grade soils, such as those frequently encountered in Brunei Darussalam and its neighbouring countries.

In flexible pavements, the sub-base serves a significant role. It is only optional when the sub-grade is strong or contains high amount of granular soils, else the sub-base is required to act as a structural layer within the pavement system to further distribute the wheel loads from the roadbase to the weaker sub-grade [4]. The sub-base provides a stress-transmitting layer to spread the wheel loads to a larger area to reduce shear and consolidation deformations [5]. It also improves load carrying capacity by

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providing higher stiffness and resistance to fatigue, and building up a relatively thick layer to distribute the wheel loads through a finite thickness [6]. A sub-base that is well-graded and dense prevents upward migration of fine-grained sub-grade soils and water into the roadbase [4]. As the quality of the low-cost sub-base granular soil is inferior to that of the high-cost roadbase granular soil [4, 5, 7], engineers and contractors are motivated to improve the engineering properties of the sub-base. Improving the properties of sub-base could also enable recycled soils, such as those reported by Reference [8], to be used in the sub-base layer for sustainability reasons. One such method is to stabilise unbound granular soils with soil/aggregate stabilisers to create bound granular soils. Bound granular soils provide additional strength and support without increasing the thickness [9]. Additionally, the thickness can be reduced due to the high bearing strength when compared to unbound granular soils [9]. Reference [10] found that, while the use of polymer emulsion for the stabilisation of granular bases has clear advantages and is becoming increasingly popular, there are relatively fewer studies that investigate the improvements to the granular properties using this method of stabilisation.

Compaction of granular soils, with or without soil/aggregate stabiliser added to water, is a crucial work package in road construction. The main objective of compaction is to increase the bulk density of the granular soils by reducing the volume of air voids. It also helps to reduce permeability and swelling. A well-compacted granular soil provides higher bulk density, bearing capacity, and durability to ensure long-term performance [11]. When compaction is insufficient, it can lead to settlement and inadequate stiffness can lead to structural distress [12]. On the other hand, excessive compaction is not desired as it can lead to unnecessarily high construction cost and time delay [12].

The objective of this paper is to present the results and observations of a laboratory investigation of the compaction properties of granular soils stabilised with cement and latex copolymer. In particular, this study focused on the effect of cement and latex copolymer contents variation on the compaction properties of the sub-base upper and lower gradation limits. The maximum dry density (MDD) and optimum water content (OMC) are expected to vary when chemical stabilisers are added, and when the ratio of gravel-to-sand changes. The compaction properties of granular soils essentially provide important indices for the construction of soil-aggregate structures. While the compaction parameters of fine-grained soils are influenced by their Atterberg's limits, the compaction parameters of coarse-grained soils are influenced by their gradations [13]. The results from this laboratory investigation will then be used to plan subsequent tests – California Bearing Ratio (CBR) test, unconfined compressive strength (UCS) test for both dry and wet conditions and (water) permeability test. This study is part of an ongoing research effort aimed to develop more sustainable and mechanically durable road as well as addressing the persisting flexible pavement distresses.

The stability of unbound soils depends on the particle size distribution, particle shape, relative density, internal friction and cohesion [6]. Unbound soil that is designed for maximum stability should possess high internal friction to resist deformation under load [6]. The internal friction and shearing resistance depend largely on the particle shape, particle size distribution and density [6]. The proportion of fine to coarse fraction is considered very important, and the presence of a wider range of particle size makes the soil mixture denser and more compacted, which gives the soil mixture greater strength under shearing [14]. When the cement and latex copolymer are added, they bind the granular soils together to form a soil-cement-polymer soil matrix when cured. While unbound granular soils may still have high tendency to slide, move and/or displace, bound granular soils have a much lower tendency to slide, move and/or displace as they are physically bound to each other.

2. Compaction test methods

The 2.5kg rammer compaction test outlined in BS 1377-4: 1990 [15] is widely used to determine the dry density and moisture content relationship of soils with particles up to medium-gravel size. Thus, no more than 30% by mass of soils should be retained on the 20mm and 37.5mm sieves (coarse gravel)

[15]. Reference [16] suggested that the ratio of mould diameter to the largest nominal particle size should not be less than 5 to 6. The ratio used in this experiment is 5.5 (105mm:19mm). Typically, a 2.5kg rammer compaction (equivalent to standard Proctor compaction) is used for normal traffic loading situations [17]. A 4.5kg rammer compaction (equivalent to modified Proctor compaction) is used to simulate field condition where a higher compactive effort is required for airfield pavements [17, 18].

3. Materials

3.1. Aggregate and gradation

In this laboratory investigation, crushed sandstone aggregate was used. The aggregate was sourced from a local quarry in the Temburong District – Brunei Darussalam which is mainly used for the sub-base layer. The physical and mechanical properties of the aggregate satisfied the local specification – GS1: 1998 Flexible Pavement [19]. A gradation envelope is established to provide quality control on the granular soils to be used in road construction, therefore to study the effects of the upper and lower bounds, it is necessary to select the appropriate envelope [18]. The upper and lower bounds for the sub-base specified by GS1: 1998 Flexible Pavement [19] are as shown in Figure. 1. Figure. 2 (a) and (b) illustrate the gravelly SAND and sandy GRAVEL samples before compaction.

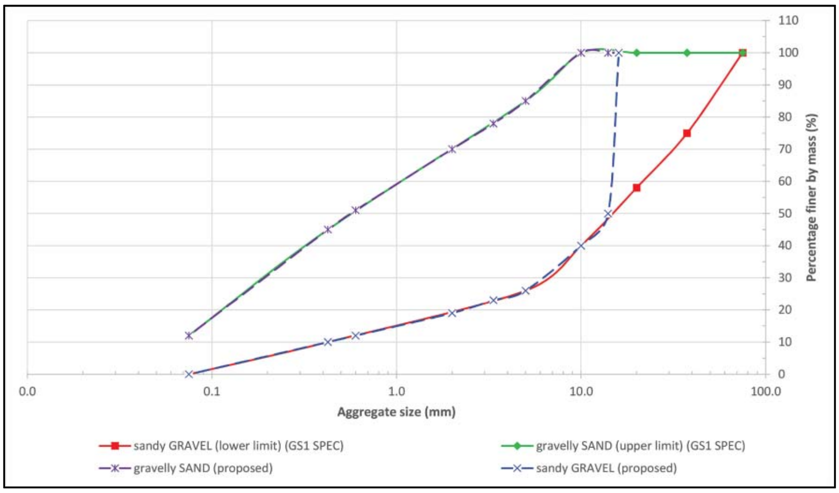

Figure. 1 Upper and lower gradation limits for the specified and proposed sub-base layer.

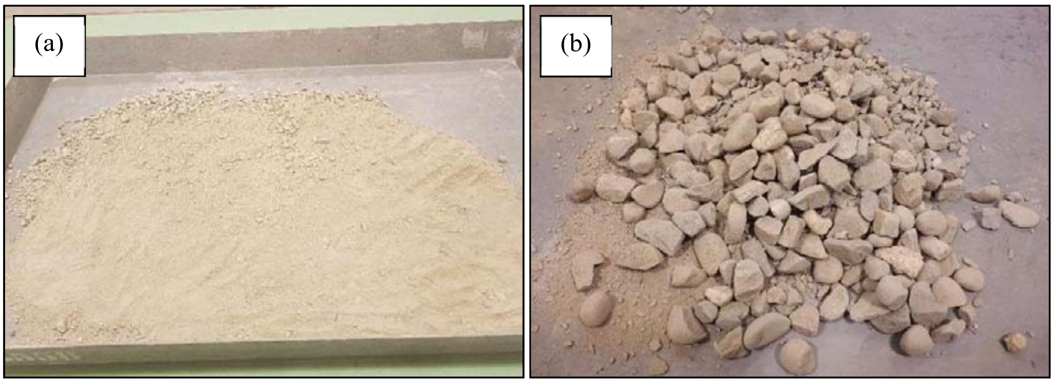

Figure. 2 (a) Uncompacted gravelly SAND and (b) uncompacted sandy GRAVEL samples.

Since the 2.5kg rammer compaction test was used, and the ratio of mould diameter to the largest nominal particle size was to be maintained, the gradation for the sandy GRAVEL was altered to satisfy the test and ratio requirements. BS 1377-4: 1990 [15] allows the same quantity of material of similar characteristics which was retained on the 20mm sieve, to be replaced with soil particles of smaller sizes. The standard stated that the substitution of large soil particles by smaller and similar soil particles generally gives dry densities (in the laboratory) which are reasonably comparable with those obtained in the field.

3.2. Cement
The cement used in the laboratory investigation was the locally manufactured Class 62.5N (62.5N/mm^2) Type I ordinary Portland cement (OPC). In Brunei Darussalam, road construction contractors typically add between 2% and 7% of cement by weight to the unbound soils to produce hydraulically-bound soils. Cement content from 6% to 10% onwards in normal condition will cause severe shrinkage cracking over a long period of time [20]. According to Reference [21], a well-graded soil mixture of stone fragments or gravel, coarse sand, and fine sand either with or without small amount of slightly plastic silt- and clay-sized soil particles will require 5% or less cement by weight for stabilisation. Based on the limitations stated above, the proposed cement contents were 2%, 3% and 5% by weight of sample.

3.3. Latex copolymer
The liquid additive used in the laboratory investigation was a white colour water-based dispersion of a latex copolymer, under the tradename Terratech T-Pro® 500. The main components of T-Pro® 500 are water (between 40% and 55% by weight) and styrene-butadiene (SB) copolymer (between 45% and 55% by weight) [22]. The latex copolymer has a specific gravity (S.G.) between 0.95 and 1.1, the dynamic viscosity is less than 500 mPa.s and the size of the SB particle is 125 nm [22]. The recommended polymer content and OMC based on the manufacturer-specified gradation is 0.75% and 9% respectively. Reference [23] used 0.5%, 0.75%, 1% and 2% of the polymer by weight to stabilise clay-soil mixture, and it was concluded that the optimum polymer content was 0.75% polymer content. The 3-day and 7-day compressive strengths for the 0.75% polymer content was 0.68MPa and 0.79MPa respectively [23]. The proposed polymer contents were 0.5%, 0.75%, 1% and 2% by weight of sample.

3.4. Latex copolymer and cement
It is common to have two additives added together to stabilise unbound soils. Unbound granular soil may exhibit poor engineering performances such as low bearing capacity, susceptibility to moisture damage and volume change, and susceptibility to environmental conditions; all of which would result in substantial pavement distress and shortening of pavement life [24]. The addition of one or two soil stabilisers to the unbound granular soils can improve its engineering properties. Previous research by References [24], [25] and [26] have concluded that 8% by weight of SB latex copolymer (tradename Mallard Creek Tylac® 4190) and 4% by weight of cement (Type II OPC) were effective to stabilise soil-aggregate roadbase. The results from References [24], [25] and [26] showed that the compressive strength for 8% polymer-4% cement increased by 94.43% when compared to 4% cement, the CBR for unsoaked condition for 8% polymer-4% cement was 412.2% while the CBR for 4% cement was 289.7% and the CBR for soaked condition for 8% polymer-4% cement was 452.8% while the CBR for 4% cement was 292.6%. It is worthwhile to note that the CBR for soaked soil samples were greater than unsoaked soil samples. The same authors found that there was an increase in 81.4% for 8% polymer-4% cement when compared to 4% cement, and 288.2% when compared to 8% polymer.

4. Results and discussion
The sizes of the granular soil particles affect the engineering behaviours of a given soil mixture, and the bulk density of a soil mixture depends mainly on the weight of the individual soil particle and the amount of water present [18]. The shape and texture of the soil particles also influence the bulk density of the

granular soil, though there is no refined geotechnical procedure to quantify it [18]. Reference [18] found that typical MDD values for granular soils are between 1.6Mg/m^3 to 2Mg/m^3, with limits between 1.3Mg/m^3 to 2.4Mg/m^3, and the typical OMC values are between 10% to 20%, with limits between 5% to 40%. The MDD and OMC obtained from the compaction test under a given compactive effort provide indications of the porosity of the soil mixture – lower MDD and higher OMC correspond to greater porosity [27].

Figure. 3 shows the compaction curves for the gravelly SAND and sandy GRAVEL treated with the latex copolymer only. It was observed that the MDD values for gravelly SAND were lesser than sandy GRAVEL. Generally, coarser soils can be compacted to a higher bulk density than finer soils [18].

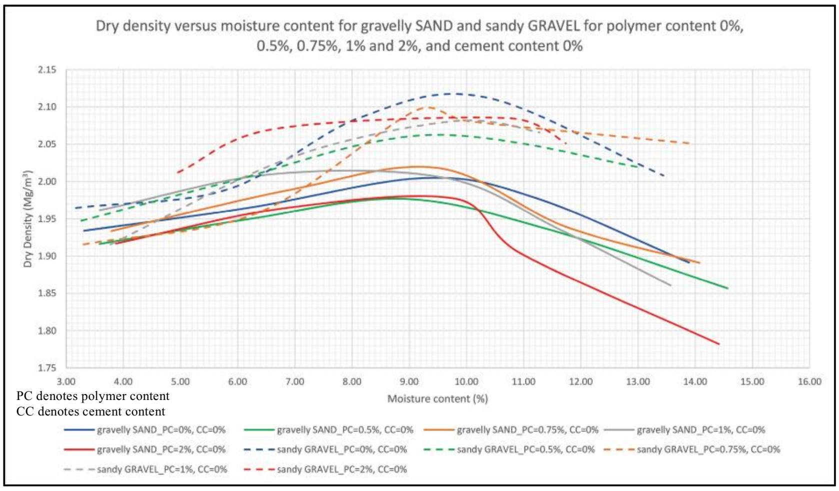

Figure. 3 Dry density versus moisture content of soil samples treated with polymer only.

Figure. 4 shows the compaction curves for gravelly SAND and sandy GRAVEL treated with 0.75% and 1% polymer content with 0%, 2%, 3% and 5% cement. It was also observed that the MDD values for gravelly SAND were lesser than sandy GRAVEL.

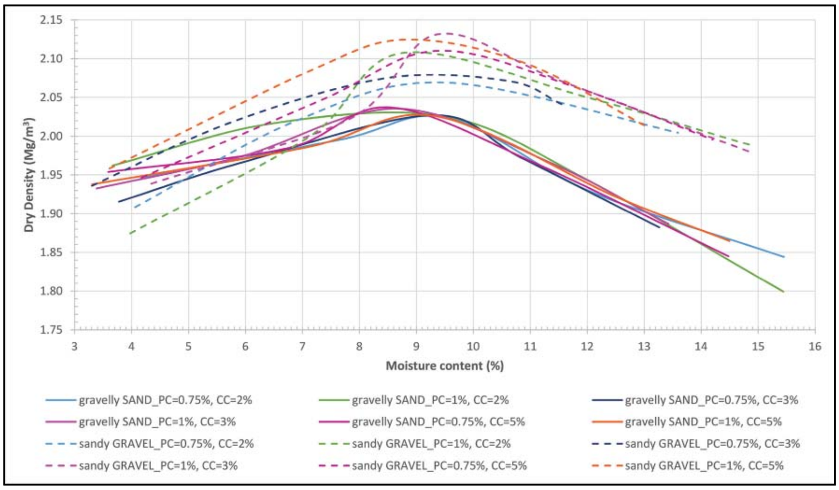

Figure. 4 Dry density versus moisture content of soil samples treated with polymer and cement.

While it was expected that the MDD values in this laboratory investigation should decrease with increasing polymer content as observed in Reference [23], as in both experiments, the same latex copolymer was used but with different gradations. However, the MDD values in this experiment did not show the expected decreasing trend. However, in the laboratory investigation by Reference [24], the MDD values increased to a peak and then decreased when 5% to 10% of SB polymer was added (peaked at 8%). This downward concave trend was as observed in this experiment when 0.5% to 2% of polymer was added. As shown in Figure. 5 (a), MDD peaked at 0.75% for both gravelly SAND and sandy GRAVEL. The MDD value for gravelly SAND was 2.02 Mg/m^3 when 0.75% polymer was added, and this value was slightly greater than when no polymer was used (2.01Mg/m^3). The drop in MDD values corresponding 0% and 0.5% polymer contents could be the result in the change of dynamic viscosity (i.e. a measure of a liquid's resistance to movement) between 100% water (< 1mPa.s) and (the addition of) polymer (< 500mPa.s). The kinematic viscosity (i.e. a measure of resistance to the fluid flowing) of water and polymer are less than 1×10^{-6} m^2/s and less than 456×10^{-6} m^2/s respectively. As the dynamic viscosity increases, the fluid impedes soil particle movement, thus preventing effective (soil particle) packing by compaction. Reference [28], in their experimental investigation, suggested that the decrease in MDD values (when soils were treated with increasing polymer content) to the differences in S.G. of water and polymer (1 and 1.1) and the soils (2.57 and 2.61), which is unlikely the case. The increase in MDD values until peak with increasing polymer content, as explained by Reference [24], was an indication of the consolidation of the rigid styrene chains and flexible butadiene chains of the SB molecular structure which improved the mechanical properties of the soil mixture. The nano-sized polymer particles penetrated and spread throughout the soil mixture to provide both toughness and flexibility [24]. The decrease in MDD values after peak was due to the presence of excessive water that inhibited effective compaction, which in turn reduced toughness and flexibility [24].

It was expected that for the polymer contents 0.75% and 1%, when the cement content increases, the MDD values should increase. However, this expectation was only observed in the gravelly SAND of polymer content 0.75% and sandy GRAVEL of polymer content 1% as shown in Figure. 5 (b). The cement acted as fine filler to fill the air void thus increasing the bulk density. The sandy GRAVEL of polymer content 0.75% observed decreasing MDD values until cement content of 3% and increased when cement content is 5%. One highly suspected contributory factor to this contradictory trend is the gravel shapes and sizes passing the 20mm sieve and retained on the 14mm sieve. It is sometimes difficult to get a consistent soil mixture of similar shapes and sizes for all the soil samples. In such a situation, it is recommended to repeat the experiment for the outliers to ascertain whether or not the gravel shape and size were the main reason for this error.

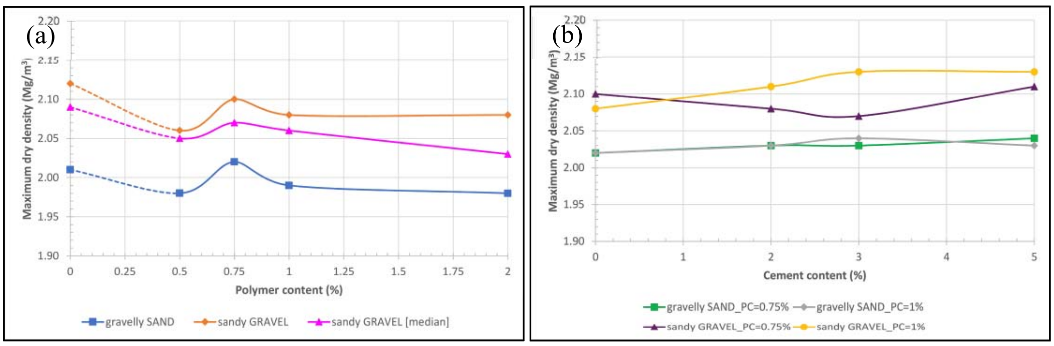

Figure. 5 (a) MDD against polymer content for 0% cement content, (b) MDD against cement content for 0.75% and 1% polymer content.

Figure. 6 (a) and (b) show the soil packing features of sandy GRAVEL and gravelly SAND close to the peak MDD values when 1% of polymer and 3% of polymer were added. Figure. 7 (a) and (b) show the packing features when 2% of polymer was added to the soil samples.

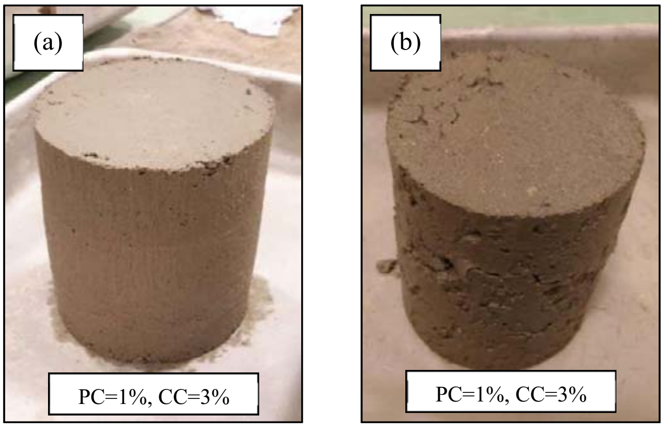

Figure. 6 (a) Compacted gravelly SAND and (b) compacted sandy GRAVEL.

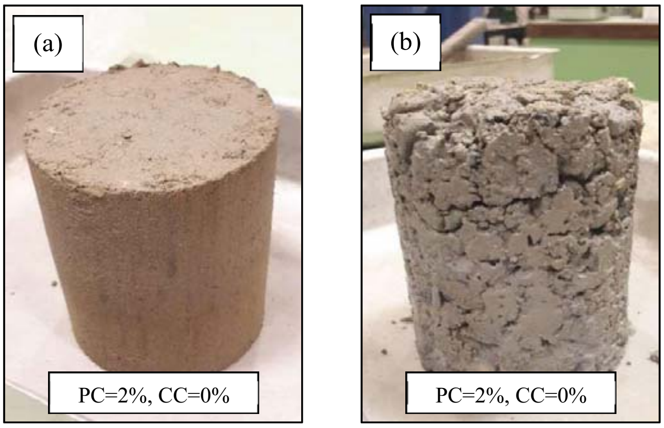

Figure. 7 (a) Compacted gravelly SAND and (b) compacted sandy GRAVEL.

Since the latex copolymer contains between 40% and 55% by weight of water, the increase in polymer content will result in the increase in the soil sample's water content. However, as shown in Figure. 8 (a), there was no consistent trend for the relationship between OMC and polymer contents from 0% to 0.75% for the gravelly SAND and sandy GRAVEL, but from 1% to 2% polymer content, the OMC values increased for the two investigated gradations. Nonetheless, the OMC values for 0% cement content for gravelly SAND and sandy GRAVEL maintained between 9%±0.5% and 10%±0.5% respectively as shown in see Figure. 8 (a).

For the polymer content 0.75% and 1%, an increase in cement content should observe slight decrease in OMC as the tricalcium silicate (C_3S) and dicalcium silicate (C_2S) react with water to produce calcium silicate hydrate (CSH) and crystallised calcium hydroxide (CH). Type I cement contains 59% C_3S and 15% C_2S [29]. The rate of reaction of C_3S is much faster than C_2S (slowest) with the former producing

CSH (Type E) and CH within the hour [30]. An initial water-to-cement ratio of 0.40 to 0.42 is required for the complete hydration of cement [30-32]. The initial setting time of Type I cement is between 70mins to 120mins, and the final setting time is between 140mins to 240mins [33]. However, these setting time ranges can change, as (anionic) SB polymer retard/suppress the hydration reaction [34]. Nonetheless, the OMC values for gravelly SAND and sandy GRAVEL treated with cement were maintained between 9%±0.5%, as shown in Figure. 8 (b).

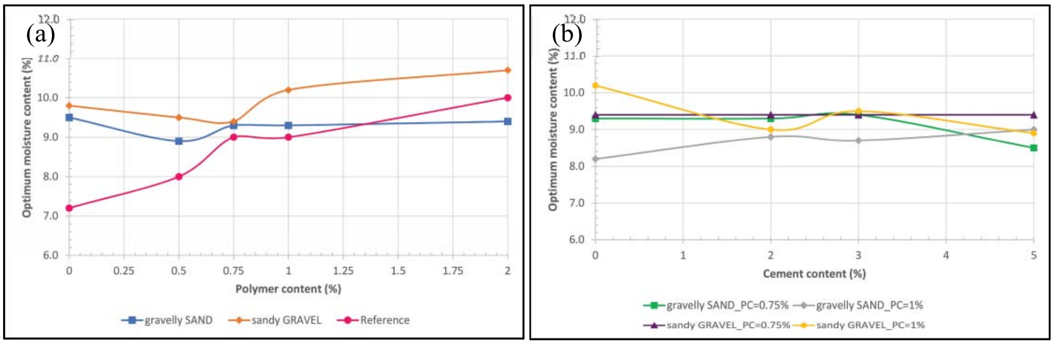

Figure. 8 (a) OMC against polymer content for 0% cement content, (b) OMC against cement content for 0.75% and 1% polymer content.

Figure. 9 shows a typical compaction curve illustrating the relationship between moisture content and dry density. The 0% air void line (AVL) corresponds to the 100% saturation line (SL), and theoretically, the compaction line should not intersect with the 0% AVL. An intersection observed in the test results may be due to incorrect test measurement and/or an incorrect specific gravity value. This was found to be a problem for the sandy GRAVEL samples at high water content (> 10%) as the water distribution throughout the soil samples was inconsistent as illustrated in Figure. 11 (c), where water was concentrated at the top of the sample and gradually decreased with increasing depth of the soil sample. In the laboratory investigation, most of the compaction curves for the sandy GRAVEL samples after the third addition of water intersected with the 100% SL, and the soil samples were all observed to be highly saturated with water.

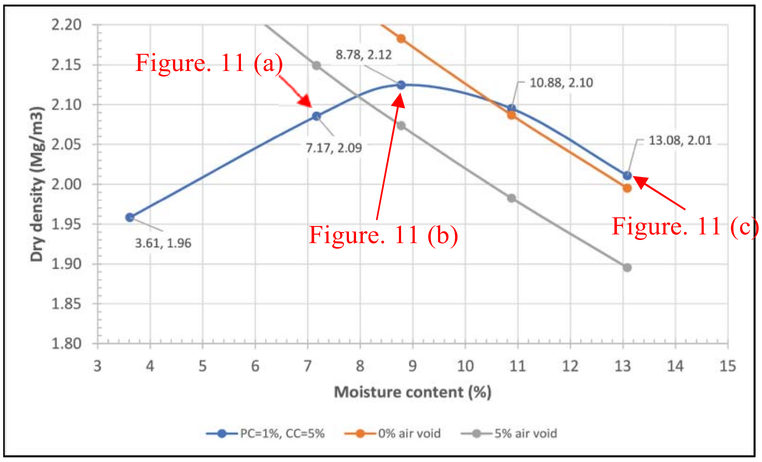

Figure. 9 Dry density against moisture content curve for sandy GRAVEL (PC = 1%, CC = 5%).

Figure. 10 (a), (b) and (c) and Figure. 11 (a), (b) and (c) illustrate the sandy GRAVEL at 0% and 5% cement content respectively. The sample with 5% cement content was able to hold the shape and was less slurry.

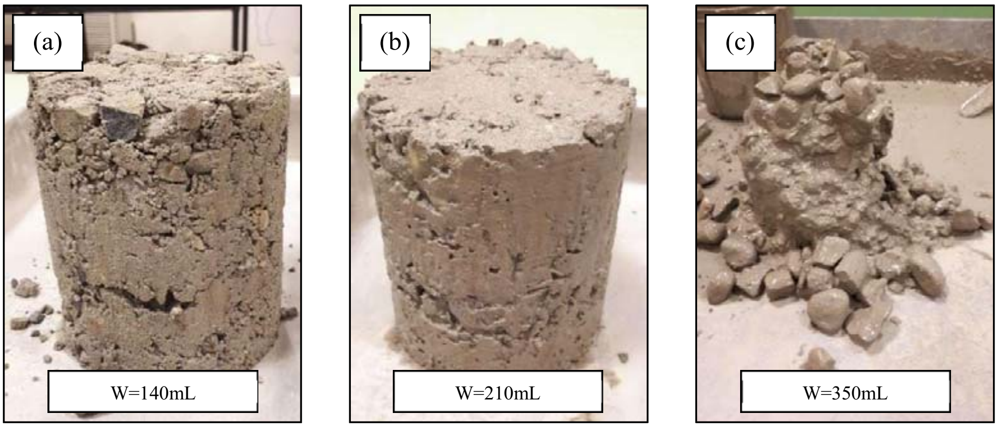

Figure. 10 (a) and (b) Saturated sandy GRAVEL and (c) highly saturated sandy GRAVEL for polymer content 1% and cement content 0% (W denotes amount of water added).

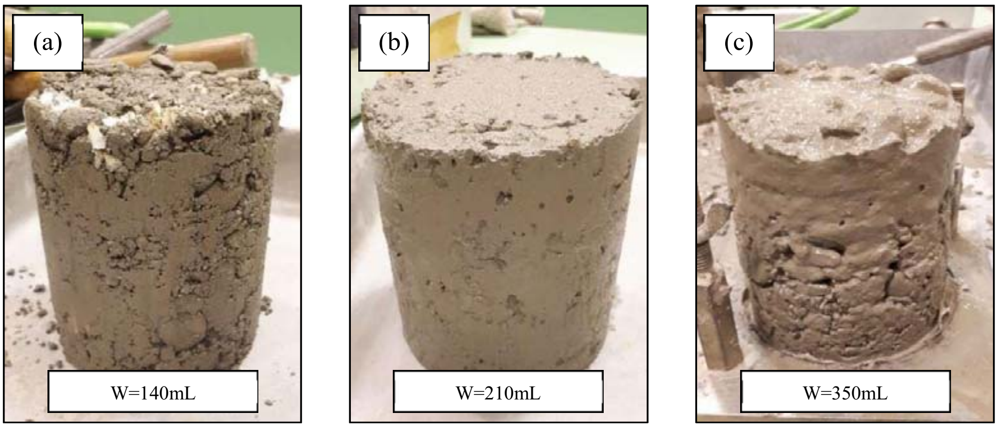

Figure. 11 (a) and (b) Saturated sandy GRAVEL and (c) highly saturated sandy GRAVEL for polymer content 1% and cement content 5%.

The decrease in saturation when 0.5% of polymer was added, as shown in Figure. 12 (a), could be explained by the change in the kinematic viscosities of the water-polymer mixture. The increase in the kinematic viscosity meant that the movement of soil particles and water-polymer was impeded for effective packing when compacted. The increase in the saturation with increasing polymer content could be due to the additional (free) water from the polymer. When 0.5% of polymer was added, an additional of 6.25mL of water from the polymer was added, and when 2% of polymer was added, an additional of 25mL of water from the polymer was added, to the same weight of soil sample. The increase in water content can displace the finer soil particles, thus reducing the MDD values. When 1% and 2% of polymer was added, while the saturation degree increased, the MDD values decreased. Furthermore, sandy GRAVEL samples inherently have larger air void, and when water cannot escape the compaction mould,

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upon compaction, water navigated through the large voids and was subsequently trapped, increasing the degree of saturation. Theoretically, gravelly SAND samples have larger surface area to volume, therefore, more water was absorbed into the soil particles and some was adsorbed on the surface, leaving the voids filled with air than water. Unlike sandy GRAVEL, the compaction curves of the gravelly SAND did not intersect with the 100% SL. The AVL for the gravelly SAND and sandy GRAVEL samples were between 7%±1% and 2%±1.5% respectively, as shown in Figure. 12 (a). Figure. 12 (b) illustrates the SL for the gravelly SAND and sandy GRAVEL samples when cement was added to 0.75% and 1% polymer. The SL and AVL are inverse of each other.

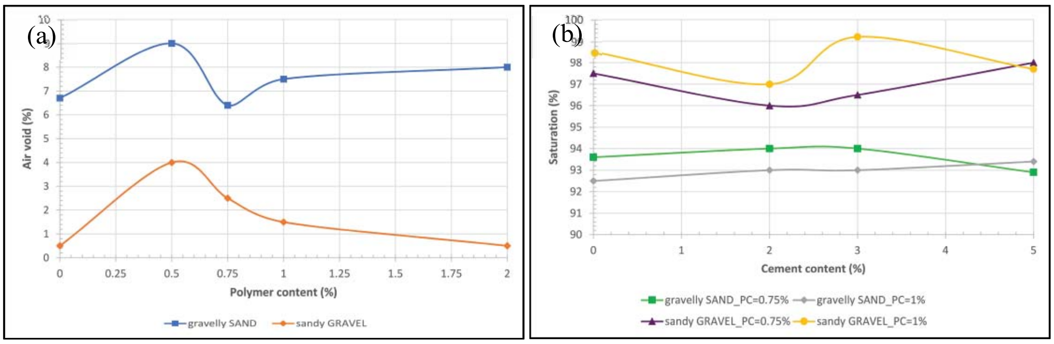

Figure. 12 (a) Air void against polymer content for 0% cement content, (b) Saturation against cement content for 0.75% and 1% polymer content.

5. Conclusion

The aim of the laboratory investigation to evaluate the compaction properties of the granular soil samples stabilised with cement and latex copolymer using 2.5kg rammer compaction test has been accomplished. The following are the conclusions drawn from the study:

- The peak MDD values of the sandy GRAVEL and gravelly SAND were when 0.75% polymer-0% cement was added to stabilise the soil samples. When 2%, 3% and 5% of cement were added, there was no consistent trend, but the MDD values for gravelly SAND and sandy GRAVEL lied between 2Mg/m^3±0.03Mg/m^3 and 2.09Mg/m^3±0.04Mg/m^3 respectively.
- While it was expected that the OMC values would gradually increase with increasing polymer content, the OMC values determined in the laboratory investigation did not follow the expected trend, but the OMC values for 0% cement content for gravelly SAND and sandy GRAVEL lied between 9%±0.5% and 10%±0.5% respectively. When 2%, 3% and 5% of cement was added, it was expected that the OMC would decrease as water was used during the hydration reaction. Contrary to the expectation, there was no definite increasing or decreasing trend for gravelly SAND and sandy GRAVEL, but the OMC values maintained between 9%±0.5%.
- For 0% cement content, the gravelly SAND has lower range of saturation degree – between 92%±2% (corresponded to 8%±2% air void) than sandy GRAVEL – between 98%±1.5% (corresponded to 2%±1.5% air void). When 2%, 3% and 5% of cement was added, there was no definite trend for gravelly SAND and sandy GRAVEL, but the air void lines lied between 7%±1% and 3%±1% respectively.

Subsequent laboratory tests – California Bearing Ratio (CBR) test, unconfined compressive strength (UCS) test for both dry and wet conditions and (water) permeability test – must to be conducted for the gravelly SAND and sandy GRAVEL to determine quantitatively the structural stability, strength and permeability properties/characteristics. While the compaction test gave initial results on the MDD values, they cannot be used as indication of strength gained. The soil samples have to be cured – allowing the hydration products to form and bind the soil particles, and water to evaporate to form the polymer film to bind the soil particles, CSH and CH – to determine the final strength gained.

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