International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:10, No:2, 2016

Strength and Permeability of the Granular Pavement Materials Treated with Polyacrylamide Based Additive

Romel N. Georgees, Rayya A Hassan, Robert P. Evans, Piratheepan Jegatheesan

Abstract—Among other traditional and non-traditional additives, polymers have shown an efficient performance in the field and improved sustainability. Polyacrylamide (PAM) is one such additive that has demonstrated many advantages including a reduction in permeability, an increase in durability and the provision of strength characteristics. However, information about its effect on the improved geotechnical characteristics is very limited to the field performance monitoring. Therefore, a laboratory investigation was carried out to examine the basic and engineering behaviors of three types of soils treated with a PAM additive. The results showed an increase in dry density and unconfined compressive strength for all the soils. The results further demonstrated an increase in unsoaked CBR and a reduction in permeability for all stabilized samples.

Keywords—CBR, Hydraulic conductivity, PAM, Unconfined compressive strength.

I. Introduction

NON-TRADITIONAL stabilizers, such as polymers, have gained attention as a result of their efficient performance in the field [1]-[3] and their improved sustainability performance in comparison with traditional ones. They have been found to increase wet strength, increase soaked CBR value and decrease permeability [4]. In addition, polymeric stabilizers reduce maintenance frequency, lower transportation cost and speed construction at lower cost [5]. However, due to the proprietary nature of non-traditional additives, little independent research has been undertaken concerning the mechanisms by which such additives interact [6].

Polymer stabilization belongs to the modified stabilization category according to Austroads [7] categorization. It is mostly adopted when desired characteristics include an increase in strength and stiffness, a decrease in moisture susceptibility and maintenance of pavement flexibility [7].

A study conducted by Wilmot [4] grouped the results of 25 years of field experience in stabilization from late 1960s to provide a broad guide for selecting the additive that is most suitable to the host soil. The study involved additives that are commonly encountered in Australian roads construction, such as cement, hydrated lime, hydrated lime and cement, cementitious binder, polymers and bitumen. The results showed that only the cementitious blends and polymeric materials were the most suitable additives for a wide range of soils.

It has been found that the interaction of soil-polymer is highly dependent on polymer properties such as type and amount of surface charge, polymer configuration and molecular weight and size, and on soil properties such as type and amount of clay, soil solution ionic strength, type of ion in solution and PH value [8], [9]. This interaction has also been confirmed with silts and sands [10], [11]. However, effective interaction of soil-particles takes place when polymers are adsorbed onto the soil particles, and the adsorption process is significantly affected by the type of polymer charge [12].

Polyacrylamide (PAM), which is a synthetic organic polymer, has been applied extensively as an important soil amendment agent, particularly in agricultural fields to stabilize soil surface structure and pore continuity [12]. It has been found that PAM enhances soil aggregate stability, particularly in sandy loam soils [13]. This kind of polymer possesses a long chain that binds soil particles together, which leads to an increase in the percentage of particles greater than 4 mm aggregates. Hence, it binds aggregates together and makes the soil more resistant to erosion, dispersion, collapse and shear forces [14], [15]. In addition, preliminary studies have estimated a reduction in greenhouse gas emission by almost 90 per cent, a significant reduction in water requirements and a significant financial savings per year on the maintenance of roads when PAM additives were used for road construction [5], [16].

The effects of PAM were tested in terms of engineering properties on highly plastic soils, and it was shown to increase the failure strain of the soil, which increased the flexibility of the soil [17]. However, a lack of laboratory work on this type of polymer was noted, since the only investigation of its effect on performance of pavement materials was limited solely on field performance monitoring. A comprehensive laboratory-based research project has been carried out to assess the benefits of using a synthetic polyacrylamide additive (PAM) on the mechanical properties of local granular materials used for unsealed roads. The standard engineering properties investigated include dry density-moisture content relationship, unconfined compressive strength (UCS), California bearing ratio (CBR) and hydraulic conductivity. The aim of the study reported herein is to characterise the suitability of local

Romel N. Georgees, Rayya A Hassan, Robert P. Evans and Piratheepan Jegatheesan are with the Swinburne University of Technology, Faculty of Science, Engineering & Technology, John St, Hawthorn, Victoria, Australia, 3122 (corresponding author: Romel N. Georgees; phone: +61 9214 8492; fax: +61 3 9214 8264; e-mail: rgeorgees@swin.edu.au, rahassan@swin.edu.au, robertevans@swin.edu.au, pjegatheesan@swin.edu.au).

granular soils for stabilisation using polyacrylamide additive (a commercially available polymeric material) as a stabilizing agent; also the study aims to assess the levels of improvement of fundamental engineering properties resulting from utilizing such polymeric material for these types of soils.

II. Materials

A. Soils

Three types of soils from three different sites in the state of Victoria, Australia, were selected for the testing program. These were a course grained Gravel with silt and sand, Clayey Gravel with Sand, and Clayey Sand with gravel. The soil samples were collected from the top 200 mm of the wearing course of unsealed roads that were being stabilized and these were air dried. The maximum size of the aggregate was typically 20 mm. The particle size distribution was performed following procedures outlined in AS 1289.3.6.1 [18]. For the fine fraction, a hydrometer test was conducted to determine the particle size distribution of particles finer than 75 μm [19]. Australian standards AS 1289.3.2.1 [20], AS 1289.3.1.1 [21] and AS 1289.3.9.1 [22] were used to determine the plastic limit, liquid limit and plasticity index of the soils. The soils were then classified according to USCS classification systems outlined in ASTM D2487 [23]. The gradation and properties of the soils are shown in Fig. 1 and Table I respectively.

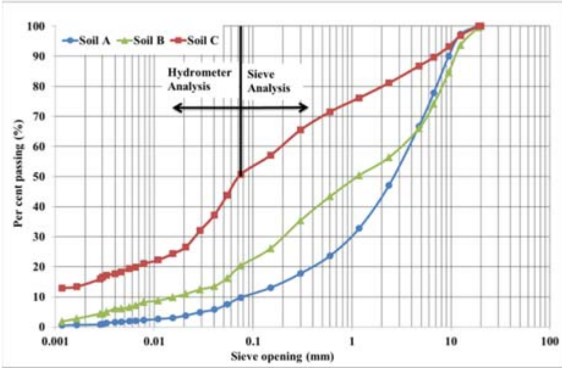

Fig. 1 Particle size distribution of soils A, B and C

TABLE I
ENGINEERING PROPERTIES OF SOILS A, B AND C

Atterberg Limits	Soil A	Soil B	Soil C
Liquid limit (%)	22.2	23.8	31.4
Plastic limit (%)	N/A	12.8	15.1
Plasticity Index (%)	N/A	11	16.3
Compaction			
Optimum Moisture Content (%)	5.8	8.5	12.5
Maximum Dry Density – Modified (g/cm^3)	2.29	2.00	1.94
Soil Classification, (USCS)	Gravel with silt and sand (GP-GM)	Clayey Gravel with sand (GC)	Clayey Sand with gravel (SC)

B. Binder

The polymeric additive used in this study was a synthetic soluble anionic polyacrylamide. The product is developed in Adelaide, Australia, by Bio-Central Laboratories Ltd, and produced in a granulated form. The PAM has a moderate charge density of about 18% and a high molecular weight of typically 12-15 mega grams per mole. The product is a non-toxic water soluble material with a specific gravity of 0.8 and a PH value of 6.9 at 25 °C. Samples for testing were provided by Earthco Project Ltd.

III. Testing Methods

A laboratory tests carried out to determine the engineering behaviour of the samples; this included modified proctor compaction, unconfined compressive strength (UCS), California Bearing ratio (CBR) and permeability testing.

Laboratory test samples were prepared in accordance with Australian standards [24]. The required amount of PAM was determined according to the supplier's recommendation, which was 0.002 per cent by dry weight of the soil. The PAM was first mixed with water in a sealed container at a rate of 2 gram per 5 litres, which created a polymer rate concentration higher than the recommended rate. This concentrated solution was then dissolved in a compensated weight of water to obtain the required moisture for the soil. The soil-water mixture was then mixed in a mechanical mixer for 15 minutes. After mixing, the soil was kept in a sealed plastic bag for 24 hours to allow even moisture distribution.

The maximum dry density and optimum moisture content were determined using modified compaction tests [25]. According to the standard, samples are compacted in Australian modified compaction moulds, which involved compacting specimens in five layers using 25 blows per layer (BPL). However, based on the results of a previous study [26] on soils treated with PAM as a stabilizing agent, the optimum number of blows was found to be 35 and 45 BPL for these soil types. This allows better reflection of the compaction effort in the field. Therefore, compactive efforts of 3574 for soils B and C and 4595KN-m/m^3 for soil A were applied using 35 and 45 BPL, respectively.

For the UCS tests, split moulds were used to keep the end faces in a parallel condition. This involved preparing at least three specimens per sample (treated and untreated), with various moisture contents. The cylindrical specimens were removed from the split moulds after compaction and stored in a curing room at a temperature of 25 ± 3°C for 14 days. All of these specimens were tested for unconfined compressive strength. Load versus deformation data was collected using data acquisition equipment that was calibrated to load the specimen at a rate of 1 mm per minute. Thus, all specimens were tested under controlled strain conditions. The specimens were loaded either to the point where the load reached a maximum value and then decreased with increasing strain, or until 15 per cent strain was reached [27], [28].

The CBR test was conducted in accordance with Australian Standards AS 1289. 6.1.1 [29]. The specimens were prepared by compacting five layers with the same compactive energy as per the UCS specimens. Two groups of CBR specimens were prepared; one was submerged in water for 4 days, and the other was left in air dry condition for 14 days. All the specimens were tested under controlled strain conditions at a rate of 1 mm per minute.

For the hydraulic conductivity tests, a falling head method was used following the Australian standards [30] to measure the permeability coefficient of the treated and untreated soils. This method is suitable for soils with a permeability coefficient between 10^{-7} to10^{-9} m/s. The specimens were compacted in five layers with the same compactive energy as per the UCS specimens. All specimens were compacted at the target density of 98% maximum dry density and at the optimum moisture content. A water level in the standpipe was measured at regular intervals over a period of not less than 3 days.

IV. Testing Results

A. Maximum Dry Density (MDD) and Optimum Moisture Content (OMC)

The effects of adding PAM on dry density and moisture content for the three soil types (soil A, B and C) were determined by conduction the compaction tests. These tests produced dry density versus moisture content relationship. Table II shows the MDD and OMC for treated and untreated samples of soils A, B and C.

TABLE II
Effect of Polymer Stabilized Additive on Dry Density And Moisture Content for Soils A, B And C

Soil Type	BPL	Untreated		Treated	
		MDD (gm/cm^3)	OMC, %	MDD (gm/cm^3)	OMC, %
A	45	2.36	5.4	2.38	5.7
B	35	2.01	8.5	2.03	8.5
C	35	1.96	12.7	1.98	12.3

Table II shows a consistent increase in maximum dry density (MDD) for all three soils treated with PAM when compared to their untreated analogues. It shows an increase in maximum dry density (MDD) for the treated samples of soil A over that of the untreated samples by approximately 0.85%. Treated samples of Soils B and C have shown same trend. The increase in MDD for both treated soils B and C were 0.95% and 1.0% respectively. However, the optimum moisture content (OMC) for each soil type was slightly different. For example, treated soil A showed an increase in OMC, treated soil B showed no change in OMC, and treated soil C showed a decrease in OMC at the MDD. Generally, PAM was able to increase the densification of soils by enhancing reorientation of particles to more densely packed sample.

B. Unconfined Compressive Strength (UCS)

Unconfined compressive strength testing was used to assess the effects of using PAM on the UCS of the stabilized samples of the three types of soils. The test was conducted using a hydraulic loading machine for all treated and untreated samples. At least three specimens were prepared per sample (treated and untreated) in order to ensure reliable results.

The UCS values of treated and untreated samples for the three soil types are presented in Fig. 2. It is worth noting that the strength of samples (treated and untreated) presented in this figure represents the average UCS values of the three specimens per sample. Error bars indicate standard error of at least three specimens per sample with a 95% confidence interval.

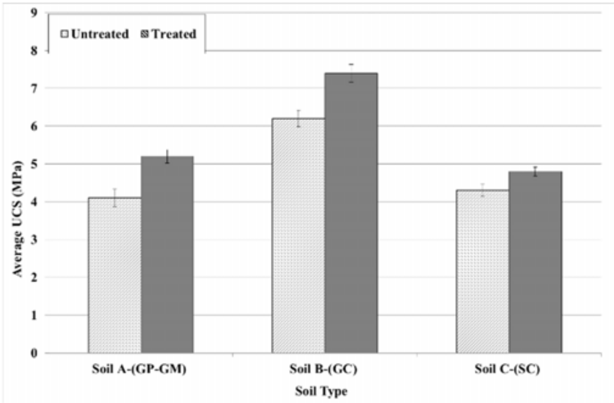

Fig. 2 Average UCS values for treated and untreated samples for Soils A, B and C

A systematic increase in strength values was observed for all three soils treated with PAM when compared to their untreated counterparts. Fig. 2 shows that the level of improvement is influenced by soil type. For example, a considerable increase in strength was observed in both treated soils A and B, while minimal increase in strength was recorded in treated soil C. The improvement in strength for both soils A and B was 26.8 and 19.4 per cent over the untreated samples, respectively, while treated soil C exhibited only 11.6 per cent increase in UCS compared with the untreated sample. The max UCS values of the untreated samples ranged from 4.1 to 6.2 MPa.

It is thought that the anionic PAM is adsorbed onto the clay particles in the soil matrix and upon drying, bonding action between the soil particles occurs. This bonding is highly pronounced in soil A, in which the contact points between the soil particles were increased, resulting in increased frictional resistance force. In addition, the increased apparent viscosity of the PAM-solution has limited its ability to penetrate deeply into the aggregates in Soil C (i.e. the soil with high clay content), and the adsorption was limited to the external aggregates [31]. On the other hand, PAM molecules were able to coat most of the clay particles in soil B, and this increased the cohesion and internal friction forces to an extent that is higher than soil C but lower than Soil A.

The increase in USC strength would significantly influence pavement design thickness when using the mechanistic approach since it correlates directly with the resilient modulus [32]. As UCS value increases the resilient modulus is also increases, which ultimately increases pavement capacity to distribute loads.

C. California Bearing Ratio (CBR)

This study used CBR testing to evaluate the effects of using PAM on the bearing capacity of the stabilized samples of the three types of soils. This was conducted using a hydraulic loading machine for all treated and untreated samples. Two specimens were prepared per sample (treated and untreated) in order to ensure reliable results. Odd results were discarded and replaced by another prepared samples.

The unsoaked and soaked CBR values of the treated and untreated samples for the three soil types are presented in Table III. The values presented in this table are the average CBR values of the two specimens per sample. Standard errors with a 95% confidence interval were also tabulated. Although CBR greater than 100 is meaningless for pavement design, such values are presented for the purposes of comparison.

TABLE III
AVERAGE CBR VALUES FOR TREATED AND UNTREATED SAMPLES FOR SOILS A, B AND C

Soil Type	Description	Parameters	Unsoaked CBR %		Soaked CBR %	
			Untreated	Treated	Untreated	Treated
A	Gravel with silt and sand (GP-GM)	Average	**188.3**	**230.5**	**169.2**	**166.9**
		St. Error	3.2	4.5	2.7	2.7
B	Clayey Gravel with sand (GC)	Average	**467.6**	**499.4**	**129.5**	**131.8**
		St. Error	3.2	2.5	1.7	1.3
C	Clayey Sand with Gravel (SC)	Average	**13.8**	**18.9**	**2.2**	**2.5**
		St. Error	1.1	1.5	0.26	0.38

In Table III, a regular increase in the unsoaked CBR values can be observed for all three soils treated with PAM when compared with the untreated ones. Table III also shows that the level of improvement varies with soil type. For instance, moderate increases in strength were observed in both treated soils A and B, while a strong increase in strength was recorded in treated soil C. Changes in the bearing capacity of soil type A show an increase of 22.3% in favour of the treated samples. Whereas, treated samples of soil type B exhibited only 6.8% increase in CBR value compared with their untreated counterparts. The rate of change in CBR for soil B is considered relatively high when compared to the high CBR values of the samples. On the other hand, a significant increase in CBR value was noted in the treated samples of soil C. The maximum difference in CBR value was 37.3%.

In the soaked CBR test, no improvement was found in the treated samples of soil A, while trivial improvement was noted in the samples of soil B treated with PAM. On the other hand, treated samples of soil C gained appreciable strength compared to the untreated counterparts. The change in CBR of the treated sample was a 13.6% increase over that of untreated samples. In fact, cohesion and frictional forces between contacted particles are the major parameters in determining the shear strength of the soil matrix. Therefore, PAM was considered as a major factor that enhanced the interlocking or adhering of soil particles, which certainly increased soil shear strength in the case of unsoaked CBR, while this effect was diminished when the specimens were inundated, particularly with soil A.

The increase in CBR values of Soil C when treated with PAM would lead to some cost savings by designing thinner pavements than with untreated. As for Soil A and B, the limited increases in CBR values for Soils A and B gives an indication of more durable materials.

D. Hydraulic Conductivity

The study assessed a potential change in hydraulic conductivity of the three types of soils when they were treated with anionic PAM by conducting a falling head permeability test. Because of time constraints and longevity of the experiment, one specimen was prepared per sample (treated and untreated). To prevent piping of water between the mould and the specimen, a thin layer of wax was applied to the inside wall of the mould. The coefficient of permeability of the treated and untreated samples for the three soil types are presented in Fig. 3.

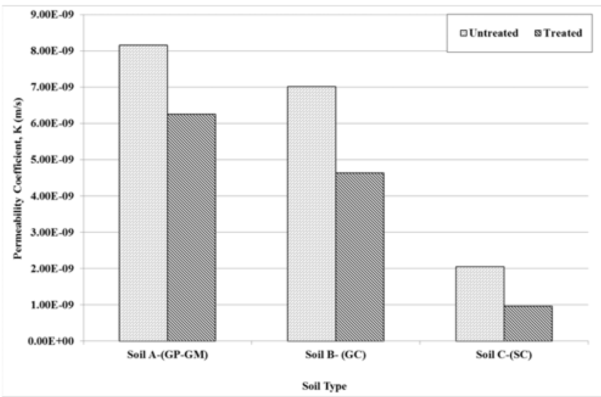

Fig. 3 Coefficient of permeability for treated and untreated samples for Soils A, B and C

In general, permeability decreased when the fine content of the soil was higher. This is because of the decreased porous volume as the fine content increased. The permeability sequence was Soil C< soil B< Soil A. Despite the low permeability of natural soils (< $1x10^{-7}$), which are practically considered impermeable [33], PAM was used only for comparison purposes.

Fig. 3 clearly shows a consistent decrease in the coefficient of permeability for all three soils treated with PAM when compared to their untreated counterparts. The rate of decrease depends significantly on the soil type. For example, comparing to the original value, the greatest reduction in permeability was noticed in treated soil C, while treated soil A exhibited minimal reduction. Treated Soil B showed moderate reduction in permeability. The coefficient of permeability of treated soils type A and B decreased by 23.3 and 33.9 per cent respectively, while the reduction of treated soil C reached 52.7 per cent. It has been proved that when PAM is added to the compacted water, the viscosity of the solution is increased [34]. As a result, the flow rate of the water-PAM solution in the conductive porous soil will decrease. Therefore, the rate at which the water can penetrate the sample is decelerated. The rate of change is highly pronounced in soil with high fines (i.e. low volume porous soil), Fig. 3.

The reduction in permeability is needed for the wearing course of unsealed pavement, as the low permeability will reduce water infiltration and minimise the risk of damaging the underlying pavement layers through loss of load bearing capacity and stiffness.

V. Conclusion

This study focused on using polyacrylamide-based additive to stabilize granular materials used in pavements. From the results of this study, it could be concluded that PAM has a good effect on such pavement materials, as highlighted below:

1- Using PAM additive as a stabilizer agent has increased the max dry density of all the treated soils. The level of improvement depended on the soil type. The recorded increases in dry density ranged from 0.85 per cent to 1.0 per cent when compared to equivalent untreated samples. Treating soils with PAM yielded an increase in unconfined compressive strength. The level of improvement was also dependent on the soil type. The level of improvement ranged from 11.6 to 26.8 per cent. Soils with less fines content exhibited the greatest strength gain and soils with higher fines content exhibited less strength gain.

2- Using PAM has increased the unsoaked CBR for all the treated soils. The level of improvement was found to vary with soil type. The level of improvement ranged from 6.8 to 37.3 per cent. Soils with higher fines content revealed greatest shear strength gain and soils with less fines content exhibited less shear strength gain.

3- The only change in soaked CBR value was found in the treated samples of soil C where the percent increase was 13.6.

4- Using PAM has reduced the permeability of all the treated soils. The rate of reduction was dependent on the soil type. The rate of change in permeability ranged from 23.3 to 52.7 per cent. Soils with high fines content showed higher reduction in permeability than soils with less fines content.

Acknowledgment

The authors would like to appreciate the support of the Earthco projects company, particularly Mr Mark Holding, for his logistic assistance.

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