

Identifying an Effective Binder for the Stabilisation of Allophanic Soils

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Allophanic soils have been identified as being problematic for the construction of roading pavements. When stabilised with lime, allophanic soils gain strength for a limited period of time, but they have been known to revert and return to their original strength. The binders that are currently used for allophanic soil treatment are lime and cement, and while the reverting process is avoided, these binders are not economical. Various potential binders for allophane were identified and put through a testing process that involved several phases, the final of which was a field trial. The field trial determined that three binder combinations provided approximately equal strength, although the cost of each dictated how useful each may become in the industry. The "Binder A" plus lime combination had the greatest ability to stabilise allophanic soil economically, and it was assumed that the cementitious nature of this binders reaction would prevent the soil from reverting over time.

1.0 INTRODUCTION

The compaction and stabilisation of soils can be problematic when the soils contain allophane. Allophane is a soil mineral that is formed when the ash from a volcanic eruption weathers under specific environmental conditions. Allophanic soils tend to lose strength with greater compaction effort, and if stabilised with lime, appear to 'revert' back to their natural state resulting in inadequate pavement support. A high-volume application of lime and cement is able to prevent the 'reversion' process, but this is an expensive option.

A 12 month research project was conducted in order to identify a binder that is effective at the stabilisation of allophanic soils. Several testing procedures were employed in various phases in order to determine which of the binders were most effective at stabilising allophanic soils.

An extensive laboratory testing program identified the binders with the most potential for stabilising soils that contain allophane. Those binders were then used in a field trial in order to simulate the conditions that are typically encountered on a roading project. Several lanes of were constructed using industry standard stabilisation equipment to allow the strength of the stabilised soil to be compared to the natural allophanic soil under typical field conditions. The strength of each section was reviewed utilising industry standard test procedures, and the cost of each binder was included in a cost analysis. It was therefore possible to make a comparison between each of the binders in terms of the soil strength achieved and the estimated cost.

2.0 BACKGROUND TO NATURE OF COMMON SOILS

2.1 Structure

The term 'soil' covers a wide range of materials. Soils range from clay, where the particles are too small to see, up to gravels, where particles can be easily separated as pebbles. Many common clay types are formed by two stable compounds that connect together in different arrangements. These two compounds are the silica tetrahedron and the aluminium octahedron, as shown in Figure 2.1 (Little, 1995; Pender, 2002).

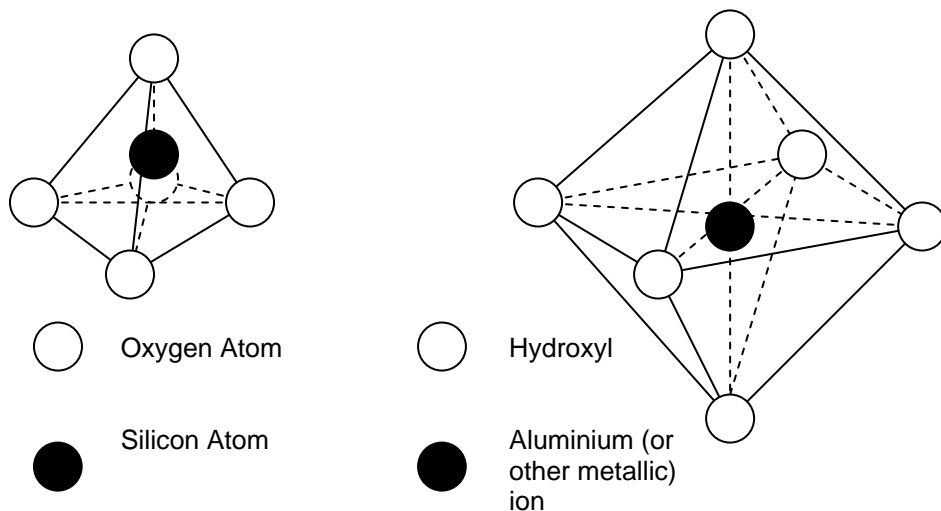


Figure 2.1: (a) Silica Tetrahedron and (b) Aluminium Octahedron (Little, 1995).

The tetrahedron and octahedron units form together to make sheets which are one unit thick, but can theoretically carry on indefinitely in a lateral direction. The silica atoms in the tetrahedron units have strong repulsion forces away from each other, so two tetrahedron units will only bond in a configuration that results in the two silicon atoms being as far apart as possible. This occurs when one oxygen atom from each of the two units bonds at a single corner. In addition to the sheets that form clay minerals, multiple tetrahedron units may also join to form rings and chains (Little, 1995; Pender, 2002). The sheets commonly formed by the tetrahedron and octahedron units are shown in Figures 2.2 and 2.3.

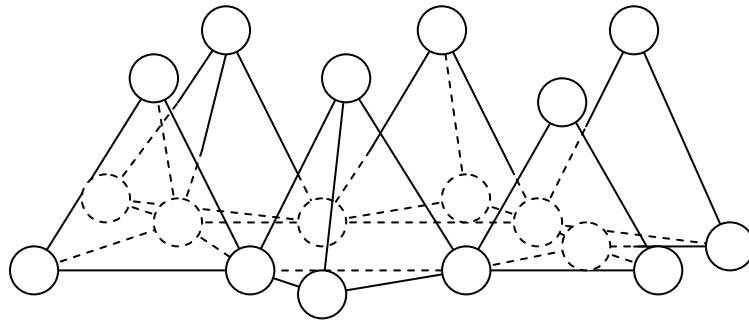


Figure 2.2: Silica Tetrahedra joined to form layers (Little, 1995).

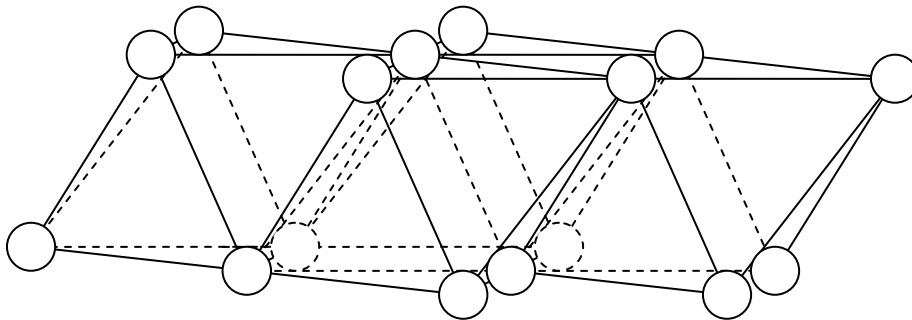


Figure 2.3: Aluminium Octahedron joined to form layers (Little, 1995).

These sheets come together in layers of different combinations to form various types of clay. Four of the most common clay minerals are; kaolinite, smectite, illite and montmorillonite. (Little, 1995; Pender, 2002).

2.2 Engineering Properties

Compaction can be defined as “the process of increasing the density of soil by packing the particles closer together” (Pender, 2002). This is particularly important for road building because of the three improvements that greater density brings to the soil mass. These are greater soil strength, increased stiffness, and reduced permeability (Pender, 2002)

For common clays, a greater effort in compaction results in a greater dry density. This is demonstrated in Figure 2.4, which is taken from a soil sample that has been compacted in laboratory conditions. Standard compaction is represented by a 2.5 kg rammer falling 300 mm, while a 4.5 kg rammer falling 450 mm represents heavy compaction.

It is assumed that readers are familiar with some of the basic behaviour of soils as demonstrated in Figure 2.4. i.e. The water content of the soil influences the dry density that is achievable after compaction, and the maximum density obtained on each curve is at the optimum water content (OWC) for the respective compaction effort (L. Wesley, 2004; Wilson, 2004).

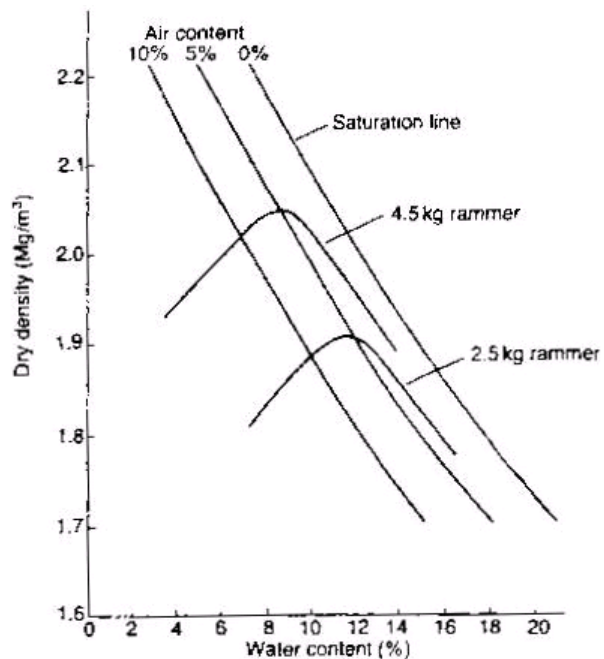
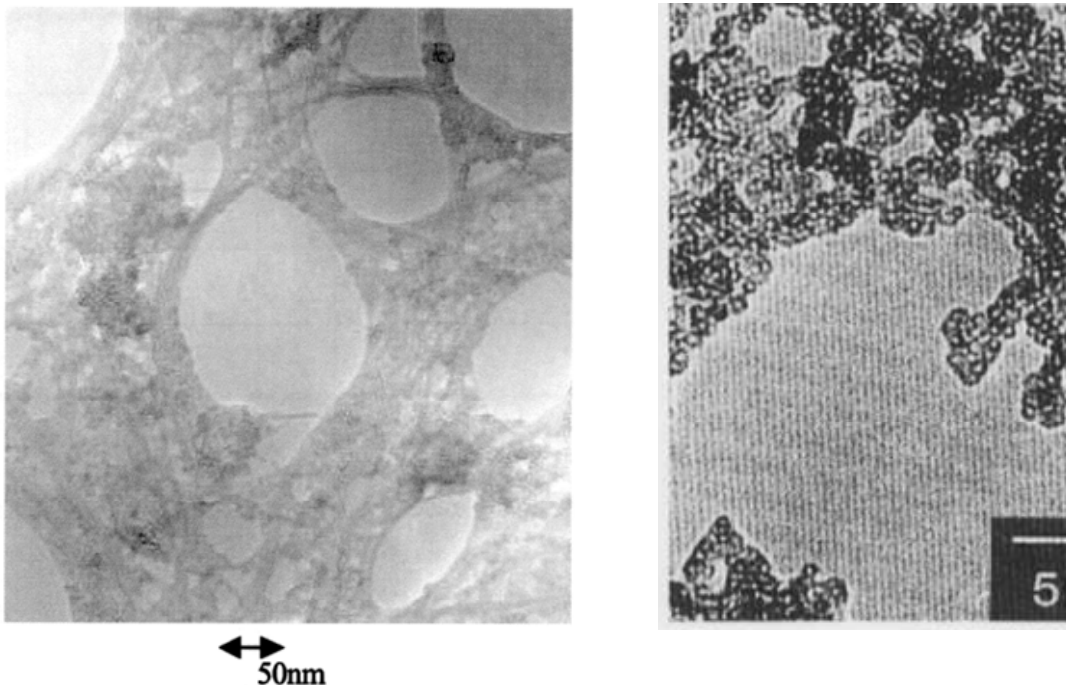


Figure 2.4: The dry density of a common soil compared to its water content, under different levels of compaction. (Pender, 2002)

3.2 Structure

The chemical structure of the allophane molecule is completely unlike that of the more common clays that were discussed in Section 2.1.1. In recent times electron microscopy has been used to show that allophane is not amorphous (non-crystalline), as was first suggested several decades ago. It is now known that allophane consists of spherical particles which, in New Zealand conditions, vary in size between 3.5 and 5.0 nanometres (Gustafsson, Karlton, & Bhattacharya, 1998; Nater, 2000; Parfitt, 1980, Wada, 1989 #56). The chemical composition of the spheres is approximately $\text{Al}_2\text{Si}_2\text{O}_5 \cdot n\text{H}_2\text{O}$. The ratio of Aluminium to Silicon in the soil has an effect on the ability of the soil to adsorb water, and this is discussed further below. Parfitt (1990) has stated that allophane deposits within New Zealand have a Al:Si ratio of between 0.9:1 and 4:1.

The spheres are connected by threads that consist of tubes known as imogolite, which has a similar chemical composition to that of allophane. Several authorities have assumed that it is these threads that contribute the majority of the strength in the allophane matrix (Gustafsson et al., 1998; Nater, 2000; L. D. Wesley, 2002). Figures 3.2 (a) and 3.2(b) are electron micrographs of allophane, on which the spherical particles and imogolite threads can be seen. Figure 3.3 is a simplified diagram of an allophane sphere.



Figures 3.2(a) and Figure 3.2(b) Electron micrographs of allophane (L. D. Wesley, 2002).

Similar to more common clays, imogolite consists of tetrahedral and octahedral units. With imogolite however, the units form small tubes rather than sheets, as was the case with the common clays. As with allophane, imogolite has an Al:Si ratio that can vary, although the suggested range of variation is not consistent between various researchers (Nater, 2000). Parfitt (1990) states that by comparison to other countries, allophane samples that originate from New Zealand have a particularly low proportion of imogolite tubes.

Research by Parfitt (1990) and Rousseaux & Warkentin (1976) has shown that the allophane molecule is effective at retaining water. Parfitt

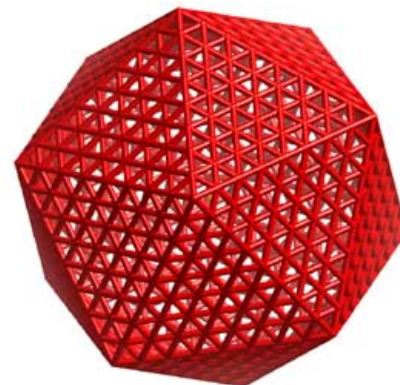


Figure 3.3: A simplified allophane sphere. (Bourgeois, 2004)

(1990) has stated that water molecules that are held on the inside of the hollow sphere are also adsorbed into its outer layer. Rousseaux & Warkentin (1976) have undertaken experiments specifically related to the allophane sphere's ability to adsorb water. Their findings demonstrated that when the allophane sphere was Al-rich it had a more open structure, resulting in a greater number of water molecules being bound to the outer layer of the sphere. The water content of allophanic soils is discussed further in section 3.3.

3.3 Engineering Properties

Wesley (2002) has reported the results obtained after measuring the Atterberg Limits of a large quantity of allophanic soils. The samples were shown to have liquid limits ranging between 80 and 240, and a plasticity index lying between 20 and 80. This demonstrates that allophanic soils are not identical and that they can have variable engineering properties between samples, as per the more common clay types (L. D. Wesley, 2002).

For contractors that have experience in constructing roads in some of the more common clay types, allophanic soils can be difficult to work with. This is because the effect of heavy compaction on allophane is generally opposite to that of other clay types. Wesley (2002) suggests that heavy compaction destroys the chemical structure of the allophane, thereby transforming the mineral into an amorphous mass with a low strength. Additionally, the breakdown of the chemical structure releases the large amounts of adsorbed water that is held within that structure, causing further strength reduction. Wesley concluded that increased compaction does not result in a return of the strength as more air voids are removed, rather the structure is increasingly broken apart. This is demonstrated in Figure 3.4, where several samples of allophanic soils have been compacted. Samples A through E are from a range of soils that have been classified as Kanto loam, which is an allophanic soil that originates from Japan. The figure shows that as the number of compaction blows increases, the cone index strength decreases. It was also evident that allophanic soils from different locations do not have identical engineering properties. Some allophanic soils are shown to be more sensitive than others, while two gain strength under light compaction. The water content of each of the soils is also shown on Figure 3.4, and these high values are typical for allophanic soils (Kuno, 1978; L. D. Wesley, 2002).

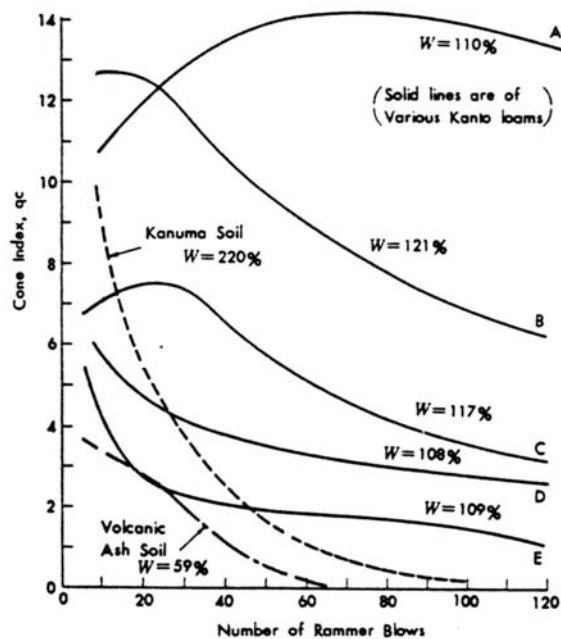


Figure 3.4: Compaction of various allophanic soils (Kuno, 1978).

Wesley concluded that increased compaction does not result in a return of the strength as more air voids are removed, rather the structure is increasingly broken apart. This is demonstrated in Figure 3.4, where several samples of allophanic soils have been compacted. Samples A through E are from a range of soils that have been classified as Kanto loam, which is an allophanic soil that originates from Japan. The figure shows that as the number of compaction blows increases, the cone index strength decreases. It was also evident that allophanic soils from different locations do not have identical engineering properties. Some allophanic soils are shown to be more sensitive than others, while two gain strength under light compaction. The water content of each of the soils is also shown on Figure 3.4, and these high values are typical for allophanic soils (Kuno, 1978; L. D. Wesley, 2002).

A soil's sensitivity value describes how sensitive a soil is to remoulding. Jacquet (1990) has confirmed that the sensitivity value can vary drastically between each sample of allophanic soil. In the tests carried out by Jacquet, the sensitivity values of various samples varied between 5:1 and 55:1. Jacquet also reported that these variations were not dependant on differences in the chemical structure of the sphere-imogolite tube matrix. Wesley's assumption that remoulding causes the soil's structure to be destroyed is confirmed by x-rays conducted by Jacquet. It was reported that the imogolite tubes are broken, and they do not appear to reform after long periods of rest (Jacquet, 1990).

The 'rule of thumb' that '*allophanic soils always have a high water content*' has been investigated by Wesley and So (So, 1995; L. D. Wesley, 2002). Their combined findings are illustrated in Figure 3.5, which shows an obvious link between allophane content and water content. The two soils that were used for investigations in this study are also plotted on the

figure. The soil utilised for the low-allophane testing fitted the trend established by Wesley and So, however the high-allophane soil did not. The water content of the high-allophane soil far exceeded the water content of comparable samples, although the reason for this was not immediately obvious.

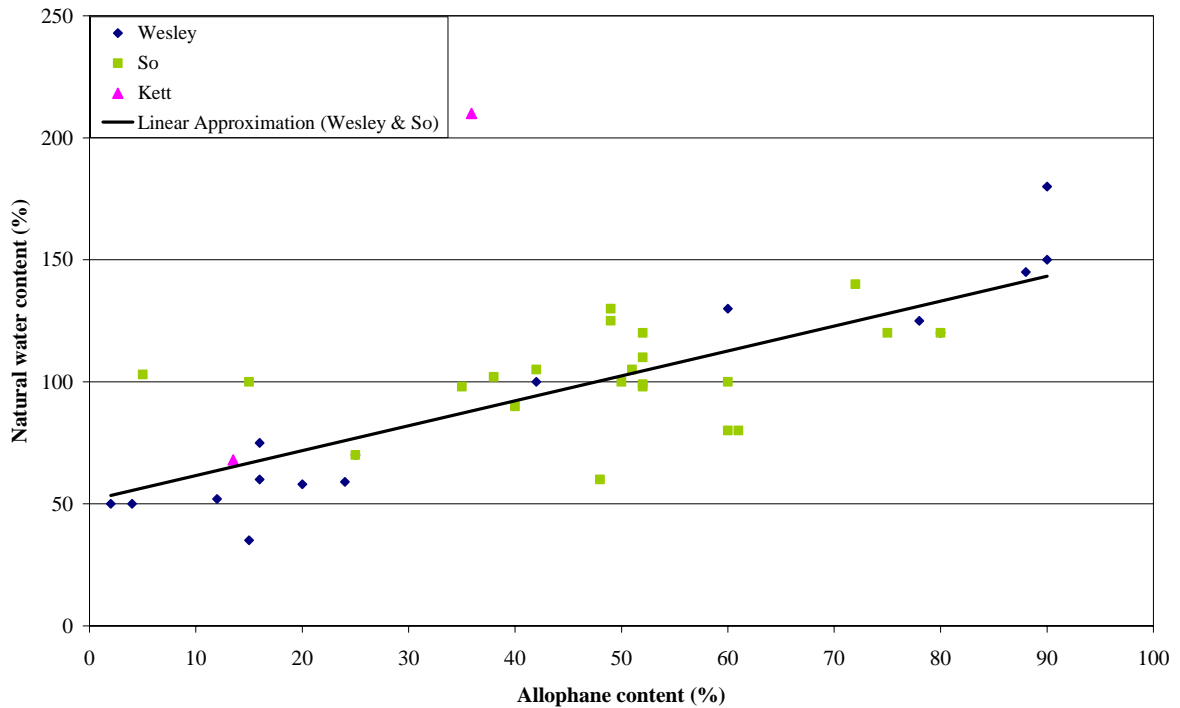


Figure 3.5: The natural water content of allophanic soils compared to their allophane content (So, 1991).

Allophanic soils have a water content – dry density relationship that is different from that of other soil types. New Zealand Standard 4402:1986 states that allophanic soils display irreversible changes in physical properties upon drying and that each point on the graph essentially relates to a different soil. It is suggested that this is because the water that is held within the structure of the soil is removed, therefore altering the structure of the soil NZS 4402 goes on to say that there is no maximum dry density, but a region where the same dry density can be achieved for a wide range of water content. Furthermore, in some cases the dry density continues to increase with a decrease in water content even to quite low values. All of these statements are verified in Figure 3.6, which illustrates the water content – dry density relationship of an allophanic clay dried back under various conditions.

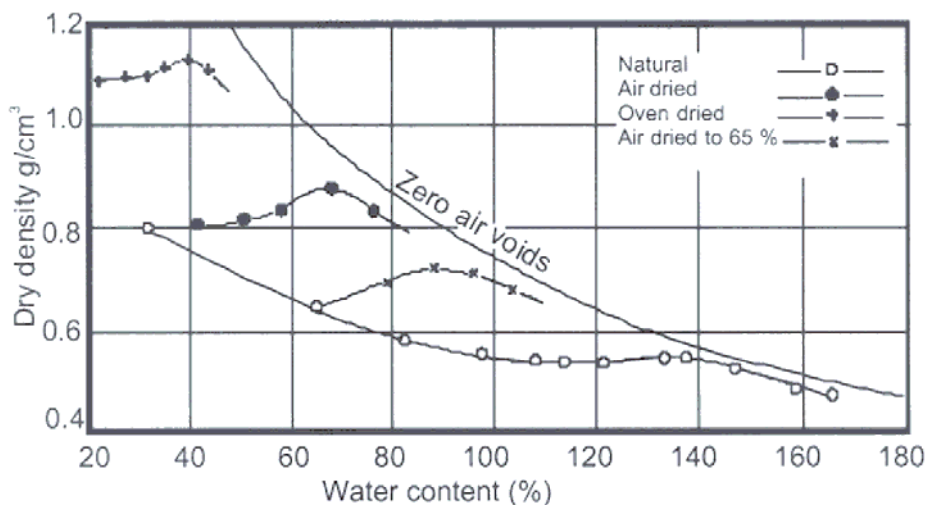


Figure 3.6: Density curves for allophane soil (L. D. Wesley, 2002).

3.4 Stabilisation of Allophanic Soils

The response obtained when allophanic soils are stabilised with lime is markedly different from that of other clay types. The common clays increase in dry density, dry out, and gain strength on a seemingly permanent basis. In preliminary tests carried out by HSL and Opus Laboratories, the strength gain of stabilised allophanic soils was shown to be only temporary in most cases. Where a long term strength gain was achieved, it has only been through the addition of excessively high volumes of lime and cement.

Allophane has been encountered in parts of Fiji, and McNamara (2003) has conducted a series of stabilisation investigations with this soil. McNamara has reported that stabilisation of these soils is not effective when the binder is 3% lime because the initial strength increase is lost over time. McNamara states that a binder content of at least 5% lime is required to avoid this reduction. McNamara has also shown that KOBM binder applied at 3%, can increase the strength of allophanic soil by 300% if a long curing time is achieved (McNamara, 2003).

Ei-Kon So (1995) has conducted an investigation into the lime stabilisation of soils containing allophane. He has determined that lime is not effective when the soil contains a substantial proportion of allophane, and that the optimum lime content increases with increasing allophane content. These findings are displayed in Figure 3.7.

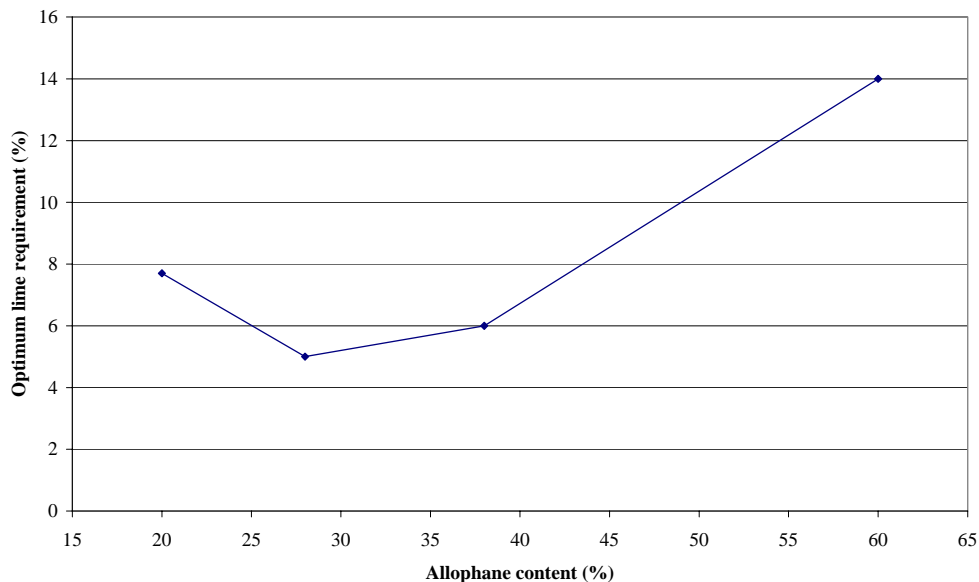


Figure 3.7: Influence of Allophane Content on the Lime Requirement (So, 1995).

Figure 3.7 shows how attempting to stabilise allophanic soils with lime would not be economical in most situations. It is not known why So reports that an increasing volume of lime oxide is optimal, as the allophane content decreases below 27%. It appears that soils with an allophane content of less than 20% were not investigated by So, but experience shows that if a soil contains more than 5% allophane, then there will be a drastic affect on the strength achieved if an attempt is made at stabilisation.

So also investigated the unconfined compression strength as a result of the amount of lime oxide that is adsorbed into the soil. As would be expected, the strength of each soil increases as more lime is adsorbed. Furthermore, the soils that had a higher allophane content did not gain as much strength as quickly as the low-allophane soil. So assumed that the 49% and 60% allophane samples shown in Figure 3.8 were significantly weaker than the other three samples because of the curing time. So hypothesises that the curing time that he employed (28 days,) was sufficient for soils containing less than 40% allophane, but not for those that contain more than this amount.

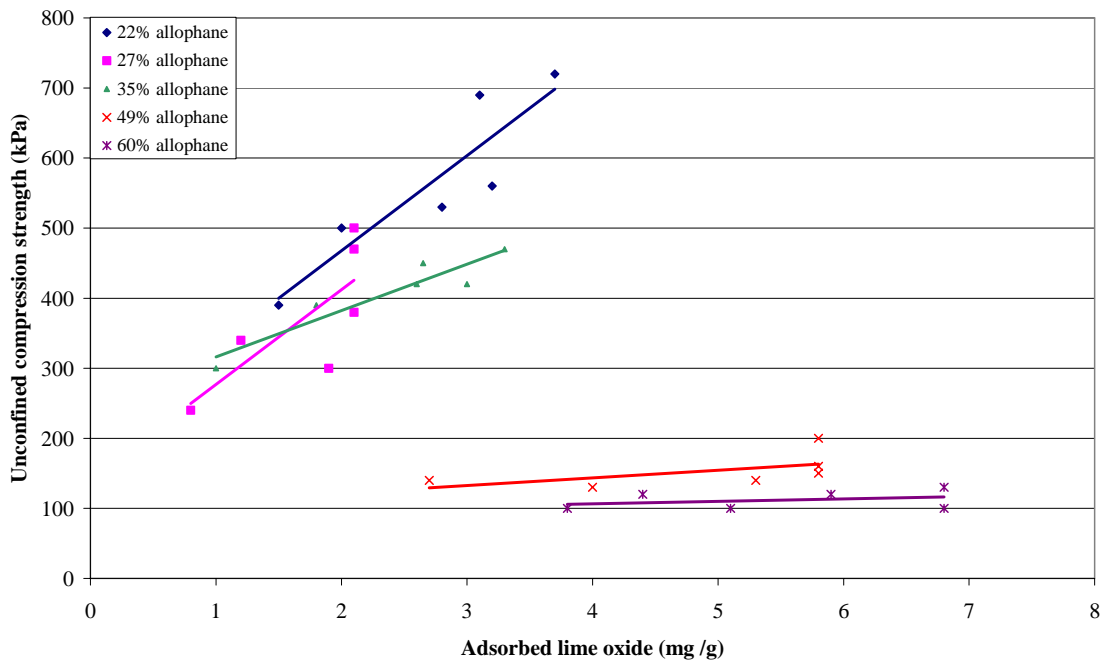


Figure 3.8: Influence of lime and allophane content on the strength of soil (So, 1995).

4.0 POTENTIAL BINDERS OF ALLOPHANIC SOILS

A wide range of binders are in production in New Zealand and around the world. Some binders, such as lime and cement, are manufactured from raw materials as products that have multiple uses, one of which is stabilisation. A number of the other binders that are available on the market are produced from the by-products of other industries.

Each binder is effective at stabilising a limited range of materials. Lime is most effective at stabilising very fine particles such as clay, while cement is most effective at stabilising aggregates. If an existing aggregate pavement is contaminated with clay, then a two-stage stabilisation with both lime and cement may be appropriate. Table 4.1 shows which material selected binders are effective at stabilising (Vorobieff, 1998). Selected binders are briefly discussed here, although it is assumed that the reader is familiar with these common industry standard binders.

Table 4.1: Materials Suitable for Selected Binders

	MORE THAN 25% PASSING 75µm			LESS THAN 25% PASSING 75µm		
	PI ≤ 10	10 < PI < 20	PI ≥ 20	PI ≤ 6 PI x % passing 75µm < 60	PI ≤ 10	PI > 10
Form of Stabilisation						
Cement and Cementitious Blends	[Solid black]			[Solid black]		
Lime	[Vertical lines]	[Solid black]	[White]	[Vertical lines]	[Solid black]	[White]
Bitumen	[Vertical lines]	[White]	[White]	[Solid black]	[White]	[White]
Bitumen/Cement Blends	[Solid black]	[Vertical lines]	[White]	[Solid black]	[Vertical lines]	[White]
Granular	[Solid black]	[White]	[White]	[Solid black]	[Vertical lines]	[White]
Miscellaneous Chemicals*	[White]	[Solid black]	[White]	[Vertical lines]	[Solid black]	[White]

Key	Usually suitable	[Solid black]	Doubtful	[Vertical lines]	Usually not Suitable	[White]
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* Depends upon grading. Single size sands require higher additive contents.

4.1 Pozzolanas

A pozzolana is defined as “a siliceous, or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide (lime) at ordinary temperatures to form compounds possessing cementitious properties” (Sherwood, 1995). Pozzolanas can be both natural and artificial. Some examples of naturally occurring pozzolanas are the common clays that react with lime (calcium hydroxide), which forms the basis of the industry-standard lime stabilisation process. Artificial pozzolanas include blastfurnace slag, which was also investigated.

4.2 Lime

Lime is particularly effective at stabilising clays, or aggregates containing a high proportion of fine clay particles. It has been determined that for lime to be effective the clay content of the material should be at least 10% while the plasticity index is between 10 and 50% (Bartley, 1998).

A document by Bartley Consultants (1998) has reported that lime stabilisation is not equally effective on all types of clay. Lime is recorded as being most effective on montmorillonite and kaolinite, followed by illite and halloysite. Investigations conducted by McNamara show that despite an initial strength increase, allophanic soils stabilised with a small amount of lime do not maintain this strength over time, and this is consistent with observations reported by Wilson and the authors. McNamara believes that at least 5% lime is required to prevent this from occurring.

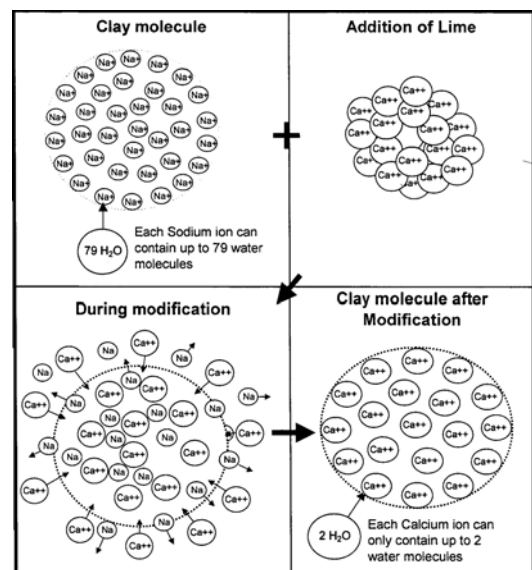


Figure 4.1: The reaction that occurs when clay is stabilised with lime

4.3 Portland Cement

Portland cement is a particular mix of chemicals that form a strong binding matrix when hydrated with water. The composition of roading aggregate or soil affects the ability of the cement to form a cementitious bond between the particles. It is stated that the plasticity index of the soil should be less than 8 to achieve an effective bond. Lime is often used prior to cement to lower the plasticity index if it is above this mark (Bartley, 1998).

The reaction that forms the cementitious bond is known as hydration. Hydration is a slow process where calcium silicate and calcium aluminate in the cement form a product that is less soluble than the original products. This process takes many days to complete, but the initial reaction upon mixing is sufficient to allow the passage of traffic after a relatively short period of time (Bartley, 1998).

4.4 Blast-furnace Slag

Blast-furnace slag is a by-product of the steel manufacturing industry and is formed when lime is used to purify iron into steel. Blast-furnace slag is cementitious when combined with water, although the reaction is considered slow even when compared to the hydration of cement. Further stabilising properties can be activated when it is used with certain other chemicals, known as activators. The most common activator is cement (Vorobieff, Clouston, & Quickfall, 2000).

In New Zealand, a similar type of slag is marketed under the name of KOBM Binder. The initials KOBM stand for Kontinuous Oxygen Blown Maxiitte, which is the name of the slag material produced at New Zealand Steel Ltd, and it has consequently been adopted as the binder name (Allan & High, 1992). Cuthers and Smith (1996) state that KOBM is not only effective at stabilising typical base course aggregates, but suggest that it is also suitable for clays and volcanic ash.

Despite allophanic soils having a high water content the literature suggests that KOBM is nonetheless effective at increasing its strength. McNamara (2003) has established that there is no reduction in strength with KOBM-stabilised allophanic soils, as is the case with modest quantities of lime.

4.5 Other binders

Several binders were also investigated throughout the laboratory tests that were conducted prior to the field trial. Three of these binders were successful in reaching the field trial, but exact nature of these binders will not be disclosed due to commercial reasons. However a brief outline of each is given below:

- Binder A: Man-made by-product that is reputed to create cementitious bonds upon combining with lime.
- Binder B: Natural product that is mined and crushed. Is known for its ability to adsorb a high volume of water, although it is also claimed to form some bonds upon combining with lime.
- Binder C: A natural product that is purified and concentrated for human use. Is not normally a stabilising agent but is said to form strong bonds with allophanic soil.

5.0 LABORATORY TESTING

5.1 Determination of Allophane Content

The presence of allophane was confirmed by testing for allophane in accordance with NZS 4402:1986, 'Methods of Testing Soils for Civil Engineering Purposes'. This test involved a small amount of soil being spread on the type indicator paper that is

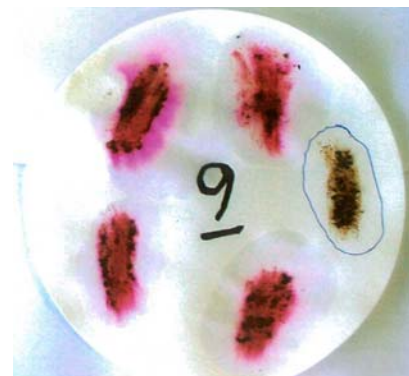


Figure 5.1: NaF test for allophane.

typically used for the measurement of pH. One drop of sodium fluoride (NaF) solution is then added to the soil. The fluoride from the NaF causes the hydroxide ions to be released from the soil, hence causing the indicator paper to change colour as the pH increases. Any colour change is observed, and the soil is placed into one of the following categories (NZS, 1986):

Red: more than 7% allophane
 Pink to red: 5% to 7% allophane
 Natural soil colour: less than 5% allophane

To determine the specific content of allophane within a soil sample, a more sophisticated procedure is used. The more advanced procedure is particularly important if a high proportion of organic material is within the soil, because the NaF can then give an incorrect positive high result (Parfitt, 2005). The NaF test is demonstrated in Figure 5.1.

The test that is used to determine the exact percentage of allophane within a soil is more time consuming and sophisticated than the NaF test. In this method, the Al:Si ratio is determined, and this is used on a chart to determine a multiplication factor. This factor is multiplied by the total proportion of silicon within the soil to determine the allophane content (Parfitt, 1990).



Figure 5.2: A flame spectrometer

To determine the Al:Si ratio a flame spectrometer is used. A flame spectrometer is used to burn a small amount of soil in liquid form, as seen in Figure 5.2. The wave length of the flame is then measured to ascertain the volume of each element within the soil.

5.2 Soil Properties

The properties of the soils that were used in the penetrometer tests are listed in Table 5.1. Westney Road soil was used to investigate low-allophane soils, while the soil from Rangitoto Road contained a high proportion of allophane.

Table 5.1: Properties of the Allophanic Soils that were used in the Penetrometer Tests

Property	Westney Road Soil	Rangitoto Road Soil
Colour with sodium fluoride	Red	Red
Percentage of allophane	13.5%	35.9%
Aluminium: Silicon Ratio	1.67	1.59
Liquid limit	65	243
Plastic limit	56	151
Plasticity index	9	92
Clay content	46%	40%
Silt content	40%	42%
Natural Water content	67.9%	215.6%

The Atterberg limits state that the soil from Westney Road was in liquid form, although it is close to being below the liquid limit. Meanwhile, the Rangitoto Road soil had very high plastic and liquid limits, and its natural water content placed it securely within the plastic condition. This seemed to be a fair assessment of the in-situ condition of both soils.

If an allophanic soil is particularly rich in aluminium it is able to adsorb and retain water due to its open structure (Rousseaux & Warkentin, 1976). The aluminium: silicon ratio of the Westney Road and Rangitoto Road soils were quite similar, at a moderate value of 1.6 – 1.7. It was obvious that the higher allophane content of the Rangitoto Road soil was the dominant reason for its higher water content, and the effects of aluminium on the water content were not observed.

As discussed previously, Wesley (2002) and NZS 4402 state that it is not possible to find a maximum dry density for allophane as it is possible to do with the more common soil types. Figure 5.3 demonstrates that as the water content of the Rangitoto Road high-allophane soil decreased, its dry density continued to increase. The highest dry density achieved during testing was measured when the water content of the allophane had reduced from above 200% to 50%.

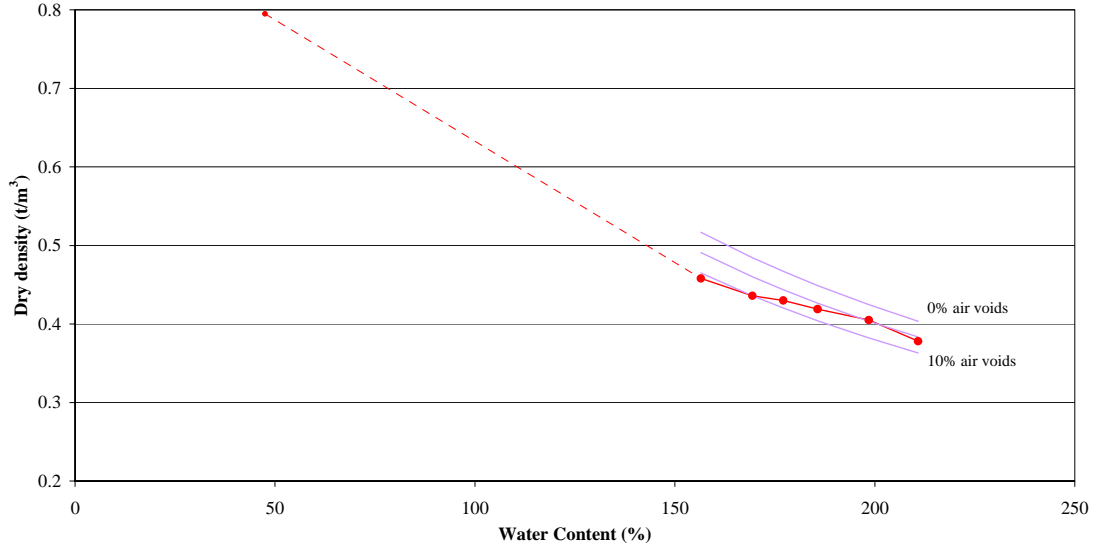


Figure 5.3: Compaction curve of high-allophane soil collected from Rangitoto Road.

The binders known to be most effective for each soil type were shown in Table 4.1. The table shows that if these were common soils, cementitious binders or granular stabilisation would be most appropriate for soil from Westney Road. Lime would be most suitable for the Rangitoto Road soil. In preliminary tests that are not summarised here, all of these options (excluding granular stabilisation) were investigated. A laboratory penetrometer test, CBRs and UCS tests were used to select the binders that were used in the field trial (discussed in Chapter 6). Prior to any new potential binders being added to the allophanic soil, the effect of adding 3% lime was observed, as it is traditionally the most common binder for stabilising clay soils. In Figure 5.4, the common clay performed as expected, but the allophanic soil had a negligible response to stabilisation.

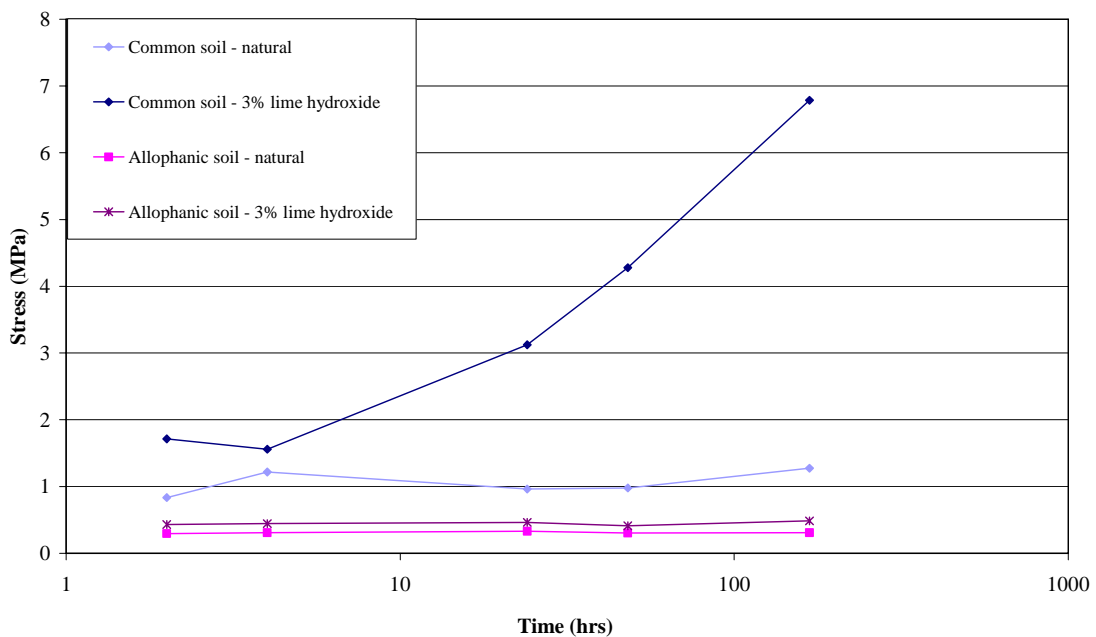


Figure 5.4: The stress required over a needle for it to be pushed into a low-allophane soil.

The ability of lime to stabilise low-allophane soil was also compared to the high-allophane soil. Figure 5.5 shows how the high-allophane soil had an even poorer response to lime stabilisation than the low-allophane soil.

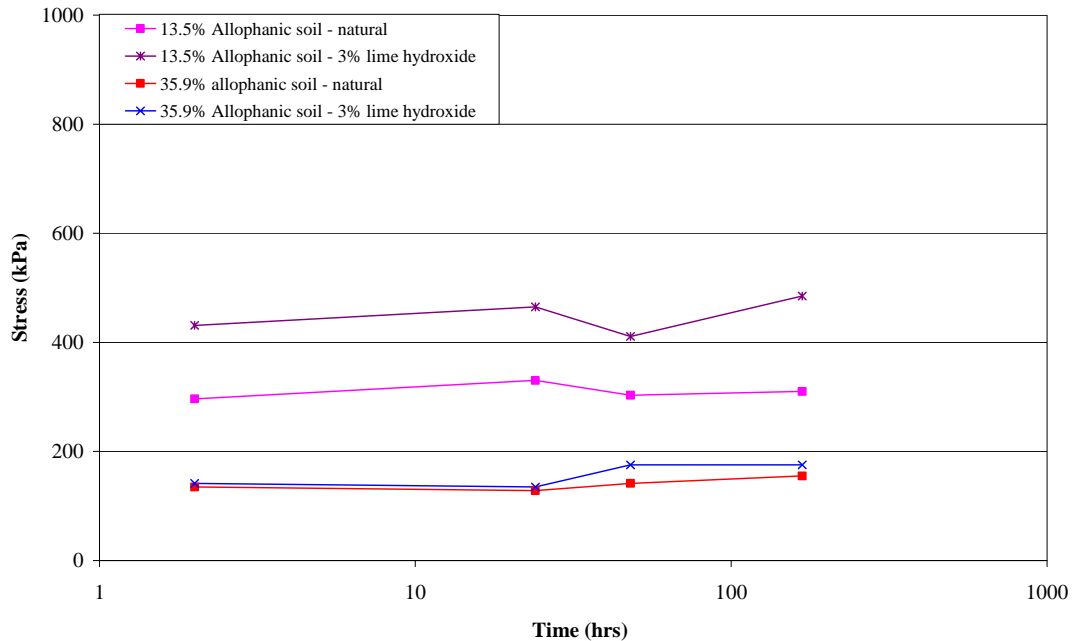


Figure 5.5: The stress required over a needle for it to be pushed into a high-allophane soil.

6.0 FIELD TRIAL

6.1 Trial Results

Preliminary penetrometer, CBR and UCS tests were conducted in order to establish which combinations of binders with the greatest potential to stabilise allophane. In order to compare the ability of these combinations, eight 20 metre long test lanes were constructed using industry standard equipment and techniques, as seen in Figure 6.1. Each of the eight lanes was used to test a different combination of binders, and these were compared to two additional lanes which contained no binder, thus representing a natural soil. Of the eight lanes, one was used to investigate the suitability of the most common stabilisation method (lime only), and a second represented the current allophane treatment method (lime and cement). The remaining 6 lanes contained various combinations of KOBM, lime, cement, and other potential binders that will remain confidential as stated previously.

The field trial was located at Westney Road, Auckland, at the same location where soils were collected for the preliminary laboratory tests. At that time the soil in the vicinity of the field trial was found to contain 13.5% allophane.

Several tests were conducted throughout the field trial, both during construction and after various periods of curing. Soil was collected from behind the hoe for use in CBR tests. The results of the CBR tests are presented in Figure 6.2.

CBR tests demonstrated that the strength of lime and cement were superior to any of the other binder combinations, but it is possible that the lower allophane content in this lane contributed to this.



Figure 6.1: Field trial stabilisation underway.

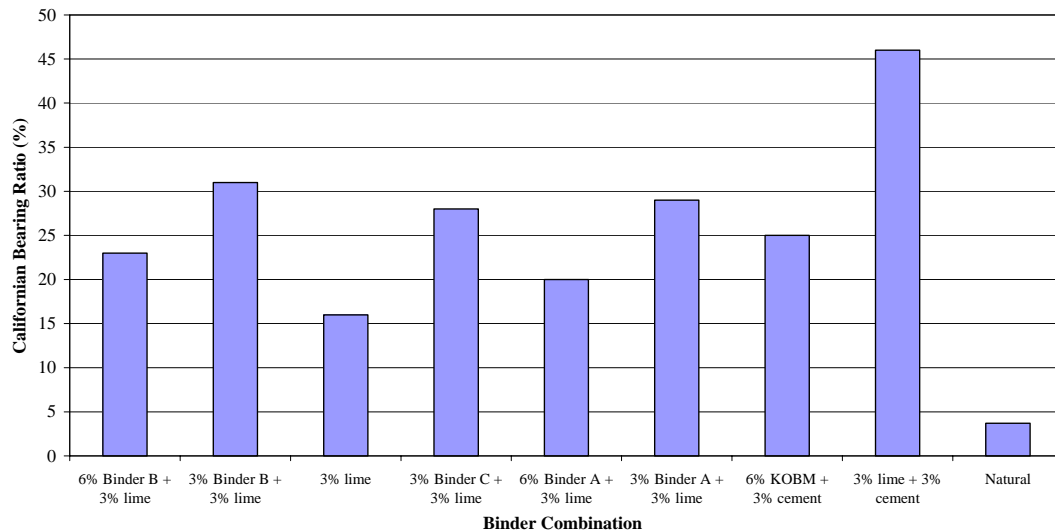


Figure 6.2: 7-day CBR of materials sampled 'behind the hoe' during the field trial.

The deflection the soil experienced while under a 8.2 tonne axle load was measured using a Benkelman beam. The deflection of each lane was measured three times, and the median deflection for each lane appeared to be an accurate reflection of the overall soil strength, with the exception being the lane that contained KOBM. Two of the lanes had a deflection that was smaller than the lime and cement lane, while another was less than half a millimetre larger, as shown by Figure 6.3.

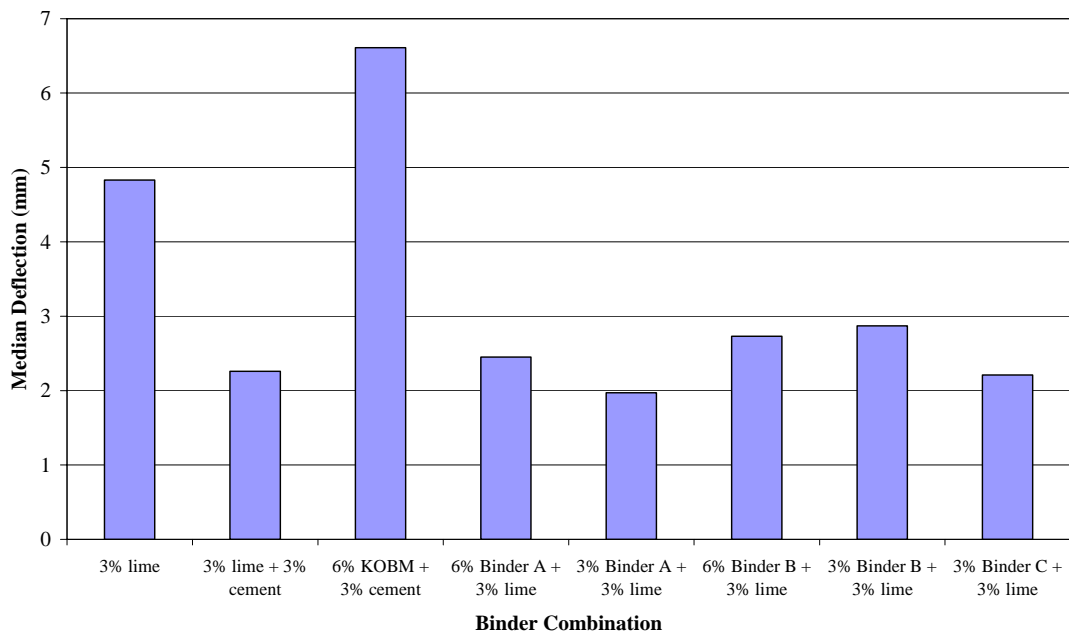


Figure 6.3: Deflection of stabilised soils under a 8.2t axle, measured by a Benkelman beam.

Clegg Impact Values were used to measure the surface strength of the stabilised soil on the day of construction, and four days, and five months after construction. Those sections that contained lime and cement, KOBM and cement, and 3% Binder A and lime had the greatest increase in strength as cementitious bonds began to form. Binder B had a smaller gain in strength, confirming an early hypothesis that although this material would dry the soil out, few cementitious bonds would be formed

The site of the field trial was revisited 5 months after construction. It appeared that the trial site had not been disturbed, although in some locations water had been pooling. Figure 6.4 shows how the increase in strength in the lane containing lime and cement was significantly greater than in the other lanes, while the 3% Binder A + 3% lime lane had the second largest increase. The lane containing KOBM also displayed a significant strength increase (CIV increase greater than 12), but the other lanes increased by a CIV of less than 10. Small

strength increases were observed in the natural lanes, where it was apparent that the surface of the soil had been dried out in the sun.

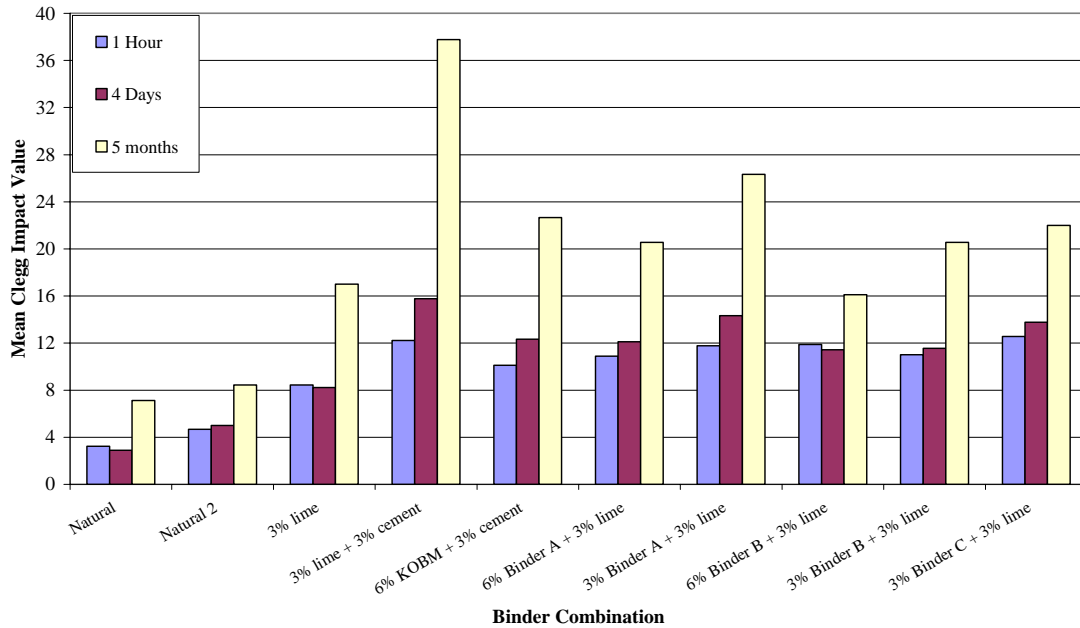


Figure 6.4: Average Clegg Impact Value of stabilised allophanic soil.

6.2 Cost Analysis

A performance based specification was used as the basis of a cost analysis. It was assumed that the contractor would attempt to maximise the strength of the subgrade so that the amount of aggregate required in the pavement would be minimised. The 'Austroads design chart for an unbound granular pavement' states that the minimal amount of aggregate can be used when the design CBR of the subgrade is 30. Only two of the binders achieved a CBR of 30 or higher; these were 3% cement and 3% Binder B (each with 3% lime). Another two binders were very close to CBR 30, achieving CBRs of 28 and 29. For those binders that did not reach the maximum design CBR of 30, the design CBR was taken as the actual strength that was obtained. The Austroads Design Chart (Austroads, 1992) was then used to determine the required aggregate thickness. The thickness of aggregate required and the total costs of the various pavement options are listed in Tables 6.1 and 6.2.

Table 6.1: Estimated aggregate price for building a pavement above stabilised subgrade.

Binder	Actual CBR (%)	Design CBR (%)	Required Aggregate Thickness (mm)	Aggregate Sale Price (per m ²)
Natural	3.7	3.7	480	\$36.00
3% lime	16	16	200	\$15.00
3% lime & 3% cement	46	30	140	\$10.50
6% KOBM & 3% cement	25	25	160	\$12.00
6% Binder A & 3% lime	20	20	180	\$13.50
3% Binder A & 3% lime	29	29	140	\$10.50
6% Binder B & 3% lime	23	23	175	\$13.13
3% Binder B & 3% lime	31	30	140	\$10.50
3% Binder C & 3% lime	28	28	145	\$10.88

Table 6.2: Estimated total price for building a pavement above stabilised subgrade.

Binder	Aggregate Price (\$/m ²)	Binder Price (\$/m ²)	Hoe Price (\$/m ²)	Total Sale Price (\$/m ²)
Natural	\$36.00	\$0.00	\$2.00	\$38.00
3% lime	\$15.00	\$3.15	\$2.00	\$20.15
3% lime & 3% cement	\$10.50	\$7.05	\$2.00	\$19.55
6% KOBM & 3% cement	\$12.00	\$6.60	\$2.00	\$20.60
6% Binder A & 3% lime	\$13.50	\$5.85	\$2.00	\$19.45
3% Binder A & 3% lime	\$10.50	\$4.50	\$2.00	\$17.00
6% Binder B & 3% lime	\$13.13	\$6.15	\$2.00	\$21.28
3% Binder B & 3% lime	\$10.50	\$4.65	\$2.00	\$17.15
3% Binder C & 3% lime	\$10.88	\$7.05	\$2.00	\$19.93

Binders A & B were the most cost effective binders when applied at a rate of 3% in combination with lime. The total cost of constructing a pavement over a subgrade containing Binder C and lime was determined to be similar to a subgrade containing either KOBM and cement or lime and cement. It was likely that the results of these cost investigations would have been different had the transportation cost been altered for the binders and the aggregate, to take into account the location of the project.

6.3 Further investigations

Stabilised allophanic soils have been recorded as reverting between 6 and 12 months after stabilisation with lime. Due to the nature of cement bonds the current allophane treatment method prevents the reversion processes, but it was not known if this was the case with the potential binders that have thus far only been monitored in the short term. It was assumed that the pozzolanic 'Binder A & lime' reaction would create cementitious bonds, but there was less certainty with regards to Binder B, which, due to the nature of the binder, is not likely to form a substantial number of cementitious bonds. To determine the long-term durability of the soils stabilised during the field trial, a Clegg Hammer and Scalar Penetrometer will be used to monitor the strength of the pavement over time. Due to the low proportion of allophane within the soil used in the field trial, it is not yet known if any reversion would be particularly noticeable.

7.0 CONCLUSIONS

A range of binder combinations were investigated in order to find an economical method for the stabilisation of allophanic soils. A two-stage CBR testing regime was conducted, and from this the binder combinations that appeared to have the greatest potential to stabilise allophanic soils were utilised in a field trial.

The field trial was located in an area that had a low proportion of allophane within the soil. It appeared that Binder A performed well when combined with lime, and was also one of the most economical solutions. Furthermore, '5% Binder A & 5% lime' appeared to stabilise the high-allophane soil successfully during the CBR tests, despite having an exceptionally high volume of allophane.

Binder B was effective at increasing the strength of the soil but it appeared that this was due to its ability to dry out the soil. It was assumed that a smaller change in the Clegg Impact Values after curing indicated that few cementitious bonds were forming within the soil.

It has been reported by various researchers that the ions of Binder C are held tightly by the allophane molecule. However it was thought that field trials conducted in a soil with a higher proportion of allophane would be required to determine if this bond could be exploited to allow Binder C to become the preferred binder for allophanic soils. This is because the high cost of Binder C would not justify its use in a project where the soils are similar to those encountered during the field trial.

There are many factors that come into a consideration as a pavement is being designed, and price is just one of them. If a significant amount of funding was available for a high-performance pavement then it is likely that a cement & lime combination will be the desired option because of the superior performance record of these binders. However many local authorities need to stabilise large areas of pavement over a number of roads, and in that case the economics will likely determine which of the binders are used. In this instance a Binder A & lime combination would be the most suitable.

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