Evaluation of Sulphonated Petroleum Products as Soil Stabilisers and Compaction Aids

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EXECUTIVE SUMMARY

An investigation into the effect of various proprietary ionic soil stabilisers or Sulphonated Petroleum Products (SPPs) on the properties of a range of soils has been carried out. Their influence on the compactability of the material, any strength gained by better compaction and their use as soil stabilisers was evaluated.

Initially 7 different SPPs were selected and tested for pH, anionic surfactant content, surface tension and specific gravity. Next 5 different soil types were taken and tested with a full range of conventional laboratory tests, as well as a series of non-routine tests such as X-ray diffraction, differential thermal and thermo-gravimetric analysis, cation exchange capacity and exchangeable cation percentages, in attempt to gain as much information as possible about the physical and chemical properties of the materials. Finally based on the data gathered from the SPP and soil tests, the soils were treated with the SPPs theoretically most likely to have the maximum benefit. The soils were then retested following the same procedure as before and a comparison was made to discover any improvements in strength.

The results produced in the laboratory show that the compacted strength of certain materials can be improved with appropriate chemical stabilisers. It was also shown that the quality of certain soils can be significantly improved using SPPs as stabilisers. Other soils only react to certain SPPs while some soils are not affected by any of the chemicals tested. Some of the SPPs also showed no reaction with the soils tested.

Additionally the thermogravimetric analyses showed that definite changes occur in the clay mineralogy supporting the claim of the suppliers of SPPs that the chemical “reactions” change the adsorbed water regime of the clays.

However despite some successes in the laboratory, various case studies obtained from a literature review indicated that although SPPs have performed successfully in the past, the data collected from a number of SPP treated roads proved inconclusive as a result of a lack of properly designed experiments with adequate control sections.

In considering all of the available information the following conclusions can be drawn.

- Standard engineering tests on road building materials are generally insufficiently discriminating to determine the effects of additives. Strength tests sometimes yield a lower result on materials combined with additive. Density tests also frequently fail to show any improvement when the compounds are added to the natural material.

- The strength of road building material generally increases when dried back to typical in-service pavement moisture conditions. This increase in strength is particularly pronounced in materials with a high clay content, which are the materials most susceptible to improvement by SPPs. In tests carried out in these in-service conditions these materials often exhibit very high strengths with or without additive (sometimes beyond the capability of the test equipment) and in excess of design requirements.

- Where more sophisticated tests are available, it may be possible to determine the type (as well as quantity) of the clay minerals present. However this is of little assistance in the user’s decision of which additive will be most effective because the chemical composition of the different products are not disclosed by the suppliers.

- Where material properties have been improved by the additives (either as a compaction aid or as a stabiliser), there is little quantitative evidence available on whether the initial cost outlay is justified by benefits from improved performance in whole-life terms. This is due to a lack of trials, which have been properly designed, constructed and monitored.

- It is not unknown for suppliers' agents to recommend the use of additive in situations where its application is unlikely to result in improvement of soil quality resulting in considerable wasted expenditure and sometimes even greater rates of deterioration than with the natural material.

- In some circumstances, the correct combination of material plus additive can undoubtedly result in an improvement of the engineering properties of soils. However, a number of major problems remain with their use.

    (a) The decision on which is the best combination of materials and additive rests with the suppliers not the users.

    (b) Many agents' of the suppliers continue to act in an unprofessional manner when recommending the use of additives

    (c) Even in circumstances where they may be beneficial, there is little quantitative evidence to show that there is an overall benefit in life-cycle terms.

    (d) It is not unknown for so-called independent advisors on the use of additives to have a financial interest in some of these products.

Until some of these issues have been resolved, it is recommended that users insist on a Product Performance Guarantee, including a retention of payment against a measure of future performance, which is defined in quantitative terms.

Contents

1 Introduction

Sulphonated Petroleum Products (SPPs) are marketed internationally as both compaction aids and soil stabilisers. Much of the marketing of these products is done by representatives who may lack objectivity and offer a “cure for all problems” product that does not exist. On the basis of the potential use as compaction aids, TRL Limited (Transport Research Laboratory) was asked to evaluate the potential of SPPs to improve the compaction of local natural materials and hence to increase their stiffness and performance in road structures, particularly in low volume roads. TRL approached CSIR Transportek to assist with some of the testing as considerable experience with SPP chemicals had been accumulated at Transportek over the years.

In order to test the potential benefits of SPPs as compaction aids and soil stabilisers, their effects on various soils were evaluated in the laboratory. Past experience has shown that the effectiveness of the chemicals is material dependent and certain products react with specific materials whilst others have no effect. A study was designed to obtain the maximum information from a limited number of tests, and to include a range of the chemical products typically available in the region. A wide range of materials, with which these products would typically be used, were tested.

This report focuses primarily on the engineering characteristics of SPPs. Information on the broader spectrum of issues surrounding SPP selection and use, including safety and the necessity to carry out a cost benefit analysis in life cycle terms can be found in a separate guideline document.

2 Background

Experience, and discussions with suppliers of Sulphonated Petroleum Products (SPPs, also known as ionic soil stabilisers) have indicated that it is essential to test materials prior to treatment with SPPs in order to evaluate whether the material will be beneficially affected by any of the chemicals (in terms of both compaction and stabilisation). In the experimental design for this project, a range of typical materials found in subgrades and used in unsealed roads, light pavement structures and even lower layers in conventional roads was identified. The first phase of the project selected seven chemicals (referred to as Products A to G in this report) that were made available by suppliers for this research project. In the second phase five materials (referred to as soils TRL1 to 5) were chosen for laboratory testing with the chemical products. Finally, the chemicals and materials were combined and tested for improvements in compaction and strength.

3 Phase 1 Selection of SPPs

Sulphonated Petroleum Products (SPPs, also known as ionic soil stabilisers) have been available since Reynolds Road Packer was first produced in the 1960s. Since then there has been a proliferation of apparently similar products on the market with in excess of 25 having been identified during this study. Many of these are probably regional Trade names for products produced in other countries. Other products marketed as generic soil stabilisers e.g. ligno sulphonates, emulsified bitumens, should not be grouped as SPPs as their mode of action differs from typical SPPs.

A typical SPP, which has an alkyl-benzo-sulphonate (Knowles 1998) as the reactive component will behave as:

- a surfactant, reducing the surface tension of the compaction water, and
- an anionic reactive material, neutralising the exchangeable cation component of the soil and allowing the adsorption of molecules with hydrophobic properties to the clay particles.

The latter behaviour (ionic exchange) is described by most of the SPP suppliers as that property that affects clay minerals and essentially “waterproofs” them against the deleterious effects of excessive soil moisture.

The surface tension effects are added benefits obtained from the surfactant nature of the reactive component of the SPP.

3.1 Product Evaluation Methodology

Various suppliers and users of SPP products in the region were approached and requested to supply about one litre of chemical for the research project. The following products were obtained:

A. **Supersol** (equivalent of Roadpacker from Canada)

B. **Chem-road** (a concentrate)

C. **CBR plus** (a concentrate)

D. **Roadbond**

E. **Conaid classic**

F. **Roadamine** (Roadplus in the Middle East)

G. **ISS 2500**

It should be noted that products B and C are concentrates and generally require twice the dilution of the other products for comparison purposes.

Simple preliminary testing was carried out in order to ascertain whether the products could be grouped into two or three groups for further testing to reduce the number of repetitive tests when the large-scale laboratory evaluation commenced. Based on previous experience and the potential requirements of the products the following testing was carried out:

- pH
- surface tension
- specific gravity
- anionic surfactant content.

3.2 Test Results

Table 3.1 shows the results of the pH and surface tension tests. These tests were carried out on different concentrations of the products. A description of the test methodology and a commentary on the significance of the results follows.

Product	pH				Surface tension (dynes/cm)			
Dilution (%)	0.10	1	10	Concentrated	0.01	0.1	1	10
A	2.8	2	1.4	0.7	88	91	91	73
B	2.2	1.3	0.9	1.7	53	40	40	-
C	2.7	2	1.5	0.9	78	78	36	34
D	3.5	2.5	1.6	1	80	87	87	33
E	3.3	2.4	1.7	1	77	75	42	42
F	2.5	1.8	1.1	0.2	82	33	33	33
G	2.2	1.6	0.9	0.2	90	86	86	86

Table 3.1. pH and Surface Tension Results

3.2.1 pH Testing

pH testing was carried out in order to compare the acidity of the various chemicals and group them into approximately similar products. The chemicals are generally acidified with various concentrated acids during production and modification of the acids is apparently carried out to “tweak” the products for application to different materials. The use of certain products on calcareous materials, for instance, apparently requires the addition of more phosphoric acid in order to “convert the calcite to apatite” (sic). An indication of the pH is also useful in determining the corrosiveness, potential environmental impacts and safety precautions necessary for handling the products.

The pH measurements were carried out on the undiluted and diluted products using a digital pH meter calibrated at a pH of 4 and 7 (it was not possible to calibrate the equipment utilised at a lower value for this work) compensated for temperature to 20 °C.

The pH results indicate the highly acidic nature of all of the products with all the materials having undiluted pH values less than 1 except Product B. This solution was very concentrated and viscous and it is unlikely that proper dissociation of the chemical occurs during pH measurement in its concentrated form. As the products are diluted with de-ionised water, the pH increases but even at dilutions of 1000 : 1 the materials are highly acidic with pH values between 2.2 and 3.5. It is notable that the pH of Product B decreases when slightly diluted supporting the earlier conclusion regarding the effect of the viscosity on the dissociation.

3.2.2 Surface Tension Testing

The surface tension of the chemicals is a measure of the capacity of the chemical to reduce the surface tension of water and thus to enhance compaction. The primary action of water in the compaction process is to lubricate the particles such that they can move against each other more readily and achieve a higher state of density i.e. to reduce the friction. The application of water to a soil in any state under full saturation of the voids in the soil, however, results in surface tension effects that attract particles to each other, the finer the grain structure of the particles, the greater the attraction to each other and the higher the stress necessary to separate them. The addition of a surfactant to the water can reduce the attraction between the particles and thus facilitate compaction i.e. a higher density is obtained for the same effort or an equivalent density can be obtained with less effort or with less water.

The measurements were obtained using the height that the liquid was drawn up a 0.4 mm diameter capillary tube at the various dilutions (at 20 °C). Using the standard equation relating the surface tension (T) to the capillary rise (h), density of water (d), gravitational acceleration (g) and radius of the tube, the surface tension was calculated. The products were tested at different dilutions to determine whether a significant reduction in surface tension occurred. It should be noted that in practice the dilution is approximately 0.01 per cent.

Surface tension measurements on the undiluted products (and product B at a 10 per cent dilution) were not possible as the chemicals were generally too viscous to be drawn up the very fine capillary tube used for the testing.

The surface tension was highly variable with 6 of the products varying from 33 to 73 dynes/cm and one with a value of 86 dynes/cm. The surface tension of water at 0°C is 75.8 dynes/cm and decreases by 0.152 dyne/cm for each degree rise in temperature2 (Duncan & Starling 1936). As the surface tension testing was carried out at 20°C a value of 72.8 dynes/cm could be expected, although the local variation in the value of acceleration due to gravity (g - taken as 9.81 ms^{-2} for these calculations) would also affect the result.

The surface tension of product G was high initially and remained at 86 dynes/cm irrespective of dilution while the surface tension of products A and D increased dramatically on dilution to significantly higher than the value for pure water. It should be noted that most of the products once diluted at 10,000 : 1 (the typical application rate in practice) had no beneficial effect on the surface tension and some (A, D and G) could possible even have a negative effect. Only product B could be expected to assist soil compaction at low dilutions.

Table 3.2 shows the results of the specific gravity and anionic surfactant content tests. A description of the test methodology and a commentary on the significance of the results follows.

Product	Specific Gravity	Anionic surfactant content (%)
A	1.133	10.0
B	1.192	69.3
C	1.023	18.2
D	1.014	1.8
E	1.008	8.5
F	1.058	10.0
G	1.154	< 0.1

Table 3.2. Specific Gravity and Anionic Surfactant Tests

3.2.3 Specific Gravity

The specific gravity is often used as an indication of the quality of the product. The test was carried out by comparing the mass of a fixed volume of chemical product in a pycnometer with that of an identical volume of water at constant temperature.

All of the specific gravities (SG) of the chemicals are in excess of 1 with a relatively small range of 1.008 to 1.192. Even this small range is equivalent to an 18 per cent variation of the most dense material over the least dense product. As the SG is a function of the densities of the individual constituents of the chemical, and the test is relatively simple and quick to carry out, it is recommended as a good quality control test. The primary constituents of the chemicals, to the best of the authors knowledge, have SG values between 1.075 and 1.838. These are mixed in various proportions (unknown to the author) and diluted with water to produce the required blend, which if consistent, should have an almost constant SG.

3.2.4 Anionic Surfactant

The anionic surfactant content is a measure of the number of available anions in the product, which are able to react with the cations in the clay or attach to any other negative exchange site in the soil material to be treated. The tests were carried out by the South African Bureau of Standards (SABS) and the results are given as a percentage (mole/mole) of anionic reactant. The test essentially involves the titration of the product against a high molecular weight cationic detergent in the presence of chloroform and a cationic dye.

Using simple chemical techniques it is possible to determine the number of gramme equivalents of anions added (GE) available for reaction with the cations in the material being tested. This is determined from the anionic surfactant content, its molecular weight and the volume of chemical added per unit volume of material.

The number of gramme equivalents in the chemical are:

GE = f(ASC (%), molecular weight of SPP, dilution)

This can be evaluated in terms of the volume or mass of product applied to the material to be treated i.e. the number of GE's in a given amount of material.

An example of this for the addition of 0.03 l/m2 (0.2 l/m3) of product with an ASC of 10 % to a cubic metre of compacted material is provided below:

$$GE = 10/100 \times (0.2 \times 1000 / 320)$$

$$= 0.0625 \text{ equivalents of anions per cubic metre}$$

There would thus be 0.0625 equivalents of anions available to react with the cations available in one cubic metre of the soil.

The ionic surfactant content is the primary indicator of the number of anions that are available in the product to react with the cations in the soil. There is a very wide range of results from < 0.1 to nearly 70 per cent, with the two highest results being for the two concentrated products, B and C. The difference between even these two is surprising with Product B having nearly four times more reactive component than Product C. Products A, E and F are all similar and equivalent to the 50 per cent dilution of product C. Only products D and G are low in anionic surfactant indicating that they probably originate from some other process. Product G, however, is particularly interesting as this is the original Ionic Soil Stabiliser and yet appears to have very little ionic reactant. The reason for this cannot be explained. This particular product has been successfully used on a heavy black clay in the past (Steyn 1993). Specific attention (i.e. the mechanism of "reaction") may need to be paid to this product, which by definition is probably not an ionic soil stabiliser although the advertising brochure specifically refers to the ionic exchange capacity (ISS Ionic Soil Stabiliser.1997).

The anionic surfactant content is recommended as a quality assurance test for users of these chemicals for stabilisation of clays as it provides a direct indication of the reactivity of the chemical. The test is a standard test, carried out routinely by independent agencies such as the SABS.

In terms of the anionic reactivity, it is possible, for a known cation exchange capacity (CEC) and a knowledge of the proportion of the individual ions making up that CEC, to calculate the number of available cations per cubic metre of soil and compare this with the number of available anions in the chemical. This will provide a useful indication of whether excessive chemical is being added to the soil, which may result in slippery conditions.

3.3 Grouping of Products

In order to reduce the amount of testing to reasonable proportions, it was proposed that the chemicals obtained would be grouped into apparently similar products. This is based on the tests carried out and described in section 3.2, and may overlook certain other potentially important characteristics, although this possibility is considered to be unlikely. It must be noted, however, that it is easy to add small amounts of various chemicals to improve the products, or make them slightly different to others. None of the products are patented as patenting would necessitate disclosure of the formulations. It is also not the intention of this project to have all of the chemicals analysed to determine their constituents. However, on the basis of the above test results and discussion, the following products appear to have the potential to perform similarly in terms of the ionic soil stabilisation:

- Group S1: A, B (diluted 1 : 7 parts water), C (diluted 1 : 2 parts water), E, F.
- Group S2: D, G.

The following groups appear to be similar in terms of their effectiveness in reducing the surface tension for compaction:

- Group C1: B, F
- Group C2: A, C, D, E, G.

For the compactability analysis, i.e. effect of surface tension reduction, Products F and G are to be used on each material with products B and D being tested on the material, which shows the most benefit when treated with products F and G.

For the clay mineral treatment, products B and G are to be used for each material and products C and D will be tested on the materials showing the most benefit when treated with products B and G.

Testing of the products as compaction aids will initially concentrate on one product from each of the two groups identified, one with low surface tension and one, which has little effect on the surface tension of water. Limited testing of selected materials with some of the other products will complement the results.

Testing of the products as soil stabilisers will follow the same route as for the compaction aids, but, on the basis of the anionic surfactant content, two different products will be used. Testing of other products on selected materials will complement the results.

4 Phase 2 Selection and Properties of Test Soils

Experiences of, and discussions with suppliers of Sulphonated Petroleum Products have indicated that it is essential to test materials prior to treatment with SPPs, in order to evaluate whether the material will be beneficially affected by any of the chemicals (in terms of both compaction and stabilisation). In the experimental design for this project it was necessary to ensure that a range of typical materials used in unsealed roads, light pavement structures and even lower layers in conventional roads were evaluated.

4.1 Experimental Design Requirements

The experimental design was centred around investigating compactability aspects as well as stabilisation benefits. Initial planning envisaged a series of materials falling into a factorial design with grading and plasticity as the factors. The low plasticity materials would be more conducive to use of the chemicals as a compaction aid and the higher plasticity materials would hold potential for ionic stabilisation. A defined level of grading parameter, typically the grading modulus, would be indicative of the overall fineness or coarseness of the material.

Consideration of previous work on chemical stabilisers (Paige-Green and Coetser 1996), however, indicated that the shrinkage product (SP - product of bar linear shrinkage and percentage passing 0.425 mm sieve) would be the most appropriate parameter on which to base material selection. As this parameter is essentially a combination of the plasticity and grading, it accounts for the same properties as the original factorial design. It would, however, provide a linear variation of materials. It was important, however, to ensure that a range of different clay minerals (the major contributor to the “stabilisation” reactions) was included in the materials tested. On this basis, different materials were selected in the mid range to cover the range of typical clay minerals.

The following levels of shrinkage product of the materials were identified for the sample selection:

SP < 50

50 < SP < 100

100 < SP < 250

250 < SP < 400

SP > 400

4.2 Material Properties Evaluated

In addition to the shrinkage product discussed above it was necessary to characterise the materials fully for later analysis purposes. Both traditional road engineering test parameters and specific soil identification and chemical properties were determined. The following range of tests was carried out on the samples collected:

- Grading (sieve and hydrometer) (TMH 12 methods A1a, A5 and A6)
- Atterberg limits and bar linear shrinkage (TMH 12 methods A1a, A2, A3 and TMH 13 A4)
- Maximum dry density and Optimum moisture content (TMH 12 method A7)

- California Bearing Ratio (TMH 12 method A8)
- Apparent and bulk relative density (TMH 12 method B14 and B15)
- pH and electrical conductivity (TMH 1 method A20 and A21T)
- X-ray diffraction analysis
- Differential thermal and thermo-gravimetric analysis
- Cation Exchange Capacity and exchangeable cation percentages
- Shakedown bulk density and weighted fractional density (Semmelink 1991)

4.3 Material Selection

Various materials were located and basic indicator tests carried out on them in order to determine whether they fulfilled the fundamental Shrinkage Product requirements. Once potentially suitable materials were identified, the full range of testing identified above was carried out.

The following materials were selected and retain the TRL sample numbers indicated throughout this project:

- Highly weathered diabase (TRL1) (Level II)
- Black clay (residual norite) (TRL2) (Level V)
- Ferruginous gravel (residual rhyolite) (TRL3) (Level I)
- Fine sandy gravel (ferruginous residual chert/dolomite wad) (TRL4) (Level IV)
- Fine gravelly sand (residual chert) (TRL5) (Level IV)

Despite sampling and testing numerous sources, no suitable material in the 100 to 250 shrinkage product group could be located. However, as most high plasticity materials contain smectite (montmorillonite) clays and low to medium plasticity materials contain kaolinite and illite (Weinert 1980), duplicate samples were collected in the SP 250 to 400 range with the intention of obtaining different types and proportions of kaolinite and illite/mica. The testing described in section 4.4 shows that this decision was vindicated.

4.4 Conventional Material Testing Results

Tables 4.1 and 4.2 show a summary of some of the more salient test results. Details of the test methodologies and the results in full can be found in Annex A.

Property	**Sample number**				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
Grading modulus	2.21	0.96	2.08	2.14	1.5
Grading coefficient	32.6	8.75	35.2	29.8	24.6
Dust ratio	0.42	0.47	0.42	0.54	0.40
Liquid limit (%)	32.7	52.5	SP	30.7	31.5
Plastic limit (%)	23.7	24.7	SP	20.7	22.1
Plasticity index	9.0	27.8	SP	10.0	9.4
Bar linear shrinkage (%)	4.8	14.1	0	5.6	5.3
Shrinkage product	85	1080	0	265	292
Activity	9.9	0.98	-	0.81	0.82
MDD (kg/m3)	2082	1680	2080	1999	1946
OMC (%)	11.7	20.0	9.0	10.5	13.0
100% Mod AASHTO Compaction Soaked CBR	40	2.9	108	58	74
Swell (%)	0.1	3.1	0.04	0.3	0
G-class	G6	< G10	G6	G6	G6
ARD > 4.75 mm	2.892	2.776	2.811	3.043	2.653
ARD < 4.75 mm	2.977	2.840	2.725	2.833	2.754
BRD > 4.75 mm	2.240	2.568	2.464	2.248	2.416
BRD < 4.75 mm	2.476	2.726	2.299	2.615	2.273
ARD/BRD < 0.075 mm	-	2.399	-	-	-
Water absorption >4.75 (%)	10.1	2.80	4.50	10.50	3.27
Water absorption <4.75 (%)	6.80	1.48	6.81	2.96	7.69
AASHTO Classification	A-2-4	A-7	A-1-b	A-2-4	A-2-4
Unified Classification	SW	SC	SW	SC	SC

Table 4.1. Traditional Soil Test Results

4.4.1 Grading

The grading analyses show the bulk of the materials have gradings within the recommended limits for unsealed roads, typical of materials that could be improved by chemical stabilisation to lightly sealed standard. The percentages passing the 0.075 mm sieve varied between 7.5 and 36.3. Typically, material with between 15 and 55 per cent passing the 0.075 mm sieve is suggested for SPP treatment (Paige-Green and Coetser 1996). It should be noted that this material was wet sieved according to TMH 12 but when dispersed with Calgon (sodium hexa-metaphosphate) for the hydrometer analysis, the percentage finer than 60 µm was higher than that passing 75 µm for three of the samples (the generally finer materials).

The percentage passing 2µm (i.e. the true colloidal clay fraction) ranged between 1.3 and 28.5. On this basis and taking past experience and theory into account, samples TRL2 TRL4 and TRL5 would be expected to react best with the SPPs. Sample TRL1 was considered to be soft and the degree of breakdown under compaction could be quite severe.

4.4.2 Atterberg Limits and Bar Linear Shrinkage

The Atterberg limits and bar linear shrinkage identify materials varying from essentially non-plastic to a very high plasticity fulfilling the basic requirements of the experimental design. The bar linear shrinkage is, however, considered to be the most useful indicator of the clay fraction and component (Paige-Green and Ventura 1999) and when weighted by the fines content (Shrinkage Product) gave a range of values between 0 and 1080. It should be noted that none of the samples complies with the South African requirement for gravel wearing course materials (TRH 20 1990) and SPP treatment would therefore be a possible option if these materials were to be considered for use in unsealed roads.

Despite the relatively low plasticity index and bar linear shrinkage, the very high Activity and “modified Activity” of sample TRL1 was notable.

4.4.3 Maximum Dry Density and Optimum Moisture Content

The maximum dry density (MDD) and optimum moisture content (OMC) at Modified AASHTO compaction showed no unusual characteristics with typical densities between 1900 and 2100 kg/m3 and optimum moisture contents decreasing as the density increased. The black clay had a lower density as expected, but it is interesting to note that the diabase, which had the highest density, also had the third highest OMC.

The maximum dry densities and OMCs determined using the vibrating table were almost identical to those using the Modified AASHTO effort except for the ferricrete (TRL 3), which was about 5 per cent higher. As the vibrating table essentially compacts the material to its refusal density, these results were surprising. What was even more surprising was that the OMCs of all but the black clay (TRL 2) increased, whilst the decrease in the black clay was 13 per cent.

4.4.4 California Bearing Ratio

As discussed earlier, the inherent variability associated with the CBR test resulted in somewhat erratic results and the soaked CBR values at various compaction efforts were determined by plotting the best fit line around the laboratory results and interpolating the CBR at the specified compaction efforts. A wide range of CBR results was obtained with values between 2.9 and 108 at 100 % Mod AASHTO compaction effort. The slope of the strength density curves was, however, highly variable and four of the five materials had CBR values of about 35 at 95 per cent compaction, resulting in their being classified as G6 materials (TRH 14 1985). The individual curves are plotted in Figure 4.1.

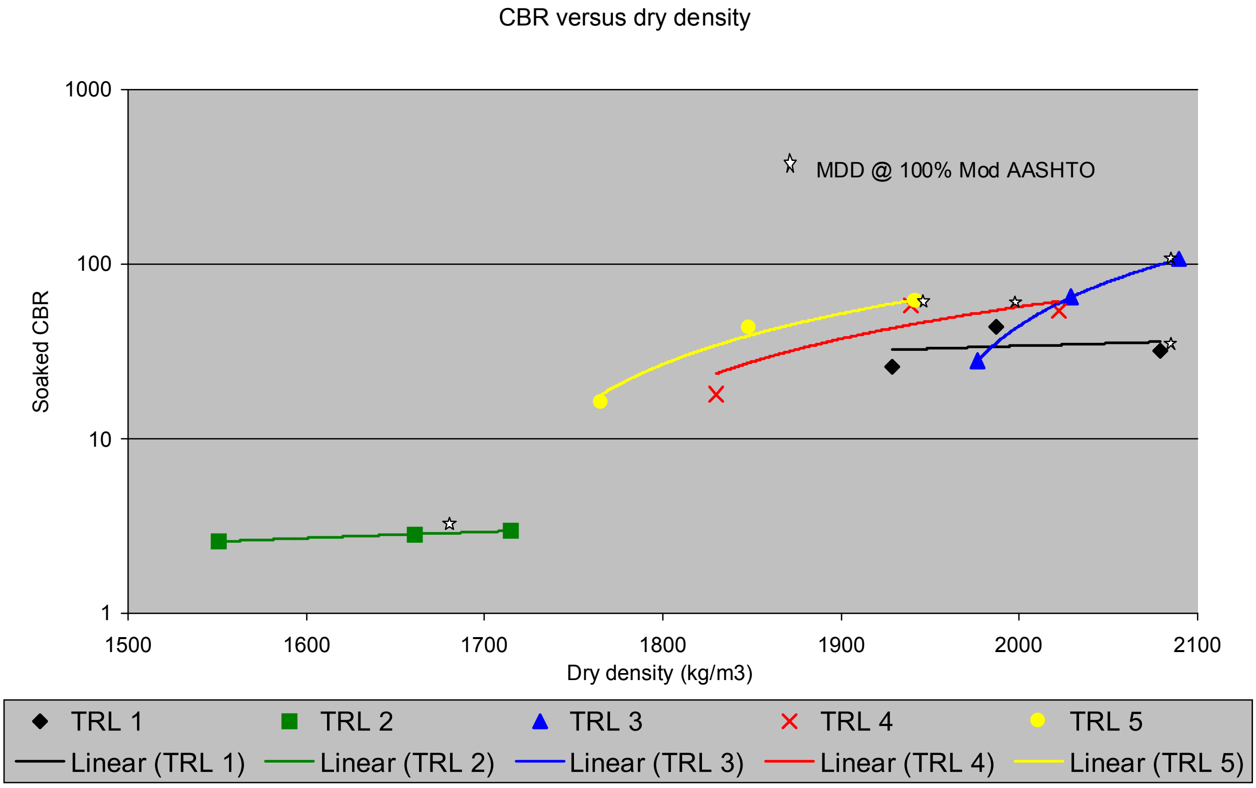

Figure 4.1: **Plots of soaked CBR against maximum dry density**

It is clear from the slopes of the curves that a slightly higher density for material TRL 3 would result in a significant increase in strength whilst a greater compaction effort would have minimal effect on the strength of samples TRL 1 and TRL 2. Samples TRL 4 and TRL 5 would be affected to a fair degree.

The weighted CBR is generally of the same order of magnitude as the values determined from Figure 4.1 except for TRL3 which is considerably stronger. This is probably the result of the grading which allowed a much higher degree of compaction than the other materials and thus the penetration resistance at 5.08 and 7.62 mm increased dramatically.

4.4.5 Apparent and Bulk Relative Densities

The apparent and bulk relative densities were determined in order to predict the maximum dry density and OMC (Semmelink 1991). The values for the ARD on the coarse fraction should approximate the specific gravities (relative densities) of the predominant minerals comprising the material. Inspection of the results in terms of the parent materials, clays and composition supports this with the diabase, black clay and ferricrete being about 2.8 (the SG of mafic minerals), the shale being about 2.65 (the SG of quartz) and the chert being about 3.0 (the SG of dolomite and manganese and iron wad). The bulk relative densities are related to the voids in the materials and are indicative of the porosity and potential water absorption of the materials. The tests are done on different fractions of the grading and a weighting of the results provides an indication of the potential compacted density of the material. High water absorptions were determined on the coarse fractions of the diabase and the chert.

Laboratory determination of the bulk relative density is fraught with difficulties (Semmelink 1991 and pers. Comm.). This problem is supported by the development of an automated method for determining the bulk specific gravity for use in Superpave design calculations such that reproducibility of the results is improved (Kandahl 1999).

4.5 Electrochemical Test Results

Property	Sample number				
	TRL1	TRL2	TRL3	TRL4	TRL5
PH	8.32	7.80	7.10	5.42	6.05
Electrical conductivity (S.m-1)	0.047	0.211	0.048	0.005	0.003
CEC (meq/100g)	41.12	35.37	4.97	10.21	5.93
Ca++ (meq/100g)	24.1	23.25	0.70	0.19	0.47
Mg++ (meq/100g)	18.43	9.43	0.58	0.15	0.73
Na+	0.33	0.33	0.02	0.01	0.05
K+	0.22	0.74	0.32	0.10	0.16

Table 4.2. Electrochemical Properties

4.5.1 pH and Electrical Conductivity

The pH of soils used for treatment with SPPs has been shown to be of critical importance with the earliest known published specification for SPP use (KEZDI, A. 1979) limiting the pH to a maximum value of 7.5. The theory behind this was that the SPP is highly acidic and various neutralisation reactions would occur between alkaline soils and the SPP. The pH of a soil is also a direct indication of the electrochemical properties of the soil in solution.

The electrical conductivity of the material is related to a certain extent to the pH in that the more soluble matter which can go into solution, the more ionisation occurs and the electrochemical properties of the material are affected. This parameter is used as a direct indicator of the soluble salt content of soils.

4.5.2 X-ray Diffraction

The X-ray diffraction analyses carried out by the two laboratories indicated generally similar results although some differences were noted. These could be the result of the sample preparation or interpretation of the outputs (unlikely as the results were compared with a data base by computer) and highlight problems typically encountered with X-ray diffraction. A range of all the common clay minerals occurring in southern Africa was present in the materials collected for SPP treatment although the mica/illite components were generally small. A notable interlayered illite/smectite component was identified in TRL 3, 4 and 5 by the Geosciences Council. Of note was the feldspar content in samples TRL 1 and 2 as this is used by some of the SPP suppliers in the region to identify the potential reactivity of soils with SPPs.

The basis of using the feldspar content for the prediction of performance of SPPs has been described by Scholen 1995 who indicates that, as feldspar is the most abundant rock-forming mineral comprising about 60 per cent of the earth’s crust, it is the primary source of clays. The hydrolysis of feldspars during weathering results in the formation of kaolinite and amorphous silica. Depending on the availability of potassium, sodium and calcium, illite and smectite may also form. This supports the use of the feldspar content in estimating the potential reactivity of soils as carried out by some of the suppliers.

4.5.3 Differential Thermal Analysis (DTA) and Thermo-Gravimetric Analysis (TGA)

The differential thermal and thermo-gravimetric analyses all showed reproducible peaks associated with the solid-state transitions, particularly quartz at about 570°C and good reproducibility for other events.

Samples TRL 1 and TRL 2 both showed significant losses of mass between the start of the test and 200 °C primarily as a result of the loss of moisture from the smectite. The bulk of the loss in mass of samples TRL 3 to 5 occurred between 400 and 500°C with smaller step-wise losses at various other temperatures. The interpretation of the DTA profiles is often complicated by the confounding effect of combinations of clay minerals but for the purposes of this investigation, the TGA results were of greater consequence when comparing the untreated materials with the treated materials later described in section 6.3.2.

4.5.4 Cation Exchange Capacity (CEC) and Exchangeable Cation Percentages

Samples TRL1 and TRL2 gave significant cation exchange capacities, in excess of 30 meq/100g. The other materials all had measurable values, generally between 5 and 10 meq/100g. On this basis, one would expect materials TRL 1, 2 and possibly 4 to react with the SPP products.

As it was possible to calculate the number of anions available for reaction with cations in soils in SPP chemicals, it is possible to calculate the number of cations (NC) available in the soils for reaction with the chemicals. This can be done in a general sense using the cation exchange capacity (assuming a common valency) or from the individual percentages of the common cations, Ca^{++}, Na^{+}, Mg^{++}, K^{+}, if determined.

Sample TRL1 has a cation exchange capacity of 42 meq/100 g (nearly all made up of the divalent cations, calcium and magnesium). This can easily be converted to equivalents per cubic metre using the density of the material as follows.

Anion content (equivalents) = (42/1000 x 10 x 1800)

= 756 equivalents of cations/m^3 of compacted material

Comparing this figure with that calculated for the equivalents of chemical added (Paige-Green 1999) a ratio of 1.2×10^4 is obtained. There are thus significantly more cations available for reaction than the amount of chemical typically added. This agrees with the figure of 103 to 104 excess soil cations calculated by Scholen 1995.

4.6 Conclusions from the Materials Tests

An evaluation of the properties in terms of existing information has indicated that the materials selected for treatment have a suitable range of grading, plasticity, clay mineralogy and strengths covering a wide spectrum of typical unsealed road and subgrade materials.

It is considered that the parameters determined should be sufficient to correlate with the effects of the SPP treatments on the materials and to indicate fully whether the chemicals have any beneficial effect on the soils and which properties can determine the degree and extent of this effect.

The use of predicted densities, moisture contents and strengths are considered to be inadequately precise for comparing the effects of the chemical additives in this evaluation.

5 Phase 3 Testing of SPP Treated Soils

The design of the laboratory testing work in this phase was centred on investigating:

i) Compactability aspects;

ii) Stabilisation benefits.

The five samples of material collected and evaluated were treated with the appropriate chemical products identified in section 3 as potentially being the most and least beneficial, in terms of their propensity to aid compaction and to achieve stabilisation. In addition, some fundamental investigations of the possible reaction mechanisms were carried out using more sophisticated non-routine soil analysis techniques.

Following these initial investigations, individual chemical products were evaluated using specific material types and curing regimes. The objective of this laboratory testing was to identify those properties that could be used to evaluate whether a natural soil material could be successfully treated with chemical stabilisers. Finally a field trial was conducted.

In summary the testing regime was as follows.

1. Compaction Aid Studies (section 5.1)
2. Stabilisation Studies (section 5.2)
3. non-routine soil analysis techniques (section 5.3)
4. Product Curing Tests (section 5.4)
5. Field Trials (section 5.5)

Each of the tests is described in more detail below

5.1 Compaction Aid Studies

The objective of this phase of testing was to determine whether the chemical products had any influence on the compaction characteristics of the materials investigated. SPPs are often marketed as soil stabilisers/improvers with the additional benefit of improving the compaction i.e. acting as a compaction aid. The addition of a surfactant to a soil should theoretically reduce the surface tension effects of the compaction water on the soil and allow for more effective compaction. This can have a beneficial effect on the construction process in two ways:

i) A higher density can be achieved for a standard compaction effort, or less effort would be necessary to achieve the required compaction.

ii) Less water would be necessary to achieve the specified density under a given compaction effort.

Field trials previously carried out have shown the former to be the case, and it was assumed that the latter could be simulated in the laboratory.

Laboratory testing was carried out to quantify the potential improvement in density as a result of compacting material with the addition of SPPs.

Products F and G were selected for the compaction studies. Initially, the vibrating table method was used for compaction of the samples as it was considered to be more reproducible. However, as the vibrating table method should, in theory, compact the materials to refusal density, standard laboratory dynamic compaction (Method A7 in TMH1) was also used. Full compaction curves were determined for each treated material and the results were compared with the untreated material.

5.2 Stabilisation Studies

Stabilisation testing was carried out on the five soil materials using the vibrating table as it was considered that more reproducible and representative CBR results would be obtained. The previous section, however, indicates that there were only small differences between the MDD derived by the two compaction methods. The materials were compacted into the standard split mould used with the vibrating table and then released and placed in a split CBR mould for soaking before penetration testing. The application rates of the chemicals were generally equivalent to the 0.03 R/m2 traditionally used for SPP stabilisation but were adjusted according to the supplier’s specification for the more concentrated products.

Products B and G were used for the initial testing. Product B is a highly concentrated material and was diluted according to instructions provided by the supplier. This resulted in an effective application rate of 1.65 x 10-6 R/m2 (or 1.1 x 10-6 R/m3) of chemical as supplied. Product G was applied at 3.0 x 10-2 R/m2 (or 2.0 x 10-1 R/m3). There is thus a large difference between the concentrations of the raw chemicals as provided, which was compensated for in the testing by the different application rates.

The CBR results were determined according to TMH1 method A8 with no deviations in respect of curing or pre-treatment, although certain SPP suppliers suggest various modifications to the standard test. The results used for comparative purposes are the weighted averages of triplicate tests as discussed previously.

The stabilisation effect was determined on each of the five materials using products B and G. Samples were compacted with both the vibrating table and the TMH1 Modified AASHTO hammer. The effect of stabilisation was quantified using the standard CBR test. Although the test is known to be somewhat erratic, this is the only cost-effective method of testing stabilisation aspects such as those produced by SPPs that is widely understood and accepted by the road construction industry. Other parameters such as Modulus of Resilience and the Texas Triaxial class, which have specific benefits, require more sophisticated equipment and are more time-consuming to carry out. Their implications are also less widely comprehended by road engineers. An attempt to reduce the inherent variability associated with the standard CBR test was made by using the weighted means of the result at 2.54, 5.08 and 7.62 mm penetrations and using duplicate or triplicate tests.

5.3 Non-routine Soil Analysis Techniques

In order to try and get a deeper understanding of the “reaction process” involved in the stabilisation of the soils, all five of the materials were treated with the most active of the products identified previously (Product B) and then saturated with water and dried for three cycles. They were then submitted for Differential Thermal Analysis/Thermogravimetric analysis (DTA/TGA) and cation exchange testing. The results were compared with those of the untreated materials. The X-ray diffraction data was also reviewed.

5.3.1 Cation Exchange Reactions

If SPPs react with soils as professed, they will attach themselves to ion exchange sites on clays and other suitable minerals as well as free cations in the soils. It is this process that theoretically leads to a reduction in the adsorbed water content of clays and amorphous materials and renders the strength of the soil less susceptible to the effects of excessive moisture. It should also allow for closer packing and even possibly aggregation of the soil particles during densification.

During the project, this aspect was specifically investigated. Product B, with the highest anionic surfactant content (i.e. the product with the greatest likelihood of replacing exchangeable cations present in the soils), was thought to be the product most likely to increase the strength of the soils. This was confirmed by the significant increases in CBR when samples TRL1and TRL5 were treated with Product B.

The total cation exchange capacity (CEC) and the individual exchangeable cations of all the materials were determined by the standard ammonium acetate method. A sample of each material was then placed in a petri dish and saturated with a solution of product B in water (as used for stabilisation testing). The material was allowed to air dry and was resaturated with distilled water. This was repeated twice before the air-dried material was re-submitted for CEC and exchangeable ion testing.

5.3.2 Thermal Analysis

The use of thermal analysis to identify clay minerals and certain of their characteristics is a sophisticated but useful tool. When any mineral (clay minerals in particular) is heated up, phase changes occur. These are accompanied by thermal changes in the form of exothermic (heat being given out) and endothermic (heat absorbed) reactions, which can be monitored by comparing the sample temperature with an adjacent inert standard (differential thermal analysis (DTA)). Typical endothermic reactions include the release of adsorbed and bound water, structural decomposition and reduction whilst oxidation and reconstruction of the crystal structure would release heat (exothermic).

The phase changes are also accompanied by changes in mass of the sample as volatiles (e.g. water, carbon dioxide, sulphur dioxide) are removed from the minerals. This loss in mass can be accurately monitored using themogravimetric analysis (TGA).

The differential thermal analysis and thermogravimetric analysis profiles of each of the original materials were obtained (see section 4.4.7). Samples of each soil were then treated in the same manner as described above for the CEC measurements using product B, and the resulting materials were subjected to DTA and TGA testing. Comparison of the thermal profiles before and after treatment with the SPP was then carried out. It should be noted that the DTA peaks are very dependent on the method of packing of the sample and various other characteristics and it is difficult to compare them quantitatively. The TGA peaks on the other hand, are far more repeatable and thus easier to compare.

5.3.3 X-ray Diffraction Analysis

A number of SPP suppliers in the region base their evaluation of whether any soil will react with their SPP on the results of X-ray diffraction analysis. Scholen compares the alteration of clay minerals using SPPs with the natural weathering process. Weathering ultimately results in primary minerals forming a stable crystalline residue. The presence of alkali metal cations and ionised water in the natural environment stalls this process and clay minerals are formed. The natural laterisation of clays occurs when cations are removed by chelation and leaching. The application of appropriate chemicals to chelate and remove the cations and ionised water from the soil will thus allow the breakdown to continue to the stable rock and clay mineral phase. SPPs are the appropriate chemicals (they mostly contain a benzene ring that has been treated with sulphur dioxide or sulphonic acid) and they react only with clay minerals.

Feldspar is the most abundant rock-forming mineral on earth and is the primary source of clay. Feldspars weather to clays, mostly kaolinite but depending on the prevailing leaching and drainage characteristics, other clays can also form. It would appear that this is the basis for certain SPP suppliers using the feldspar content, estimated from routine X-ray diffraction analyses, as an indicator of reactivity of a material. X-ray diffraction is the most common method of identifying clay minerals but the accuracy of quantitative analysis is generally poor and specific treatments are usually necessary to differentiate between the clay mineral groups. X-ray diffraction was not carried out on the samples after treatment with the SPP as it was considered unlikely that the small structural changes in the clay mineralogy would be observed.

Evaluation of the X-ray diffraction results indicates that samples TRL1 and TRL2 have significant feldspar contents. The X-ray results from the two laboratories, however, have quantified the feldspar contents differently. The Geosciences Council identified 34 per cent feldspar in TRL1 and 18 per cent in TRL2 while the Agricultural Research Council identified 16 per cent in TRL1 and 37 per cent in TRL2. Feldspar was not identified in any of the other materials. The clay minerals identified by the two laboratories showed less variation. The role of the mineralogy in predicting reactivity of the soils is discussed further in Section 7.3

5.4 Product Curing Tests

Although routine laboratory tests have been followed for most of the testing, there is a growing tendency for the SPP suppliers to suggest modifications to the standard tests (i.e. curing for four days with the SPP before compaction into the mould) in order to obtain more realistic results. It should be noted that the traditional road engineering tests were developed for untreated materials and when treatment with pozzolanic and bituminous stabilisers was initiated, changes to the test methods were made, or more correctly, test techniques that were more appropriate to the properties being evaluated, were developed.

The literature states that the cation exchange reactions, for example, associated with lime or cement stabilisation, are very rapid. It appears, however, that these reactions associated with SPPs are slow. This may not be totally correct, as the beneficial effect is associated more with the expulsion of adsorbed water from the clay component than a direct chemical change of the clay mineral structure. Limited testing has shown differences in the reaction time of different SPPs.

Savage has discussed this aspect of ionic soil stabilisation. He indicated that to be successful, the process requires a combination of drying and water expulsion under load (i.e. trafficking during the “green” phase) before reaching the “mature” state. Once this has been reached, the strength of the treated material is sufficiently improved. On this basis a laboratory simulation of the expected process was carried out.

Both untreated and treated (with product A at 0.03, 0.04 and 0.02 per cent respectively) samples of materials TRL1, 2 and 4 were compacted and allowed to dry (at 65°C to about 50 per cent of the soaked moisture content - actual range 39 to 61 per cent) prior to being subjected to a static load of 20 kN for one minute, repeated five times with an interval of one minute. The specimens were then soaked and the process repeated three times prior to soaked CBR tests being carried out.

5.5 Performance Aspects and Case Studies

The use of “anionic linear polymers” when modified with sulphonic acids was identified as assisting interparticle bonding and aggregation of soil particles as long ago as 1952. A study of the use of chemical admixtures was carried out at TRL in the early 1960s following a previous one carried out between 1945 and 1950. This project did not specifically identify any of the admixtures (more than 70 had been investigated by this time) as SPPs although chemicals with ion exchange properties defined as soil conditioners were described. The first ionic soil stabilisers in terms of current thinking were developed in the early 1960s. Despite their long history, the postulated cost effectiveness and their technical benefits, there are no specified engineering standards, specifications or codes of practice for these products and they have failed to become an accepted component of road construction. This is probably the result of the lack of credible scientific research and properly controlled road experiments using the products.

The performance of SPPs in roads is generally difficult to evaluate for a number of reasons:

1. Very few SPP treated roads have been constructed with scientifically designed control sections. Typically, a problem road (that may be a problem more through poor construction than poor materials) is rebuilt with an SPP treated layer using better controlled construction techniques and thus performing better. It is essential that proper control sections are built adjacent to treated sections using identical materials and construction techniques and carefully monitored.

2. In many cases poor roads are rebuilt with an SPP and an in situ CBR is determined immediately after compaction and at intervals thereafter using the DCP test, without any reference to the in situ density or moisture content. Most examples of high in situ strengths after treatment can be related to the test being carried out with the road at a low moisture content.

3. Poor roads are frequently rebuilt with the addition of a binder or gravel to the in situ material prior to treatment with an SPP. The improvement in many cases is attributed to the SPP. Any improvement as a result of the mechanical stabilisation of the material is seldom quantified or totally ignored.

Despite these problems, however, the author has first-hand experience of a number of successful projects where there is no doubt that the local material was improved by SPP treatment. Knowles, based on work in Tanzania and Indonesia, also concludes that “there is no doubt that SPPs are safe to use and are successful for the stabilisation of most in situ materials for road pavements”.

An interesting aspect of the performance of treated roads is the effect of water. A strong benefit marketed by the suppliers of the chemicals is the waterproofing effect of the product on the clay minerals in the soil by reducing the adsorbed water. This project has identified that this can be simulated in the laboratory and evaluated using DTA/TGA techniques. It should, however, be noted that this theoretically allows a greater degree of compaction, tighter interlock of the soil particles and an overall reduction in void ratio. Under dry conditions a significantly higher strength will result. Under soaked conditions the strength will probably decrease but not necessarily as much as untreated material. When soaked and loaded by traffic, however, the capillary water will be subjected to stress and effective stress conditions will prevail. The overall strength of the material will therefore be reduced by the excess pore water pressures, this effect being exacerbated if the permeability of the material is decreased.

A search of the literature identified a number of papers and articles in periodicals and journals concerning particular case studies. Relevant information has been summarised and is included in Annex C.

5.6 Field Evaluation

As part of the project, an evaluation of full-scale trials was proposed. To the best of the authors knowledge, no suitable trials which have included proper control sections have been constructed during the course of the project. However, in parallel with various other projects, a number of SPP treated roads (both sealed and unsealed) in Kwazulu Natal, South Africa have been investigated. The aim was to determine whether there were any significant differences between the treated roads and adjacent untreated roads.

Eighteen sections of one kilometre length were selected in District 4 for the field investigations. These represented gravel surfaces, SPP treated base course with a light blacktop surface and light blacktop surfaces without treatment. Nine sections were selected in District 7 where no SPP treatment had been used. Attempts were made to select two sections, both gravelled and blacktop surfaced, on each road. Details of the location of the roads selected are given in Table 5.1.

During the field investigation the following aspects were evaluated:

- Visual inspection of surface and drainage conditions in the vicinity of the centre of the section
- Rut depth measurements using a 2 m straight edge and a wedge at the centre of each section
- DCP measurements to a depth of 800 mm at a point on the inner wheel path.
- Base course moisture contents at every DCP measurement point
- Riding quality measurements over the 1 kilometre test section.

District	Road No.	Section (km)	Sealed/unsealed?	SPP used?
4	P10/1	45.5 - 46.5	Unsealed	No
4	P10/1	10 - 11	Sealed	No
4	P10/2	0.5 - 1.5	Sealed	No
4	P10/2	10 - 11	Sealed	No
4	P10/2	4.5 - 5.5	Sealed	No
4	P10/2	12 - 13	Sealed	Yes
4	P10/2	8 - 9	Sealed	Yes
4	P164	17 - 18	Sealed	Yes
4	P164	3 - 4	Sealed	No
4	P212	13.5 - 14.5	Sealed	Yes
4	P212	25 - 26	Sealed	No
4	P28/1	45.5 - 46.5	Sealed	Yes
4	P28/1	40 - 41	Sealed	Yes
4	P29	31 - 32	Sealed	Yes
4	P29	28.5 - 29.5	Sealed	No
4	P331	2.5 - 3.5	Sealed	Yes
4	P394	0.5 - 1.5	Unsealed	No
4	P394	23 - 24	Sealed	Yes
7	P254/1	0.5 - 1.5	Unsealed	No
7	P529	4 - 5	Unsealed	No
7	P529	0.8 - 1.8	Sealed	No
7	P262	24.5 - 25.5	Unsealed	No
7	P262	18 - 19	Sealed	No
7	P58	0.5 - 1.5	Sealed	No
7	P58	4.5 - 5.5	Unsealed	No
7	P69	9.5 - 10.5	Unsealed	No
7	P69	2.5 - 3.5	Unsealed	No

Table 5.1. Details of sections investigated

6 Treated Soil Test Results

6.1 Compaction

The maximum dry densities (MDD) and optimum moisture contents (OMC) of the materials after treatment at the minimum recommended concentration of product for compaction were initially determined using the Transportek vibrating table. Products F and G were used and the full results are included in Annex B and summarised in Table 6.1. They are also graphically illustrated in Figures 6.1 and 6.2.

<table>
<tr><th rowspan="3">Sample number</th><th colspan="6">Treatment</th></tr>
<tr><th colspan="2">None</th><th colspan="2">Product F</th><th colspan="2">Product G</th></tr>
<tr><th>MDD</th><th>OMC</th><th>MDD</th><th>OMC</th><th>MDD</th><th>OMC</th></tr>
<tr><td>TRL1</td><td>2090</td><td>13.9</td><td>2075</td><td>13.1</td><td>2075</td><td>13.5</td></tr>
<tr><td>TRL2</td><td>1674</td><td>17.4</td><td>1658</td><td>19.8</td><td>1692</td><td>20.5</td></tr>
<tr><td>TRL3</td><td>2188</td><td>9.3</td><td>2168</td><td>10.0</td><td>2168</td><td>10.5</td></tr>
<tr><td>TRL4</td><td>2000</td><td>11.2</td><td>2000</td><td>12.0</td><td>2000</td><td>12.6</td></tr>
<tr><td>TRL5</td><td>1950</td><td>14.0</td><td>1965</td><td>13.3</td><td>1955</td><td>13.8</td></tr>
</table>

Table 6.1. Maximum dry density (MDD in kg/m3) and optimum moisture content (OMC in %) of materials tested using the Transportek vibrating table

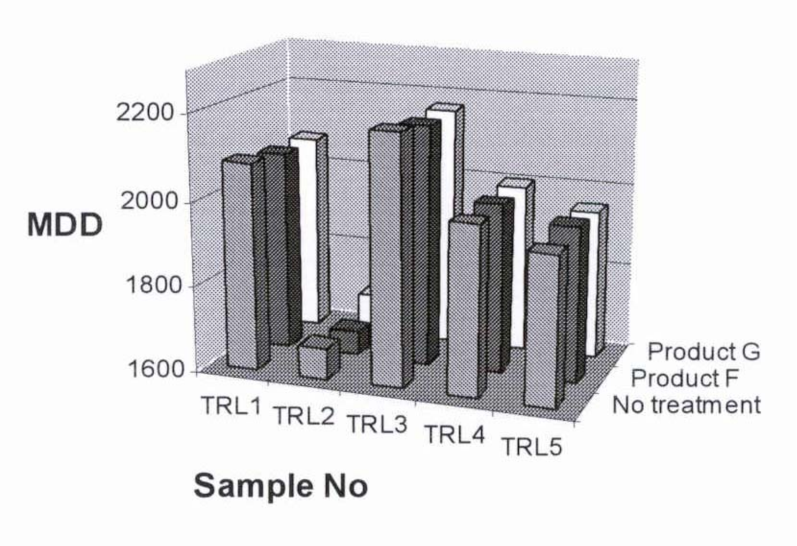

Figure 6.1: Changes in MDD on treatment with SPPs (vibrating table)

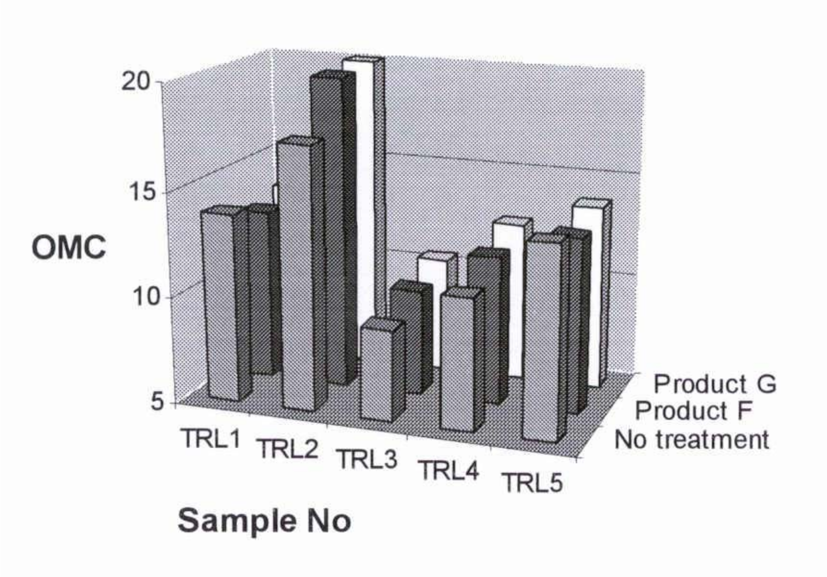

Figure 6.2: Changes in OMC after treatment (vibrating table)

As the vibrating table was considered to probably compact the material to refusal density for the specific grading and particle characteristics, the potential usefulness of the SPPs as compaction aids was investigated further using the standard Mod AASHTO dynamic compaction procedure. Products B and D were used for this testing. The results are summarised in Table 6.2 and illustrated in Figures 6.3 and 6.4.

Sample number	**Treatment**					
	None		**Product B**		**Product D**	
	MDD	**OMC**	**MDD**	**OMC**	**MDD**	**OMC**
TRL1	2082	11.7	2126	11.6	2075	13.5
TRL2	1689	20.0	1658	19.8	1692	20.5
TRL3	2080	9.0	2168	10.0	2168	10.5
TRL4	1999	10.5	2000	12.0	2000	12.6
TRL5	1946	13.0	1965	13.3	1955	13.8

Table 6.2. Maximum dry density (MDD in kg/m3) and optimum moisture contents (OMC in %) of materials tested using Mod AASHTO dynamic

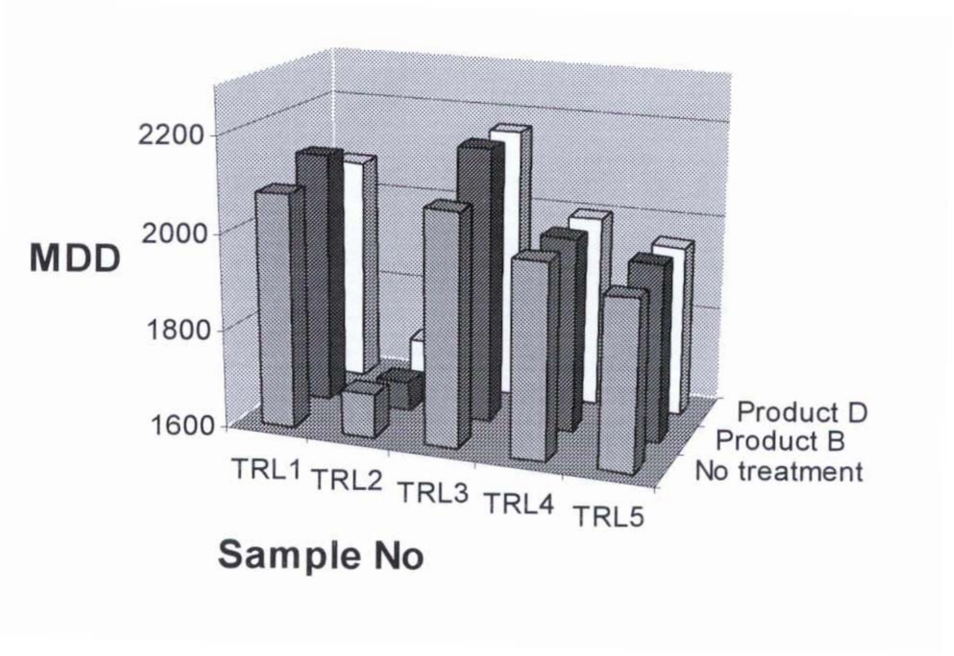

Figure 6.3: Change in MDD after treatment with SPPs (Mod AASHTO compaction)

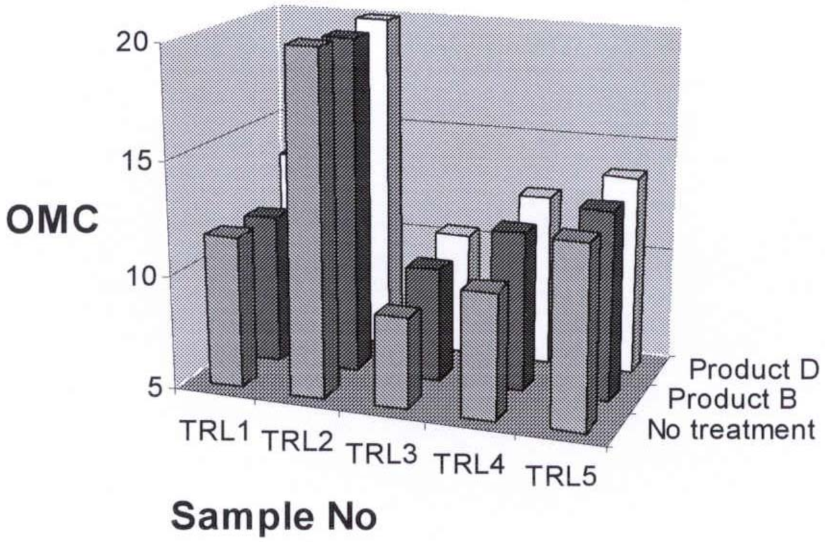

Figure 6.4: Change in OMC after treatment with SPPs (Mod AASHTO compaction)

The effect of SPPs as compaction aids and the potential to increase the strength of materials through better compaction only (i.e. no stabilisation effect assuming that the dosage was insufficient to cause "chemical reactions") was evaluated on all the samples compacted using the vibrating table and the suggested low chemical application rates. CBR tests were carried out after compaction and the results are summarised in Table 6.3. Products F and G were used for this investigation as these two products showed the weakest and strongest surface tension effects respectively.

Penetration (mm)	**CBR**								
	2.54	**5.08**	**7.62**	**2.54**	**5.08**	**7.62**	**2.54**	**5.08**	**7.62**
Treatment	**None**			**F**			**G**		
TRL1	38.1 29.2	36.5 30	32.8 29.6 **32.3**	51.1 34.1	47.7 41.9	41.1 43.9 **43.3**	26.5 36.3	31 43.4	33.8 41.9 **36.6**
TRL2	3.4 2.8	2.4 1.9	1.7 1.4 **2.0**	3.6 3.9	2.3 2.6	1.6 1.8 **2.3**	3.2 3.7	2.1 2.4	1.5 1.7 **2.1**
TRL3	173.8 107.8	221.1 139	234.7 155.7 **181.1**	100.9	131.4	152.6 **136.9**	81.9 106.7	108.4 138.5	126.2 150.4 **126.0**
TRL4	45.7 58.2	40 65.2	34.7 64.9 **51.1**	34.0 34.5	32.3 37.3	30.1 42.6 **35.5**	31.0 27.9	32.3 27.1	32.2 25.9 **29.3**
TRL5	41 42.4	34.3 35.8	29.5 29.7 **33.4**	48.9 50.6	37.7 38.7	29.5 29.7 **35.8**	45.0 38.7	34.2 30.2	26.9 24.0 **30.4**

Table 6.3. Soaked CBR results of SPP treated materials compacted using a vibrating table

6.2 Stabilisation

The results of the stabilisation testing are summarised in Table 6.4. The weighted averages include all results shown in the table, with duplicate tests on the untreated material and triplicate tests on the treated materials. Even with vibrating table compaction, large variations in the results are noted and even the trends within individual specimens vary. Some materials increase in penetration resistance as the penetration increases and some decrease. This is indicative of potential strain hardening or strain softening in practice, respectively.

Penetration (mm)	**CBR**								
	2.54	**5.08**	**7.62**	**2.54**	**5.08**	**7.62**	**2.54**	**5.08**	**7.62**
Treatment	**None**			**B**			**G**		
TRL1	38.1	36.5	32.8	71.2	69.9	63.5	57	58	56.8
	29.2	30	29.6	81.7	78.4	76.1	80.9	74.4	64.7
				77.9	82.9	84.8	80.2	71.4	62.3
			32.3			**75.9**			**65.4**
TRL2	3.4	2.4	1.7	2.3	1.9	1.7	2.5	2.0	1.8
	2.8	1.9	1.4	2.4	1.9	1.7	2.5	2.1	1.9
				2.2	1.7	1.5	1.9	1.5	1.4
			2			**1.8**			**1.9**
TRL3	173.8	221.1	234.7	104.9	124.9	130.9	103.8	130.8	141.7
	107.8	139	155.7	102.7	129.9	140.8	89.9	115.9	130.3
				134.9	158.9	162.9	145.5	181.9	192.7
			181.1			**137.4**			**143.9**
TRL4	45.7	40	34.7	39.8	40.5	39.3	32.1	40.1	44.9
	58.2	65.2	64.9	34.0	32.4	30.6	40.3	40.8	40.2
				47.3	45.8	43.4	37.8	40.2	41.0
			51.1			**38.8**			**40.6**
TRL5	41	34.3	29.5	51.0	48.5	45.8	46.5	41.0	38.7
	42.4	35.8	29.7	48.7	43.0	40.2	42.7	34.7	31.2
				41.2	35.5	33.1	42.7	36.0	32.7
			33.4			**41.8**			**36.8**

Table 6.4: Effect of SPP stabilisation using vibrating table compaction (values in bold are weighted averages)

Based on the initial compaction studies, the testing was repeated using Products C and D on samples TRL1, 4 and 5. These results are summarised in Table 6.5.

Penetration (mm)	CBR								
	2.54	**5.08**	**7.62**	**2.54**	**5.08**	**7.62**	**2.54**	**5.08**	**7.62**
Treatment	**None**			**C**			**D**		
TRL1	38.1 29.2	36.5 30	32.8 29.6 32.3	76.4 83.9	68.9 81.4	61.1 71.0 71.4	76.4 74.9	71.4 70.4	66.3 66.3 69.4
TRL4	45.7 58.2	40 65.2	34.7 64.9 51.1	105.7 86.9	98.9 76.9	89.5 70.2 85.3	40.5 41.2	49.0 40.0	53.2 39.4 44.8
TRL5	41 42.4	34.3 35.8	29.5 29.7 33.4	43.5 61.5	39.0 53.5	36.7 49.7 45.8	42.7 45.0	35.5 39.0	36.3 35.5 37.7

Table 6.5: Soaked CBR after SPP treatment using a vibrating table (values in bold are weighted averages)

On the basis of the results obtained previously and discussions with suppliers of the products, the following product specific testing was also carried out:

i) Product D on TRL3 - this product was supposed to perform well on low plasticity materials and it was suggested by the supplier that the dosage versus CBR strength relationship should be obtained and the optimum dosage determined.

ii) The supplier of Product G recommends various curing steps during the compaction process. These were followed on sample TRL1 which showed the most promise for this product. Testing was carried out in duplicate on a sample prepared normally (as in TMH 1), and on a sample allowed to cure for four days after addition of the chemical but before compaction into the mould. A parallel test was carried out with identical treatment but without the addition of chemical for comparative purposes.

The results of these two test programmes are summarised in Tables 6.6 and 6.7 respectively. The data from Table 6.6 has also been plotted graphically in order to indicate trends (Figure 6.5).

Concentration (mP/kg)	Penetration (mm)	Soaked CBR				
		Test 1	Weighted mean	Test 2	Weighted mean	Mean of tests 1 and 2
0.015	2.54	154.4	154	122.9	149	151
	5.08	154.9		147.9		
	7.62	153.8		159.3		
0.03	2.54	146.9	130	157.4	168	149
	5.08	134.9		166.9		
	7.62	121.5		173.5		
0.06	2.54	76.4	87	224.8	265	176
	5.08	89.4		269.8		
	7.62	89.9		275.3		
0.09	2.54	184.4	225	157.4	152	188
	5.08	222.8		152.4		
	7.62	240.6		149.9		
0.12	2.54	179.7	154	173.9	199	176
	5.08	154.9		196.8		
	7.62	145.9		209.0		

Table 6.6: Soaked concentrations (vibrating table) CBR of duplicate samples of TRL3 after treatment with Product D at different

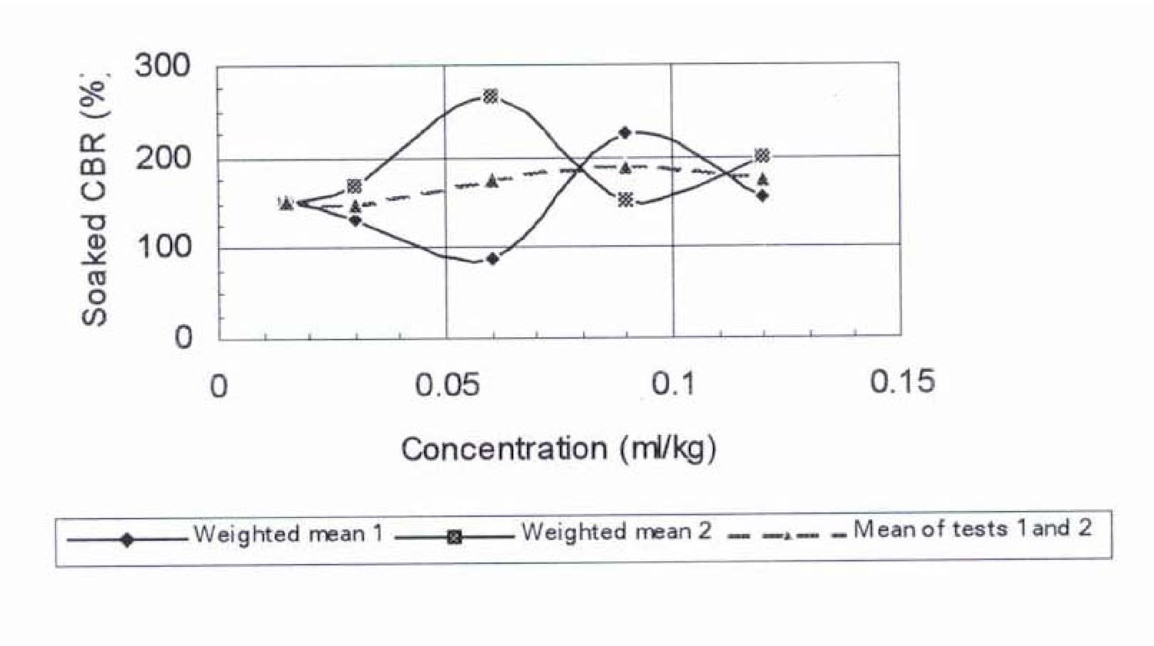

Figure 6.5: Plot of soaked CBR strength of sample TRL3 against concentration of Product D

Treatment	Soaked CBR (%)			
	Penetration (mm)			Weighted mean
	2.54	**5.08**	**7.62**	
TMH 1	41.2 30.0	35.5 26.5	30.4 24.8	30
Add SPP and cure for 4 days prior to compaction	33.0 32.2	27.0 28.0	25.2 24.5	27
No SPP and cure for 4 days prior to compaction	32.2 36.0	29.5 30.0	26.8 25.6	29

Table 6.7: Effect of curing of sample TRL1 with product G (0.03 P/m^2) during the compaction process on soaked CBR

6.3 Non-routine Soil Analysis Results

6.3.1 Cation Exchange Capacity (CEC) and Exchangeable Cation Percentages

The results of this testing are summarised in Table 6.8.

Property	Chemical	Sample number				
		TRL1	TRL2	TRL3	TRL4	TRL5
CEC (meq/100g)	No	41.12	35.37	4.97	10.21	5.93
	Yes	31.93	36.37	6.66	6.16	7.45
Ca++ (meq/100g)	No	24.10	23.25	0.70	0.19	0.47
	Yes	14.72	35.28	0.87	0.50	0.61
Mg++ (meq/100g)	No	18.43	9.43	0.58	0.15	0.73
	Yes	17.05	15.38	0.74	0.33	0.97
Na+	No	0.33	0.33	0.02	0.01	0.05
	Yes	0.29	0.57	0.09	0.08	0.11
K+	No	0.22	0.74	0.32	0.10	0.16
	Yes	0.21	1.02	4.69	0.40	0.73

Table 6.8: Cation exchange capacity and exchangeable cation percentages before and after treatment with Product B

The inherent variability with this test is clearly illustrated by the variation in the test results. It should be noted, however, that it is thought that certain of the chemical additives may have various salts in their composition. This could affect the individual cation exchange capacity values of the soils resulting in higher readings after addition of the chemical, depending on the chemical nature of the soil and the salts in the SPP. It should also be noted that the test was originally developed for agricultural use, particularly for estimating fertiliser needs and is thus biassed towards determination in an alkaline environment. The addition of highly acidic SPPs results in a degree of neutralisation of the SPP during the test, which could possibly affect the final result.

Despite these comments, it can be concluded that TRL1 and TRL4 show significant decreases in total CEC, in line with the expected reaction caused by SPPs. TRL1 certainly reacted with all four of the products applied to it and TRL4, although not reacting positively with product B (the product used for the CEC sample preparation) or products D and G in the strength testing, reacted well with product C. Development of the CEC test to handle acidic materials thus appears to be promising as an indicator of potential reactivity of soils with SPPs.

6.3.2 Thermal Analysis results

Full results of the thermal analysis can be found in Annex B. The following aspects were noted:

TRL 1 - No significant changes in the DTA profile were observed (note that the charts are at different scales) indicating no changes in the dehydration and decomposition process before and after treatment. There was, however, a significant deviation in the TGA profile above 600 °C where the mass loss in the untreated material was more than one percentage unit greater than the treated material. It is in this area that the loss of sorbed water and dehydroxylation of the smectites occur. This is particularly prevalent when the exchangeable cations have high hydration energy (Ca++ and Mg++). It can thus be concluded that the adsorbed water associated with the clays in the weathered diabase was reduced by the SPP treatment.

TRL 2 - A dissimilar trend is exhibited to that of TRL1. No notable changes in the DTA profile are observed. This is expected as the mineralogy of the material remains essentially unchanged. The TGA profile, however, shows a change in profile between 300 °C and 650°C with the treated material showing a reduced mass loss between 100 and 320°C and then an increased loss between 320 °C and 500°C, before the mass loss continues in parallel to the untreated material. The overall loss is generally similar to the treated material.

TRL 3 - No differences between the TGA or DTA profiles before and after treatment with SPP were observed. This is not unexpected as the material consisted mostly of quartz with small quantities of goethite and clays, these generally being in too small concentrations to produce significant peaks in the DTA profiles.

TRL 4 - The DTA profiles of the treated and untreated material showed no significant differences. The TGA profile, after correction for the initial hygroscopic moisture content (it was less in the treated sample) showed a significantly lower mass loss (nearly two per cent) above 500 °C with the loss which occurred between 625 and 730°C in the untreated sample, not occurring in the treated sample. The only possible mineral which dehydroxylates and decomposes within this range is interlayered illite/smectite which was shown to be present in the material by the X-ray diffraction analysis carried out by the Council for Geosciences . It can thus be concluded that this material has been affected by the treatment with the SPP as theoretically predicted.

TRL 5 - There was no significant difference between the before and after treatment DTA profile of this material. A slightly increased loss in mass was evident in the DTA profile (about 0.6 per cent). No reason for this could be determined and it was an unexpected finding as the material is in many respects similar to TRL4 which showed a significant change. The X-ray diffraction analyses, however, showed distinct differences in the kaolinite/mica ratios, this being the probable difference in behaviour of the materials.

6.4 Curing Trials Results

Table 6.9 shows the results from the curing and loading trials carried out on soils TRL1, 2 and 4 using chemical product A.

Sample	Treatment	Soaked CBR (%)
TRL1	None	25.4
	A (0.03%)	27.8
TRL2	None	2.1
	A (0.04%)	1.8
TRL4	NoneA	28.7
	A (0.02%)	31.0

Table 6.9: Results of laboratory curing/loading experiment.

Samples TRL1 and TRL4 showed a marginal but probably insignificant increase in CBR after the treatment. No significant changes in the moisture content after each soaking cycle was determined for any of the materials. It should be noted that this investigation was only carried out on one material with one SPP. The practice of slushing treated layers (i.e. repeated rolling with a pneumatic tyred roller with copious water) has been seen to improve the performance of treated layers. This may in effect simulate to a degree, the theory proposed above.

6.5 Field Test Results

The results of the field investigation are summarised in Table 6.3. Visual and drainage condition were assessed on a 3 point scale as poor, fair or good. Drainage was assessed as the ability of the road section and drains to adequately shed rain water and on their level of maintenance.

Road No.	Section (km)	Sealed/ Unsealed ?	SPP used?	Mean QI	PSI	Rut depth	Visual cond.	Drainage	DSN8000	Moisture content (%)
P10/1	45.5-46.5	Unsealed	No	72	0.53		Good	Good		
P10/1	10-11	Sealed	No	30	1.67	2	Good	Good	163	
P10/2	0.5-1.5	Sealed	No	28	1.80	2	Good	Good	354	12.1
P10/2	10-11	Sealed	No	31	1.63	35	Good	Fair	185	6.3
P10/2	4.5-5.5	Sealed	No	35	1.47	10	Good	Good	179	10.6
P10/2	12-13	Sealed	Yes	30	1.67	55	Fair	Fair	163	4.8
P10/2	8-9	Sealed	Yes	34	1.51	8	Good	Fair	102	6.5
P164	17-18	Sealed	Yes	26	1.91	2	Good	Fair	78	9.7
P164	3-4	Sealed	No	33	1.55	10	Good	Good	266	7.5
P212	13.5-14.5	Sealed	Yes	25	1.92	20	Good	Good	178	7.9
P212	25-26	Sealed	No	46	1.08	25	Fair	Poor	37	11.7
P28/1	45.5-46.5	Sealed	Yes	57	0.81	20	Good	Fair	118	7.2
P28/1	40-41	Sealed	Yes	77	0.46	10	Good	Good	151	6.7
P29	31-32	Sealed	Yes	31	1.64	15	Fair	Fair		7.5
P29	28.5-29.5	Sealed	No	42	1.21	20	Good	Fair	53	7.3
P331	2.5-3.5	Sealed	Yes	32	1.62	20	Fair	Fair	98	4.2
P394	0.5-1.5	Unsealed	No	29	1.76		Good	Good	271	16.0
P394	23-24	Sealed	Yes	41	1.26	25	Fair	Fair	161	9.9
P254/1	0.5-1.5	Unsealed	No	70	0.55		Good	Good	170	2
P529	4-5	Unsealed	No				Fair	Fair		3.4
P529	0.8-1.8	Sealed	No	56	0.91	20	Good	Good		
P262	24.5-25.5	Unsealed	No	76	0.45		Good	Good		4.9
P262	18-19	Sealed	No	46	1.29	20	Good	Good	193	6.2
P58	0.5-1.5	Sealed	No	68	0.6	25	Fair	Fair	145	8.9
P58	4.5-5.5	Unsealed	No	103	0.18		Poor	Fair	179	4.2
P69	9.5-10.5	Unsealed	No	105	0.17		Fair	Fair	44	5.1
P69	2.5-3.5	Unsealed	No	130	0.07		Poor	Good	96	2.4

Table 6.3: Summary of field investigation results

6.5.1 Visual Condition and Drainage

Seventy two percent of the sections investigated in District 4 were in good condition. The rest of the road sections were rated as fair. There were no observable differences between the sections treated with SPPs and those without.

Forty four percent of the sections investigated in District 7 were in good condition. Thirty three percent were in fair condition and the remaining twenty two percent were poor. The sections in poor condition were unsealed and had suffered gravel loss and were corrugated.

The standard of drainage was generally high in both districts.

It was not possible to determine whether the generally better condition of the roads in District 4 compared with District 7 was the result of the SPP treatment or differing maintenance strategies/techniques, materials or environmental conditions. It was clear, however, that the ratio of good to fair condition was much higher for the untreated sections in District 4 than the treated sections. It is thus assumed that differences exist in the two districts that are not related to the action of the chemicals.

6.5.2 Riding Quality

Riding quality measurements were taken in both directions over the one kilometre test sections. The values summarised in Table 6.3 have been averaged for both directions and converted to Present Serviceability Index (PSI).

No unsealed sections had been treated with SPPs. The average PSI for the untreated blacktop sections was 1.32 and for the treated sealed sections was 1.42. The difference is marginal and it cannot be concluded that the SPP contributed to an improvement in riding quality.

6.5.3 DCP and moisture content measurements

The DCP structural number DSN800 and in-situ base moisture content are summarised in Table 6.3. Most of the sections tested had structural numbers greater than 80.

The average DSN800 value of the SPP treated roads was 131 whilst that of the untreated roads was 175. As this value can be significantly influenced by the underlying layer and is not a measure of the base strength, little can be inferred from this. Cases have been reported where the SPP has migrated with depth and affected the layers beneath the treated material over time. This does not appear to have been the case in the roads investigated in this study where the untreated pavements are generally stronger.

The average moisture contents of the treated and untreated sections were calculated to determine whether the SPP was in fact reducing the moisture content of the pavement materials. The average of the treated sections was 7.15 per cent and the untreated sections was 7.24, a marginal difference. It should, however, be noted that the capillary water is not likely to be affected by SPP treatment and the so-called “waterproofing” of the layer cannot easily be quantified on this basis.

6.5.4 Rut Depth

Rut depth measurements are summarized in Table 6.3. The average rut depths on the untreated sections was 17 mm and on the treated sections was 19 mm. The difference is minimal and is related more to the past traffic and overall DSN800 of the roads than the performance of the treated layers.

7 Results Discussion

7.1 Compaction

The following points were noted:

- The addition of 0.01 R/m2 SPP to the five soil materials resulted in very little change in the maximum dray density obtained or the OMC when compacted using the Transportek vibrating table.

- The MDD remained unchanged or was either increased or decreased by a maximum of one per cent, probably within the experimental error/variability of the test method and the material.

- The OMC increased by between 13 and 18 per cent for samples TRL2, 3, and 4 and decreased by between 3 and 5 per cent for samples TRL1 and 5. The increases are probably outside normal testing variability while the small decreases are likely to be the result of material or test variability.

- The addition of 0.01 R/m2 SPP to material compacted using the traditional Mod AASHTO hammer resulted in slightly larger changes in the MDD.

- Product D had no impact on materials TRL1, 2, 4 and 5 with all of the density results being within 0.5 per cent of the untreated density. TRL3 increased in density by more than 4 per cent with Product D.

- Product B resulted in increases in the density of materials TRL1 and TRL3 of between 2 and 4 per cent. This is outside the normal variation to be expected from this testing and an increase in the field density of this magnitude would result in a reduction in the rutting potential of between 3 and 6 mm for a 150 mm thick pavement layer.

- Small increases in the OMC were generally obtained when using Product B but Product D gave a larger increase in OMC for each material.

It can be concluded from this that the chemicals when used with vibrating table compaction did not contribute to achieving better compaction. The use of chemical B with dynamic compaction resulted in a significant increase in the density of Samples TRL1 and TRL3. This was unexpected as the vibrating table was thought to compact the material to “refusal” density, which should be higher than that using the Mod AASHTO hammer. It thus appears that the addition of SPP chemical is more beneficial when a more dynamic type of compaction is employed and should have greater implications when used in conjunction with light impact rolling than when used with conventional vibratory compaction. It is also evident that the lower plasticity and coarser materials were affected to a greater extent than the finer, more plastic materials.

In all cases, the optimum moisture contents remained essentially unchanged or increased. On this basis it appears unlikely that the use of SPPs could significantly reduce compaction water requirements despite the findings of full-scale trials in the Sultanate of Oman, where significantly higher densities were obtained and it was surmised that water requirements could be reduced. It should be noted that the materials used in these trials were low plasticity coarse gravels. Properly controlled field trials to assess this aspect fully are recommended.

Although the increases in density using the SPP and the vibrating table for compaction were negligible, the evaluation of the strength after compaction using the chemicals as a compaction aid showed that higher strengths could be obtained. This was particularly notable for material TRL1. Although the chemicals resulted in a marginally lower density, strength increases between 13 and 34 per cent were achieved. These were attributed to an incipient stabilisation reaction more than the result of better compaction. Treatment of the other materials produced lower or only marginally higher strengths.

7.2 Stabilisation

The results summarised in Table 4.1 show the following:

- Products B and G have a significant effect on sample TRL1 with an increase in strength in excess of 100 per cent.
- Product B caused a 25 per cent increase in strength in sample TRL5 while product G produced a marginal increase in strength (10 per cent).
- Treatment of material TRL1 with products C and D resulted in significant increases in strength (in excess of 100 per cent) while the strength of TRL5 increased by between 14 and 37 per cent.
- Product C caused a significant increase in strength on material TRL4 (66 per cent increase) but product D reduced the strength of TRL4.
- A number of the materials decreased in strength or showed no significant change on the addition of various chemicals. The strength decreases were attributed to an excess of chemical resulting in lubrication of the particles and a concomitant reduction in strength after soaking. For this reason it is essential that prospective stabilisers are carefully tested on the materials for which they are planned to be used and the optimum chemical content is determined.

Material TRL3 was tested at various concentrations of Product D as this product is reported to react with low plasticity materials. TRL3 has a naturally high strength but even this was shown to increase by more than 20 per cent at concentrations of chemical between 0.06 and 0.09 mP/kg. The duplicate test results were fairly variable but overall trends are evident in Figure 6.5.

The use of pre-curing prior to compaction was evaluated during one brief experiment. Sample TRL1 was treated with Product G following the standard TMH1 method for CBR. Two other sets of duplicate moulds were also prepared, the only differences being that in the one, the material was mixed with Product G and allowed to cure for 4 days prior to compaction, while the other sample was treated identically except that the chemical was omitted. The soaked CBR strength of the untreated material following TMH 1 was 32 per cent and irrespective of the treatment, the values obtained were between 27 and 30. It can thus be concluded that the use of Product G, with or without pre-treatment had no significant effect on TRL 1, the material that was generally the most reactive of those evaluated.

It was also quite clear from this testing that certain materials can be treated with certain products but that not all products work with all materials. This has been discussed previously, and is a very important aspect. The use of any SPP therefore requires testing with the appropriate material both to ensure that a “reaction” occurs and to determine the optimum chemical application rate before use.

7.3 Curing Trials

In order to evaluate the effect of the products on materials being treated, it is essential that any deviations from traditional test methods in the laboratory testing can be replicated during road construction. For example, curing under high temperatures or rapid periods of cycled curing under artificial conditions should be avoided unless they are used to accelerate some other condition that occurs in the field, in which case they should be calibrated under both conditions. The majority of the testing for this project utilised standard test methods and it is clear that it is possible to simulate the expected increases in strength where the material and product "react" appropriately.

It has also been shown that special curing conditions are not necessary to determine the effectiveness of SPP treatment. Standard laboratory techniques are suitable. In some cases it may be acceptable to allow some damp curing (in order to simulate field conditions) prior to CBR testing. Damp curing in the field (e.g. by water spraying twice a day) for a period of three to seven days is recommended by various SPP suppliers.

An objective of the project was to determine a mechanism for predicting which soils will react with an SPP and to quantify the increase in strength. The test results available from this project were analysed in an attempt to identify the relationships between material properties and probability of successful SPP treatment. This process was complicated by the fact that not all SPPs react with soils to the same extent.

In order to determine the susceptibility of the materials tested to successful treatment with SPPs, the probability of success was rated for each material. Success was "defined" as an increase in strength of more than 15 per cent after treatment. This resulted in the materials being rated TRL1, TRL5, TRL3, TRL4 and TRL2 with probabilities of success of 100, 50, 33, 25 and 0 per cent respectively. Each of the materials was treated with at least three different chemicals.

The probability of success was then compared with all the material test results. No relationship between any of these was found as in most cases the black clay (material TRL2) results were problematic. The water absorption results correlated loosely and when the weighted water absorption was determined (weighting for the coarse (> 4.75 mm) and fine (< 4.75 mm) fractions a reasonably good correlation was obtained (r2 = 0.7). In some respects the use of this parameter makes sense but after careful consideration, doubt was raised. Similar water absorption trends have been obtained from totally inert materials (e.g. power station ash), which probably would not react with SPPs. On this basis, a composite value using the product of the weighted water absorption and the modified activity of the material (Table 3.4 in CR-99/021) was correlated and gave a high correlation (r2 = 0.82). By doing this, it is ensured that a measure of the clay content and nature is included in the result. Further manipulation of the data attempted to bring a measure of the potential increase in strength into the function. The probability of success was thus multiplied by the typical percentage increase in strength of each material and an r2 value of 0.99 was obtained. Examination of the results showed a poor distribution along the line with a very strong influential point at 10 000 and the other four points all being in the range of zero to 1500.

From the data available, it is not possible to specify a definite range of values for which any material will be successfully treated. This is particularly notable, as a result of the different performances of different chemicals. By specifying limits, potentially treatable soils may be excluded from use with specific chemicals. However, a value for the product of the weighted water absorption and the modified activity of greater than 1000 would indicate at least a 33 per cent probability of success with the probability increasing as this value increases, but this parameter requires rather unconventional testing. In general, it is considered that any material that is considered for use should be subjected to standard CBR testing with the proposed SPP or a range of SPPs and the results evaluated. Any signs of strength improvement obtained should lead to more detailed testing with various concentrations of the selected SPP to determine the optimum dosage for that material.

The fact that laboratory testing (e.g. Atterberg limits and grading analysis) of treated samples generally shows little or no change over the untreated material has been noted by Scholen. He attributes this to the development of Gibbsite, a more resistant “clay” mineral that encloses remnant clay minerals, which has little effect on the grading and Atterberg limits of a laboratory sample as the structure is destroyed during sample preparation and testing. An analogy is the increase in plasticity index of lateritic soils after remoulding. The significant difference between untreated and treated materials is the neutral charge associated with Gibbsite compared to the negative charge and consequent hydrophilic nature of clay minerals.

7.4 Field Results

The overall performance of the sections of roads selected for the field investigation was good. There were no major differences in the performance of the blacktop roads treated with SPPs and those without SPPs that could be attributed to the effect of the SPPs. Since both types of road have performed satisfactorily, it can be concluded that there are certainly no additional risks associated with the use of SPPs. However, it was not possible, without properly controlled experimental sections, to identify whether there were any cost or structural benefits of using SPPs.

8 Conclusions

8.1 Laboratory Testing

It is essential when planning to use any chemical for a project that the material to be treated is tested with that chemical to ensure that the chemical “reacts” with that material and also to determine the optimum application rate (dosage) for that material. This is becoming increasingly necessary as the composition and concentrations of the different chemicals become more variable.

Standard engineering tests on road building materials are generally insufficiently discriminating to determine the effects of additives. Strength tests sometimes yield a lower result on materials combined with additive. Density tests also frequently fail to show any improvement when the compounds are added to the natural material.

In some circumstances it has been shown that standard laboratory test methods can be used to determine whether a soil material will benefit from the addition of a chemical stabiliser. In these cases the tests may provide a quantification of the magnitude of benefit to be expected from treatment. This is considered to be a conservative estimate and if the construction process is properly executed and controlled, curing and traffic loading will usually achieve in excess of the laboratory result. In terms of the design requirements, if the design strength requirement can be achieved in the laboratory, the treated material can confidently be used in the field.

8.2 SPP Chemistry

All of the products are highly acidic and have specific gravities slightly above unity. There are significant differences in their surface tension properties and their anionic surfactant contents, the two properties particularly relevant to their use in chemical soil stabilisation.

8.3 Effectiveness of SPPs

This investigation has conclusively shown that treatment with SPPs can have a significant beneficial effect on the strength of certain soils. It has also shown that only some materials can be improved with SPP treatment and some of the SPP products only affect certain soils. However, where the combination of soil and chemical is correct, strength increases in excess of 100 per cent can be achieved. It is also considered that in practice, significantly better strength increases may be obtained. This will be facilitated by curing, drying back and traffic loading.

The strength of road building material generally increases when dried back to typical in-service pavement moisture conditions. This increase in strength is particularly pronounced in materials with a high clay content, which are the materials most susceptible to improvement by SPPs. In tests carried out in these in-service conditions these materials often exhibit very high strengths with or without additive (sometimes beyond the capability of the test equipment) and in excess of design requirements.

Where more sophisticated tests are available, it may be possible to determine the type (as well as quantity) of the clay minerals present. However this is of little assistance in the user's decision of which additive will be most effective because the chemical composition of the different products are not disclosed by the suppliers.

Where material properties have been improved by the additives (either as a compaction aid or as a stabiliser), there is little quantitative evidence available on whether the initial cost outlay is justified by benefits from improved performance in whole-life terms. This is due to a lack of trials, which have been properly designed, constructed and monitored.

It is not unknown for suppliers' agents to recommend the use of additive in situations where its application is unlikely to result in improvement of soil quality resulting in considerable wasted expenditure and sometimes even greater rates of deterioration than with the natural material.

In some circumstances, the correct combination of material plus additive can undoubtedly result in an improvement of the engineering properties of soils. However, a number of major problems remain with their use.

(a) The decision on which is the best combination of materials and additive rests with the suppliers not the users.

(b) Many agents' of the suppliers continue to act in an unprofessional manner when recommending the use of additives

(c) Even in circumstances where they may be beneficial, there is little quantitative evidence to show that there is an overall benefit in life-cycle terms.

(d) It is not unknown for so-called independent advisors on the use of additives to have a financial interest in some of these products.

It is therefor essential that a properly controlled quality assurance programme is designed for each project and strictly adhered to in the field.

Until some of these issues have been resolved, users must insist on a Product Performance Guarantee, including a retention of payment against a measure of future performance, which is defined in quantitative terms.

9 Recommendations

Additional soils and SPP stabilisers should be evaluated. It is not cost-effective to carry out a full research exercise using different combinations of soil and SPP but this type of evaluation should be project specific. Sufficient evidence exists to conclude that SPPs can be effective and information is now available to justify and plan this type of exercise for specific projects.

1. Full-scale trials should be carried out to evaluate the effect of SPPs as compaction aids. These trials should be designed to identify whether compaction effort can be reduced and whether water requirements can be reduced. The later is of particular importance in semi-arid and arid areas.

2. Refinement of the Cation Exchange Capacity (CEC) test to facilitate the testing of acidic materials should be carried out.

3. The use of a Product Performance Guarantee System (PPGS) should be implemented in order to ensure that SPP suppliers become more involved with the construction and early performance of projects making use of SPPs.

4. A data base of material test results and project performance should be established to allow all data to be collected and analysed. Only in this way will the credibility of the products be improved and guidelines for their use be derived. This guideline should include a detailed testing procedure and a procedure for interpreting the results.

Recent findings have shown that the construction process is critical. Many of the failures that have involved SPPs and have been attributed to ineffective chemicals can be blamed on unsatisfactory construction procedures. Any material that is poorly compacted, compacted too dry, poorly finished during the final cutting and levelling, contains aggregate that is too large, too soft or too hard or is trafficked before adequately dry will perform poorly, with or without chemical. It is thus essential that the suppliers of the chemical products take responsibility for ensuring that the construction procedures are correct and the quality achieved is to the standards required, both according to conventional construction specifications as well as to the product suppliers' specifications.

In many cases where SPPs are used, construction control is reduced or ignored. The quality of material being treated must be monitored on an ongoing basis and the compaction (density) must be controlled at the end of each job lot. If the compaction is insufficient, additional rolling must be applied before the layer dries out. It is recommended that treated layers are compacted to refusal for the available plant (subject to an appropriate specified minimum) and not to a method specification or prescribed density. Quality control testing must at least follow conventional requirements and preferably be increased to include better materials control and more density testing.

It is suggested by some SPP suppliers that the treated layer should be compacted at least at optimum moisture content or preferably slightly wetter (one to two per cent) than optimum. Trials in Indonesia demonstrated that treatment of soils at moisture contents dry of optimum resulted in poor performance. Compaction at OMC or higher is essential for successful use of SPPs. Dry compaction is probably the reason for ”failure” of many trials, and not inappropriate material or ineffective chemicals. Normal construction practice requires compaction at about optimum moisture content (OMC) but never more than 2 percentage points above OMC as the material is considered to be too wet. Compaction at high moisture contents results in pore water pressures building up, lower densities being achieved and even shearing of the layer. It is recommended that despite the requirement of certain SPP suppliers that the material is compacted wet of optimum, it should never be more than OMC at the time of compaction. It is recommended that the material is compacted at between 90 and 95 per cent of the saturation moisture content of the material to refusal and then slushed afterwards.

There is some debate as to whether the compacted layer should be opened to traffic immediately after compaction or allowed to cure for a period before being trafficked. It has been found that materials with an inherently low CBR before treatment with an SPP have deformed badly when trafficked after compaction. Curing of the layer by spraying with water to keep it continuously moist for a period of 4 days (3 to 7 days has been recommended) before trafficking overcame this problem. In view of the theory proposed by Savage it is suggested that perhaps the best solution would be to water cure the road for three days before opening to traffic while continuing to cure it for an additional 7 days. It should be noted that success has been achieved with SPP treatment on roads with very light traffic, indicating that the traffic compaction is not necessarily essential.

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Annex A. Pre Treatment Soil Test Results

Grading

Grading analyses were carried out on all of the materials following standard TMH 1 methods. The results are summarised in Table A-1.

Percentage passing sieve size (mm)	Sample number				
	TRL1	TRL2	TRL3	TRL4	TRL5
37.5	100		100		
26.5	98.1		98.0	100	100
19.0	92.6	100	96.3	94.2	99.2
13.2	88.3	99.7	92.9	89.3	98.9
9.5	83.7	99.4	87.9	86.0	97.6
6.7	78.0	98.0	79.5	80.8	94.3
4.75	72.3	96.2	69.5	75.4	87.7
2.0	53.0	90.9	47.4	60.5	72.0
0.425	17.7	76.6	31.3	47.4	55.1
0.075	7.5	36.3	13.2	25.6	22.1
Grading modulus	2.21	0.96	2.08	2.14	1.5
Grading coefficient	32.6	8.75	35.2	29.8	24.6
Dust ratio	0.42	0.47	0.42	0.54	0.40

Table A-1 Grading analyses of materials tested

Hydrometer Analysis

An analysis of the gradation of the fine fraction (passing 40 mesh) was carried out using the standard TMH 1 hydrometer method (A6). The material was dispersed with a sodium hexametaphosphate (Calgon) solution which differs from the standard method that uses a sodium silicate/sodium oxalate solution. The results are summarised in Table A-2.

Percentage finer than (mm)	Sample number				
	TRL1	TRL2	TRL3	TRL4	TRL5
0.06	6.5	45.7	11.7	33.4	30.6
0.02	4.0	38.2	5.5	24.7	21.0
0.006	2.6	34.5	3.7	17.4	15.7
0.002	1.3	28.5	2.5	12.4	11.4

Table A-2. Hydrometer analyses of materials tested

Atterberg limits and BLS test results

The Atterberg limits were carried out on the minus 40 mesh fractions recovered during the grading analyses according to TMH 1. The bar linear shrinkage (BLS) is not included in the current TMH 1 but is still routinely carried out using method A4 from the previous version of

TMH 1. A strong case has, however, been presented for its reintroduction as a standard test method 6, 7. The results of the testing are presented in Table A-3.

Property	Sample number				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
Liquid limit (%)	32.7	52.5	SP	30.7	31.5
Plastic limit (%)	23.7	24.7	SP	20.7	22.1
Plasticity index	9.0	27.8	SP	10.0	9.4
Bar linear shrinkage (%)	4.8	14.1	0	5.6	5.3
Shrinkage product	85	1080	0	265	292
Activity	9.9	0.98	-	0.81	0.82

Table A-3. Atterberg limits and BLS test results

Atterberg limits and BLS test results of minus 75um fraction

The activity of the materials was calculated using the standard Skempton method i.e. ratio of PI to clay content with no weighting for the fines content. The diminishing effect of dilution of the non-clay minerals on the activity as their percentage increases9 has not been taken into account in these values. During the course of the evaluation, the influence of the plasticity of the minus 75µm fraction was considered to possibly be more applicable to this type of stabilisation. These values were thus determined and the results are provided in Table A-4. The modified activity is determined in the same way as the activity described above but use was made of the PI of the material passing the 0.075 mm sieve.

Property	Sample number				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
Liquid limit (%)	49.3	79.8	26.2	42.0	47.8
Plastic limit (%)	27.8	19.6	21.9	15.5	27.4
Plasticity index (%)	21.5	60.2	4.3	26.5	20.4
Bar linear shrinkage (%)	9.4	21.6	3.7	10.3	12.2
Modified Activity	16.5	2.1	1.7	2.1	1.8

Table A-4. Atterberg limits and BLS test results of minus 75µm fraction

MDD & OMC

The maximum dry density (MDD) and optimum moisture content (OMC) at Modified AASHTO compaction effort (method A7) were determined for each material. The results are summarised in Table A-5.

Property	**Sample number**				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
MDD (kg/m3)	2082	1680	2080	1999	1946
OMC (%)	11.7	20.0	9.0	10.5	13.0

Table A-5. Maximum dry density and optimum moisture content results

MDD & OMC using vibrating table

In addition to this, the MDD and OMC were determined using a vibrating table as this method was considered to have a far better repeatability and probably simulates the conventional compaction operation closer than the standard Mod AASHTO test. The results of this testing are summarised in Table A-6.

Property	**Sample number**				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
MDD (kg/m3)	2090	1674	2188	2000	1950
OMC (%)	13.9	17.4	9.3	11.2	14.0

Table A-6. MDD and OMC using vibrating table compaction

CBR

The CBR strength of the material was determined using the traditional three compaction efforts and the usual scatter of results was obtained. The results were plotted against density and the best fit line drawn. The estimated CBR values at the specified densities were read off this line and the results are summarised in Table A-7.

% Mod AASHTO compaction	**Soaked CBR**				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
100%	40	2.9	108	58	74
98%	37	2.8	70	45	57
95%	34	2.7	32	34	37
93%	32	2.6	17	27	25
90%	28	2.4	8	19	17
Swell (%)	0.1	3.1	0.04	0.3	0
G-class	G6	< G10	G6	G6	G6

Table A-7. Soaked CBR at % Mod AASHTO compaction

Compaction weighted soaked CBR

For the purpose of comparing the CBR with and without SPP treatment a slightly different approach was taken. The CBR strength is usually calculated from the stress at a penetration of 2.54 mm whereas the stress at 5.08 mm penetration is used in a number of other standards. (Semmelink 1991) thus developed a composite model for a representative CBR based on the weighted CBR determined at 2.54, 5.08 and 7.62 mm as follows:

$CBR_w = (CBR_{2.54} + 2CBR_{5.08} + 3CBR_{7.62})/6$

This allows the use of all of the CBR measurements taken and, when averaged for duplicate or triplicate tests, probably produces a more representative result. The use of this method resulted in the following weighted CBR values (Table A-8).

% Mod AASHTO compaction Weighted soaked CBR	TRL1	TRL2	TRL3	TRL4	TRL5
100	32	2	181	51	33

Table A-8. Soaked CBR (weighted) at % Mod AASHTO compaction

Apparent and Bulk Relative Densities (ARD & BRD)

The apparent and bulk relative densities were calculated as they are necessary for evaluating the air voids content in the compacted samples, the percentage saturation as well as predicting the maximum dry density as a percentage of the solid density of the material. This testing is conventionally done on the plus and minus 4.75 mm fraction but for the black clay (TRL2) it was necessary to test the minus 75 µm fraction separately using paraffin as the immersion fluid. The results are summarised in Table A-9.

Property	**Sample number**				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
ARD > 4.75 mm	2.892	2.776	2.811	3.043	2.653
ARD < 4.75 mm	2.977	2.840	2.725	2.833	2.754
BRD > 4.75 mm	2.240	2.568	2.464	2.248	2.416
BRD < 4.75 mm	2.476	2.726	2.299	2.615	2.273
ARD/BRD < 0.075 mm	-	2.399	-	-	-
Water absorption >4.75 (%)	10.1	2.80	4.50	10.50	3.27
Water absorption <4.75 (%)	6.80	1.48	6.81	2.96	7.69

Table A-9. Apparent (ARD) and bulk (BRD) relative density test results

PH & Electrical conductivity

The results of the pH and electrical conductivity testing are summarised in Table A-10.

Sample number	TRL1	TRL2	TRL3	TRL4	TRL5
PH	8.32	7.80	7.10	5.42	6.05
Electrical conductivity (S.m-1)	0.047	0.211	0.048	0.005	0.003

Table A-10. pH and electrical conductivity

X-Ray diffraction

X-ray diffraction analyses were carried out to identify the crystalline minerals within each material sample. The samples were tested at both the Agricultural Research Council (ARC) and the Geosciences Council (GC). The testing was carried out on the bulk material and that finer than 2 μm (clay fraction) by ARC and on material passing the 2 mm sieve which was hand ground to less than 20 μm by GC. The results are summarised in Tables A-11 and A-12 respectively .

Whole sample Clay fraction

Mineral	**Sample**				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
Calcite	-	10	-	-	-
Dolomite	29	-	-	-	-
Talc	11	-	-	-	-
Feldspar	16	37	-	-	-
Quartz	-	47	98	96	94
Kaolinite	-	-	1	4	6
Mica	-	-	1	-	-
Smectite	44	6	-	-	-
Qtz	-	7	38	66	37
Smect	73	69	-	-	-
Talc	23	6	-	-	-
Kaol	1	9	20	24	53
Goethite	-	-	19	-	5
Mica	-	9	23	10	5

Table A-11. X-ray diffraction results (Agricultural Research Council)

Mineral	Sample				
	TRL1	TRL2	TRL3	TRL4	TRL5
Calcite	-	10	-	-	-
Dolomite	-	11	-	-	-
Goethite	-	-	6	6	8
Pyroxene	18	-	-	-	-
Feldspar	34	18	-	-	-
Quartz	-	42	82	75	73
Kaolinite	-	-	3	10	14
Mica	-	-	5	3	-
Talc	10	-	-	-	-
Amphibole	2	-	-	-	-
Smectite	35	19	-	-	-
Ill/smect	-	-	4	6	6

Table A-12. X-ray diffraction results on whole sample (Geosciences Council)

Differential thermal (DTA) and thermo-gravimetric (TGA) analysis

Differential thermal and thermo-gravimetric analysis are useful tests for the identification and characterisation of minerals, which decompose under high temperatures. When the minerals change properties during heating to a temperature of about 1200 °C (either by losing volatiles such as water (adsorbed and inter-crystalline) or gases (e.g. carbon or sulphur dioxide)), an exothermic or endothermic reaction occurs. The DTA apparatus measures the temperature at which these reactions occur as well as the intensity of the thermal change. The TGA test measures the loss in mass of the material as volatiles are lost. The main objective of carrying out this testing was to identify the characteristic adsorbed water phases and to compare these with the material after treatments with the chemical stabilisers to determine whether the chemicals reduce the adsorbed water thickness or have any other beneficial effect on the material as proposed by the chemical suppliers.

Testing was carried out by an independent laboratory, Thermoanalytical Services in Pretoria, the results can be seen in figures A-1 to A-5.

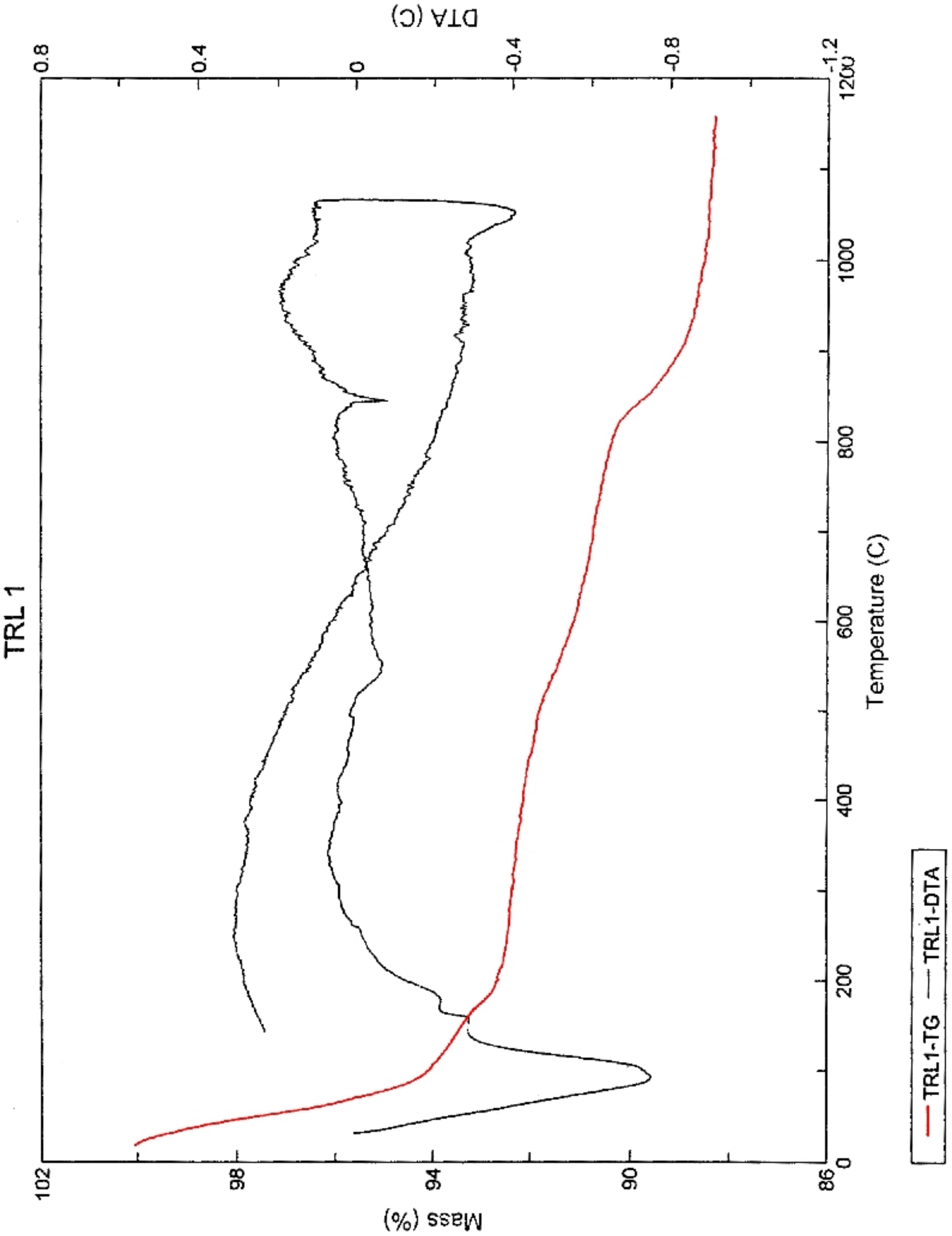


Figure A-1. TGA and DTA Results for Soil TRL 1

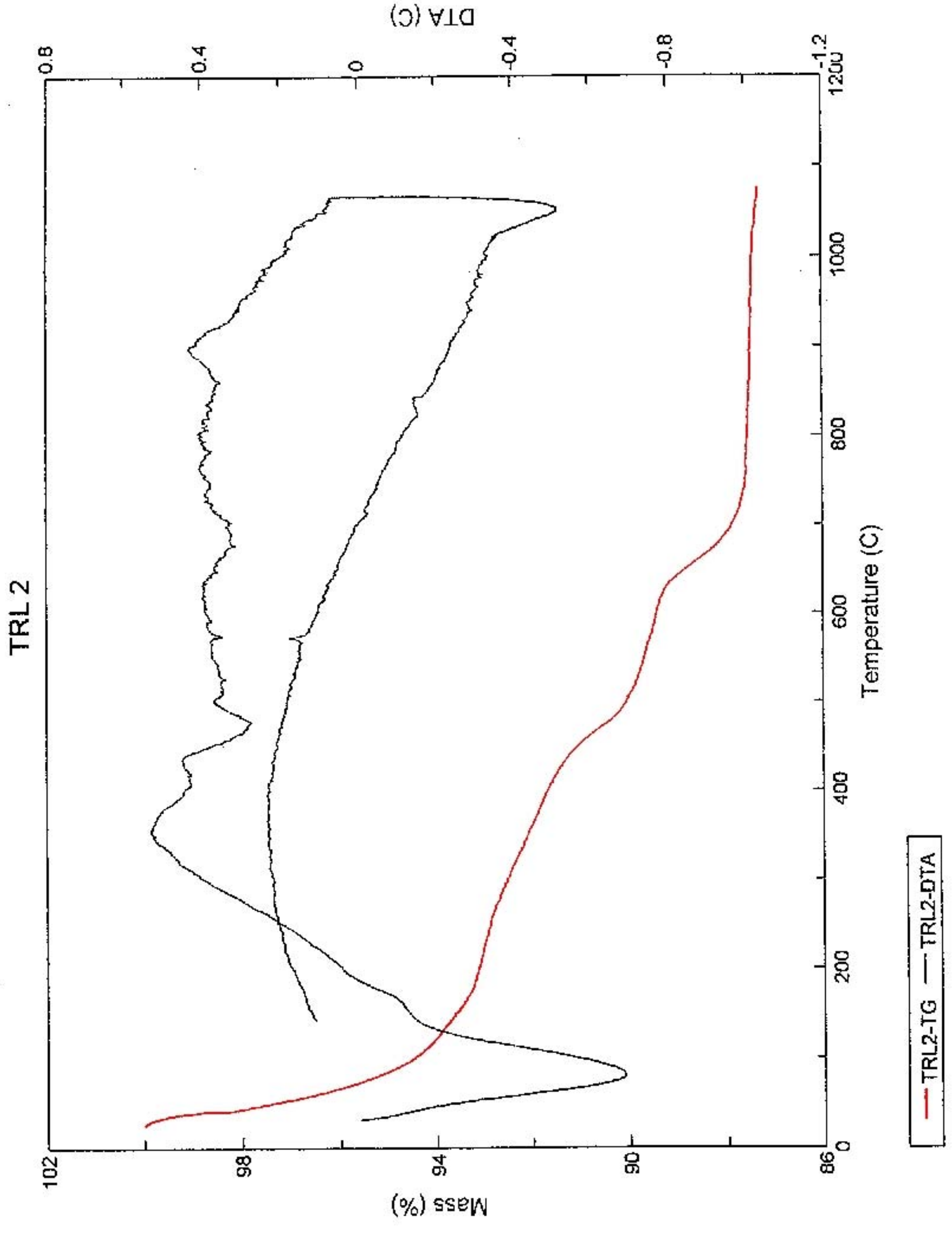


Figure A-2. TGA and DTA Results for Soil TRL 2

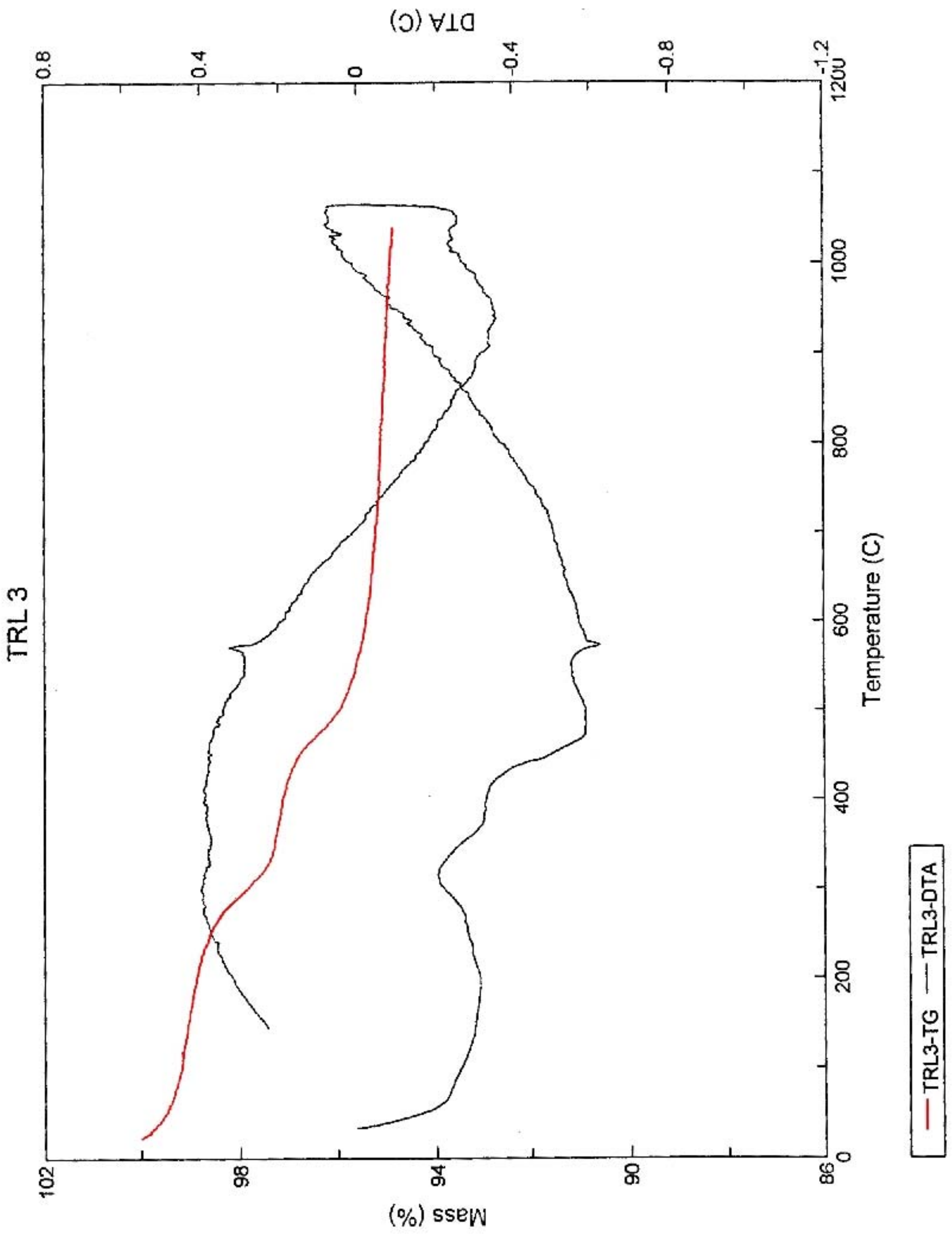


Figure A-3. TGA and DTA Results for Soil TRL 3

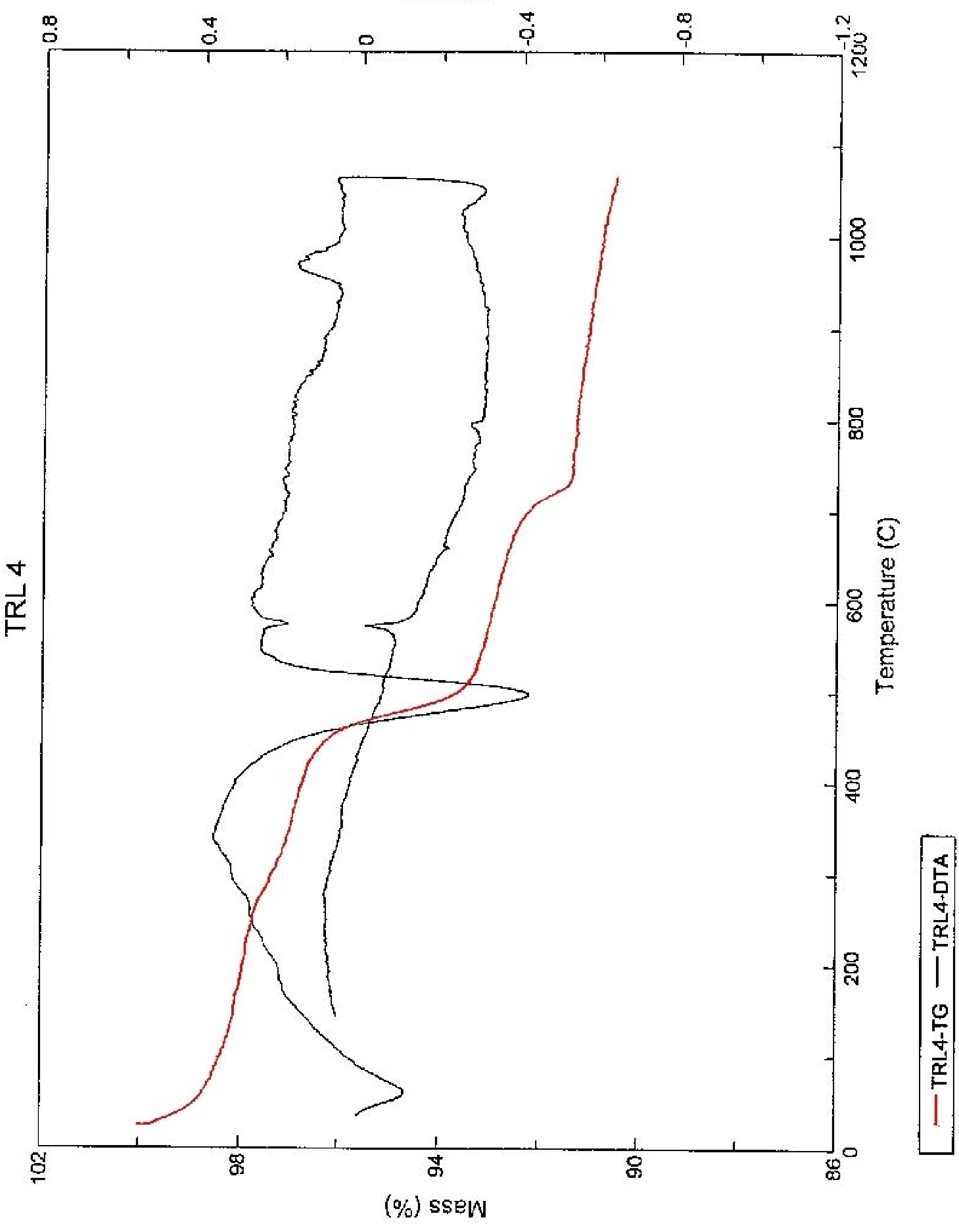


Figure A-4. TGA and DTA Results for Soil TRL 4

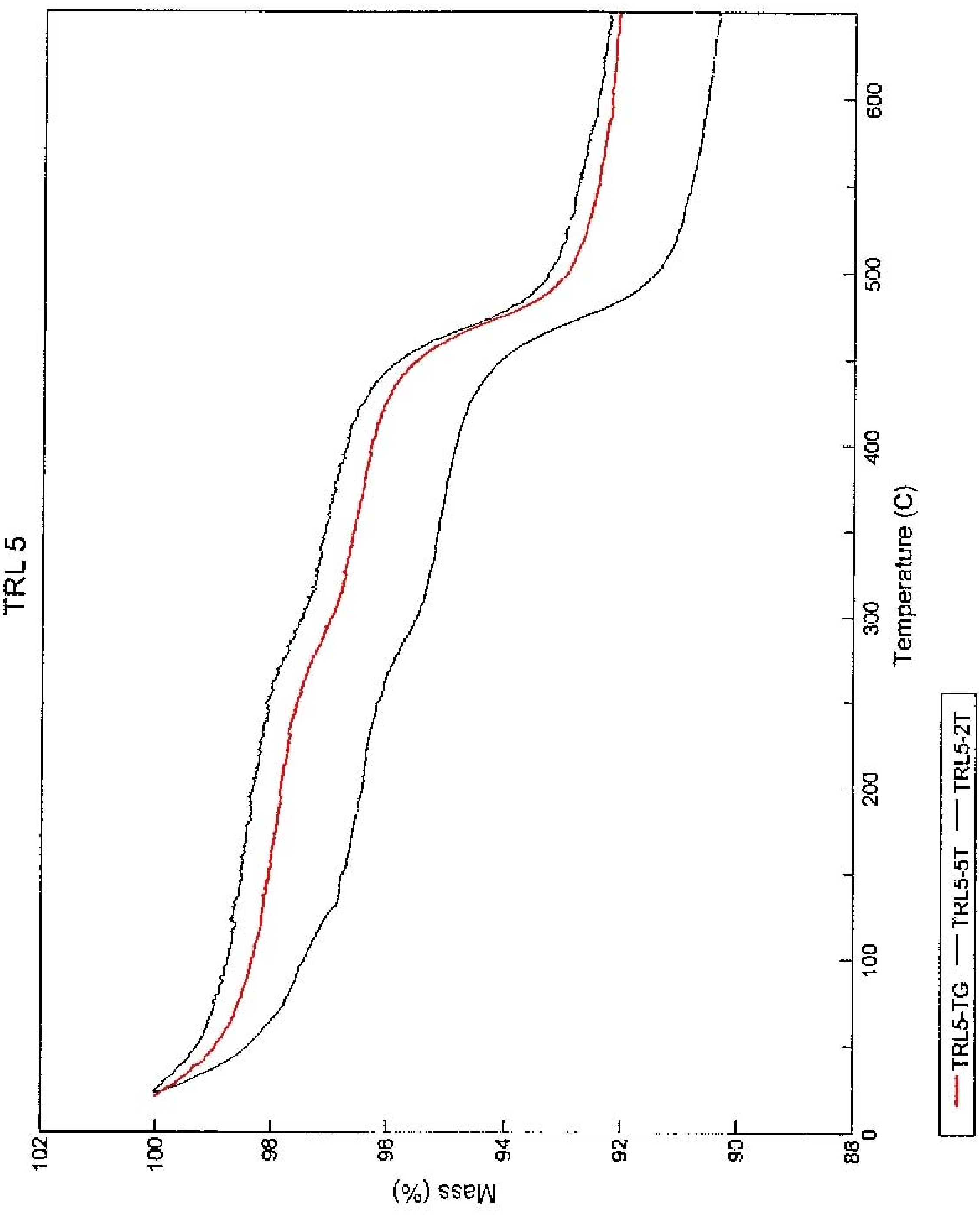


Figure A-5. TGA Results for Soil TRL 5

Cation Exchange Capacity (CEC) and Exchangeable Cation Percentages

As all of the chemicals supplied were classified as ionic soil stabilisers which rely for their successful performance on replacing or bonding with the cations in the clays, it is considered essential to evaluate any changes which may occur. The CEC was determined to identify the potential of the clays within the different materials to react with the chemicals with the aim of re-testing the materials after treatment (and probably various degrees of curing) to evaluate whether any changes in the CEC have occurred. The CEC testing is backed up by the identification of the specific cations in each material making it possible to see whether successful treatment (if it occurs) is associated with any particular cation. The typical cations evaluated are Ca++, Mg++, Na+ and K+. The results of the determination are summarised in Table A-13.

Property	Sample number				
	TRL1	TRL2	TRL3	TRL4	TRL5
CEC (meq/100g)	41.12	35.37	4.97	10.21	5.93
Ca++ (meq/100g)	24.1	23.25	0.70	0.19	0.47
Mg++ (meq/100g)	18.43	9.43	0.58	0.15	0.73
Na+	0.33	0.33	0.02	0.01	0.05
K+	0.22	0.74	0.32	0.10	0.16

Table A.13. Cation exchange capacity (CEC) and exchangeable cation percentages

A number of these materials were resubmitted for repeat testing and gave wide variations in results, indicating the inherent problem with traditional cation exchange capacity testing.

Shakedown bulk density (SBD) and weighted fractional density (WFD)

These two parameters were developed by Semmelink for the prediction of material strength (CBR) from various models developed during an extensive project evaluating the compactability of road construction materials. The methods have been discussed fully (Semmelink 1991) and are not covered in this document. It should be noted that the relative density of the material is used in the calculation of these two parameters and changes to these affect the SBD and WFD results. The results are summarised in Table A-14.

Property	Sample number				
	TRL1	TRL2	TRL3	TRL4	TRL5
SBD	68.17	42.82	78.34	60.83	68.60
WFD	52.68	40.57	61.38	48.38	50.39

Table A-14. SBD and WFD results of materials

Predicted MDD, OMC and CBR Using COMPACT

Using the COMPACT software (COMPACT User Manual 1997), the MDD, OMC and CBR were predicted for each material using the data collected in the tests. Comparison with the vibrating table and Modified AASHTO MDD, OMC, and CBR could thus be carried out. The results from COMPACT are summarised in Table A-15.

Property	**Sample number**				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
Vib Table MDD (kg/m3)	1932	1457	1954	1911	1718
Vib table OMC (%)	16.7	27.4	11.3	16.0	18.4
Vib table CBR (%)	43	12	26	59	16
Mod MDD (kg/m3)	1849	1493	1863	1866	1679
Mod OMC (%)	15.2	20.0	12.9	15.1	17.9
CBR @ 100 % Mod AASHTO (%)	12	15	17	41	6

Table A-15. Prediction of MDD, OMC and CBR using COMPACT

It was immediately evident from the initial results that major discrepancies occurred. These were attributed to two aspects - break-down of aggregate during compaction (i.e. the after compaction grading is necessary for the prediction when break-down of the material is possible) and variability of the bulk relative densities, particularly with the clayey materials. This problem has recently been highlighted in the United States (Kandahl 1999). The COMPACT manual recommends that, because of the difficulties with determining the apparent bulk density of the fine fraction for clayey materials, the apparent relative density should be used.

It is clear that the MDDs are under predicted, the OMCs are over predicted and the CBR values are very badly under predicted.

Grading analyses were thus carried out after compaction of each sample and COMPACT rerun for each of the materials. Various values of the bulk relative density were also evaluated. The results of these predictions are summarised in Table A-16

Property	**Sample number**				
	TRL1	**TRL2**	**TRL3**	**TRL4**	**TRL5**
Vib Table MDD (kg/m3)	2006	1459	2164	1946	1704
Vib table OMC (%)	15.3	27.6	7.8	15.6	17.8
Mod MDD (kg/m3)	1941	1495	1886	1886	1660
Mod OMC (%)	13.0	19.9	12.8	15.5	16.6

Table A-16. Prediction of MDD, OMC and CBR using COMPACT

Recalculation of the data using the grading after compaction and adjusted apparent densities generally improved the prediction of the MDD and OMC and caused a slight improvement of the CBR predictions but these were still poor, particularly in terms of the density/strength sensitivity.

Material classification

The materials were classified in terms of both the AASHTO and Unified classification system on the basis of their properties. The classifications are summarised in Table A-17.

Classification	**Sample number**				
	TRL1	TRL2	TRL3	TRL4	TRL5
AASHTO	A-2-4	A-7	A-1-b	A-2-4	A-2-4
Unified	SW	SC	SW	SC	SC

Table A-17. Soil classification

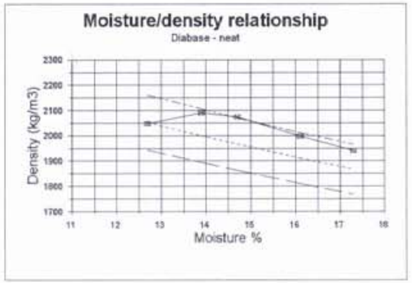
Annex B. Results from Testing of SPP Treated Soils.

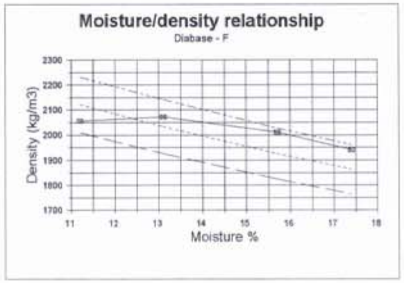
DIABASE - TRL1

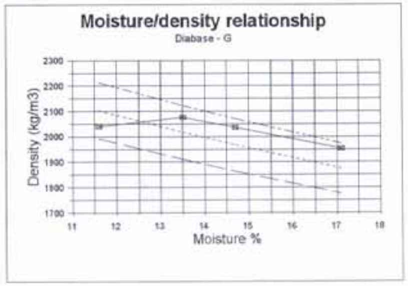
	Additive	neat	SG	2.977					Air voids (%)		
Sample No.	Height (mm)	Diam (mm)	Moist%	Wet mass (g)	Dry mass (g)	Radius (mm)	Vol (m³)	Density (kg/m³)	0	5	10
1	96.43	152.64	12.7	4074.4	3615.26	76.32	0.001765	2049	2160	2052	1944
2	90.9	152.69	13.9	3962.2	3478.67	76.345	0.001664	2090	2106	2000	1895
3	95.06	152.47	14.7	4130.5	3601.13	76.235	0.001736	2075	2071	1967	1864
4	95.63	152.45	16.1	4050.8	3489.06	76.225	0.001746	1999	2012	1912	1811
5	95.9	152.62	17.3	3994.2	3405.12	76.31	0.001754	1941	1965	1867	1768

	Additive	F							Air voids (%)		
Sample No.	Height (mm)	Diam (mm)	Moist%	Wet mass (g)	Dry mass (g)	Radius (mm)	Vol (m³)	Density (kg/m³)	0	5	10
1	96.59	152.85	11.2	4053.6	3645.32	76.425	0.001772	2057	2233	2121	2009
2	95.86	152.91	13.1	4128.1	3649.96	76.455	0.001760	2073	2142	2035	1928
3	98.58	152.28	15.7	4178	3611.06	76.14	0.001795	2011	2029	1927	1826
4	100.81	152.86	17.4	4216.7	3591.74	76.43	0.001850	1941	1961	1863	1765
5					0.00	0	0.000000				

	Additive	G							Air voids (%)		
Sample No.	Height (mm)	Diam (mm)	Moist%	Wet mass (g)	Dry mass (g)	Radius (mm)	Vol (m³)	Density (kg/m³)	0	5	10
1	96.81	153.02	11.6	4052.2	3631.00	76.51	0.001780	2039	2213	2102	1992
2	95.27	152.99	13.5	4126	3635.24	76.495	0.001751	2076	2124	2017	1911
3	97.48	152.55	14.7	4159.7	3626.59	76.275	0.001782	2035	2071	1967	1864
4	100.52	153.05	17.1	4230.2	3612.47	76.525	0.001849	1953	1973	1874	1775
5					0.00	0	0.000000				







BLACK CLAY - TRL2

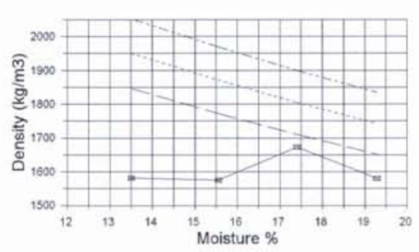
	Additive	neat		SG	2.84				Air voids (%)		
Sample N	**Height (m**	**Diam (mm)**	**Moist%**	**Wet mass**	**Dry mass**	**Radius (m**	**Vol (m^3)**	**DD (kg/m^3**	0	5	10
1	123.91	152.52	13.5	4063	3579.74	76.26	0.002264	1581	2053	1950	1848
2	123.82	152.9	15.55	4137.9	3581.05	76.45	0.002274	1575	1970	1872	1773
3	116.7	152.56	17.4	4192	3570.70	76.28	0.002133	1674	1901	1806	1711
4	123.08	153.04	19.29	4267.7	3577.58	76.52	0.002264	1580	1835	1743	1651
					0.00	0	0.000000				

	Additive	F							Air voids (%)		
Sample N	**Height (m**	**Diam (mm)**	**Moist%**	**Wet mass**	**Dry mass**	**Radius (m**	**Vol (m^3)**	**DD (kg/m^3**	0	5	10
1	118.33	152.96	16.29	4148	3566.94	76.48	0.002174	1640	1942	1845	1748
2	120.14	153.3	18.17	4220.6	3571.63	76.65	0.002217	1611	1873	1780	1686
3	116.53	153.26	20.27	4293.8	3570.13	76.63	0.002150	1661	1802	1712	1622
4	118.96	152.68	24.59	4341	3484.23	76.34	0.002178	1600	1672	1589	1505
5					0.00	0	0.000000				

	Additive	G							Air voids (%)		
Sample N	**Height (m**	**Diam (mm)**	**Moist%**	**Wet mass**	**Dry mass**	**Radius (m**	**Vol (m^3)**	**DD (kg/m^3**	0	5	10
1	123.38	153.07	16.44	4166.6	3578.32	76.535	0.002270	1576	1936	1839	1742
2	116.97	153.55	18.48	4219.2	3561.11	76.775	0.002166	1644	1863	1769	1676
3	115.93	152.71	20	4284	3570.00	76.355	0.002123	1681	1811	1721	1630
4	120.88	152.61	24.55	4402	3534.32	76.305	0.002211	1598	1673	1590	1506
5					0.00	0	0.000000				

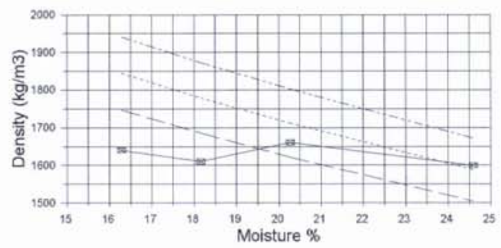
Moisture/density relationship

Black clay - neat



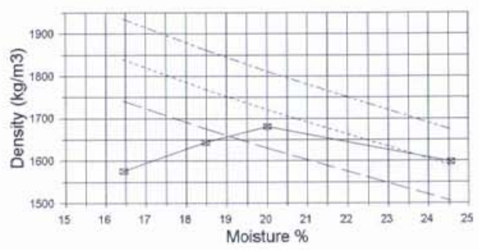
Moisture/density relationship

Black clay - F



Moisture/density relationship

Black clay - G

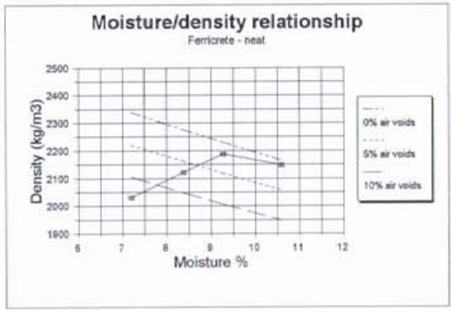


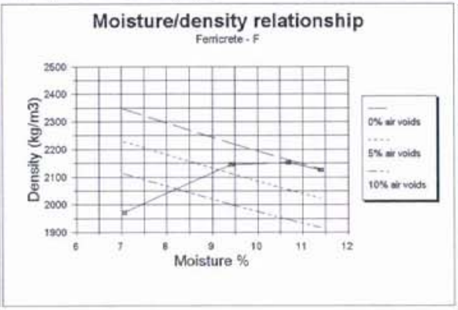
FERRICRETE - TRL3

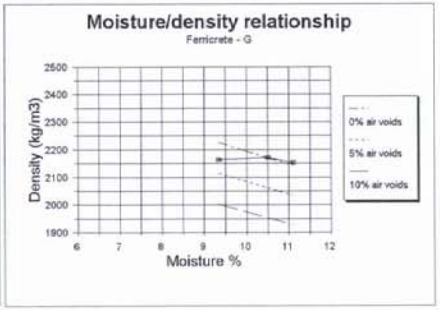
	Additive	neat		SG	2.811				Air voids (%)		
Sample No.	**Height (mm)**	**Diam (mm)**	**Moist%**	**Wet mass (g)**	**Dry mass (g)**	**Radius (mm)**	**Vol (m^3)**	**DD (kg/m^3)**	0	5	10
1	103.22	151.8	7.2	4064.8	3791.79	75.9	0.001868	2030	2338	2221	2104
2	97.98	152.28	8.37	4102.6	3785.73	76.14	0.001784	2121	2276	2162	2048
3	94.19	152.57	9.27	4117.6	3768.28	76.285	0.001722	2188	2230	2118	2007
4	95.37	152.67	10.59	4146.3	3749.25	76.335	0.001746	2148	2166	2058	1950
					0.00	0	0.000000				

	Additive	F							Air voids (%)		
Sample No.	**Height (mm)**	**Diam (mm)**	**Moist%**	**Wet mass (g)**	**Dry mass (g)**	**Radius (mm)**	**Vol (m^3)**	**DD (kg/m^3)**	0	5	10
1	104.86	152.91	7.05	4063.7	3796.08	76.455	0.001926	1971	2346	2229	2111
2	97.28	152.17	9.42	4152.9	3795.38	76.085	0.001769	2145	2222	2111	2000
3	97.17	151.7	10.68	4184.3	3780.54	75.85	0.001756	2153	2162	2054	1946
4	94.81	153.25	11.39	4141	3717.57	76.625	0.001749	2126	2129	2023	1916
5					0.00	0	0.000000				

	Additive	G							Air voids (%)		
Sample No.	**Height (mm)**	**Diam (mm)**	**Moist%**	**Wet mass (g)**	**Dry mass (g)**	**Radius (mm)**	**Vol (m^3)**	**DD (kg/m^3)**	0	5	10
1	95.27	152.83	9.35	4136.4	3782.72	76.415	0.001748	2164	2226	2115	2003
2	95.74	152.61	10.5	4202.1	3802.81	76.305	0.001751	2171	2170	2062	1953
3	93.7	152.83	11.11	4112.4	3701.20	76.415	0.001719	2153	2142	2035	1928
4					0.00	0	0.000000				
5					0.00	0	0.000000				


Moisture/density relationship
Ferricrete - neat


Moisture/density relationship
Ferricrete - F


Moisture/density relationship
Ferricrete - G

CHERT - TRL4

Additive neat SG 2.84

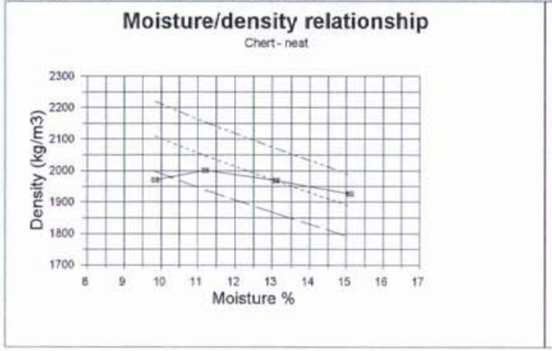
Sample N	Height (m	Diam (mm	Moist%	Wet mass	Dry mass	Radius (m	Vol (m³)	DD (kg/m³	Air voids (%)		
									0	5	10
1	103.86	152.81	9.84	4122.2	3752.91	76.405	0.001905	1970	2220	2109	1998
2	102.67	152.63	11.21	4179.4	3758.12	76.315	0.001879	2001	2154	2046	1939
3	104.57	152.65	13.09	4261.3	3768.06	76.325	0.001914	1969	2070	1967	1863
4	107.54	152.32	15.1	4346	3775.85	76.16	0.001960	1927	1988	1888	1789
					0.00	0	0.000000				

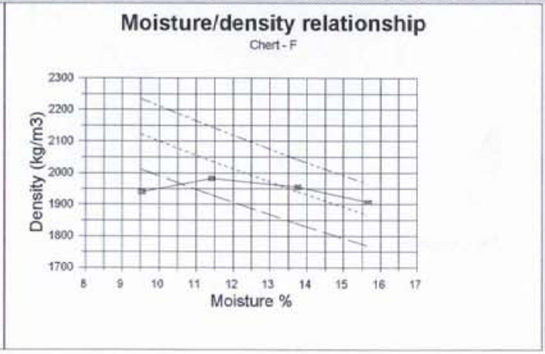
Additive F

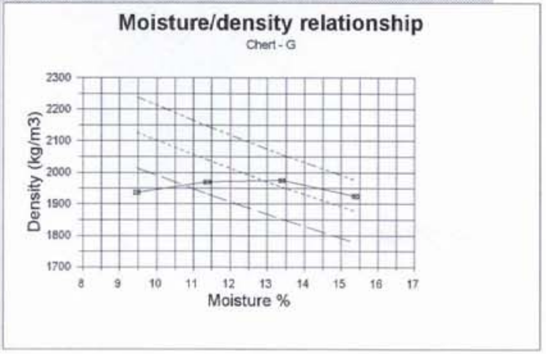
Sample N	Height (m	Diam (mm	Moist%	Wet mass	Dry mass	Radius (m	Vol (m³)	DD (kg/m³	Air voids (%)		
									0	5	10
1	105.27	152.94	9.53	4110	3752.40	76.47	0.001934	1940	2235	2123	2012
2	103.63	152.73	11.43	4194.6	3764.34	76.365	0.001899	1983	2144	2037	1930
3	104.95	152.57	13.76	4267	3750.88	76.285	0.001919	1955	2042	1940	1838
4	107.8	152.01	15.66	4315.2	3730.94	76.005	0.001956	1907	1966	1867	1769
5					0.00	0	0.000000				

Additive G

Sample N	Height (m	Diam (mm	Moist%	Wet mass	Dry mass	Radius (m	Vol (m³)	DD (kg/m³	Air voids (%)		
									0	5	10
1	106.01	152.78	9.46	4120.2	3764.11	76.39	0.001943	1937	2239	2127	2015
2	104.44	152.8	11.38	4201.1	3771.86	76.4	0.001915	1969	2146	2039	1932
3	103.84	152.49	13.4	4246.6	3744.80	76.245	0.001896	1975	2057	1954	1851
4	107.36	151.96	15.4	4323.4	3746.45	75.98	0.001947	1924	1976	1877	1778
5					0.00	0	0.000000				


Moisture/density relationship


Moisture/density relationship

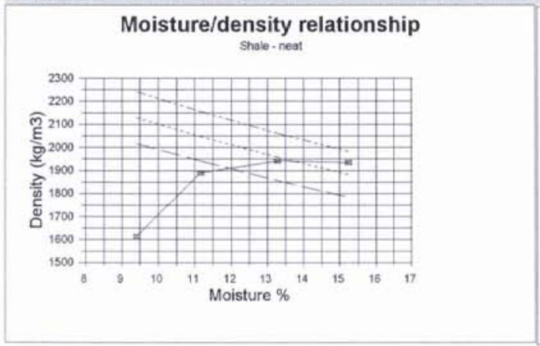

Moisture/density relationship

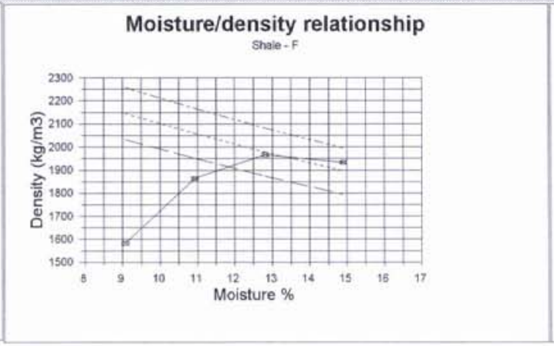
SHALE - TRL5

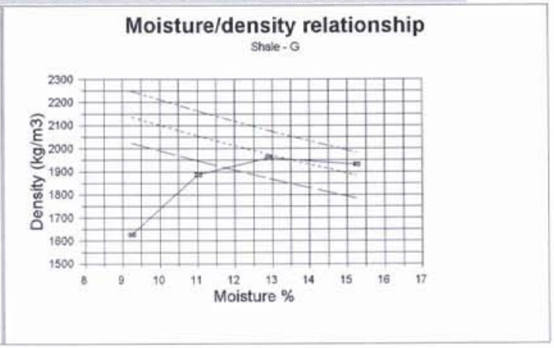
	Additive	neat		SG	2.84				Air voids (%)		
Sample N	**Height (m**	**Diam (mm**	**Moist%**	**Wet mass**	**Dry mass**	**Radius (m**	**Vol (m³)**	**DD (kg/m³**	0	5	10
1	124.99	153.06	9.41	4064	3714.47	76.53	0.002300	1615	2241	2129	2017
2	108.03	153	11.15	4169.8	3751.51	76.5	0.001986	1889	2157	2049	1941
3	105.32	152.7	13.29	4242.8	3745.08	76.35	0.001929	1942	2062	1959	1856
4	106.23	152.52	15.24	4329	3756.51	76.26	0.001941	1936	1982	1883	1784
					0.00	0	0.000000				

	Additive	F							Air voids (%)		
Sample N	**Height (m**	**Diam (mm**	**Moist%**	**Wet mass**	**Dry mass**	**Radius (m**	**Vol (m³)**	**DD (kg/m³**	0	5	10
1	126.3	153.68	9.07	4048	3711.38	76.84	0.002343	1584	2258	2145	2032
2	110.01	152.98	10.93	4181.8	3769.76	76.49	0.002022	1864	2167	2059	1951
3	104.76	152.75	12.81	4259.3	3775.64	76.375	0.001920	1967	2082	1978	1874
4	105.88	152.85	14.9	4316	3756.31	76.425	0.001943	1933	1996	1896	1796
5					0.00	0	0.000000				

	Additive	G							Air voids (%)		
Sample N	**Height (m**	**Diam (mm**	**Moist%**	**Wet mass**	**Dry mass**	**Radius (m**	**Vol (m³)**	**DD (kg/m³**	0	5	10
1	123.26	153.48	9.25	4054.5	3711.21	76.74	0.002280	1627	2249	2137	2024
2	108.48	152.88	11.03	4171.6	3757.18	76.44	0.001991	1887	2163	2054	1946
3	104.73	152.75	12.91	4245.3	3759.90	76.375	0.001919	1959	2078	1974	1870
4	105.6	152.77	15.26	4309.9	3739.29	76.385	0.001936	1932	1981	1882	1783
5					0.00	0	0.000000				







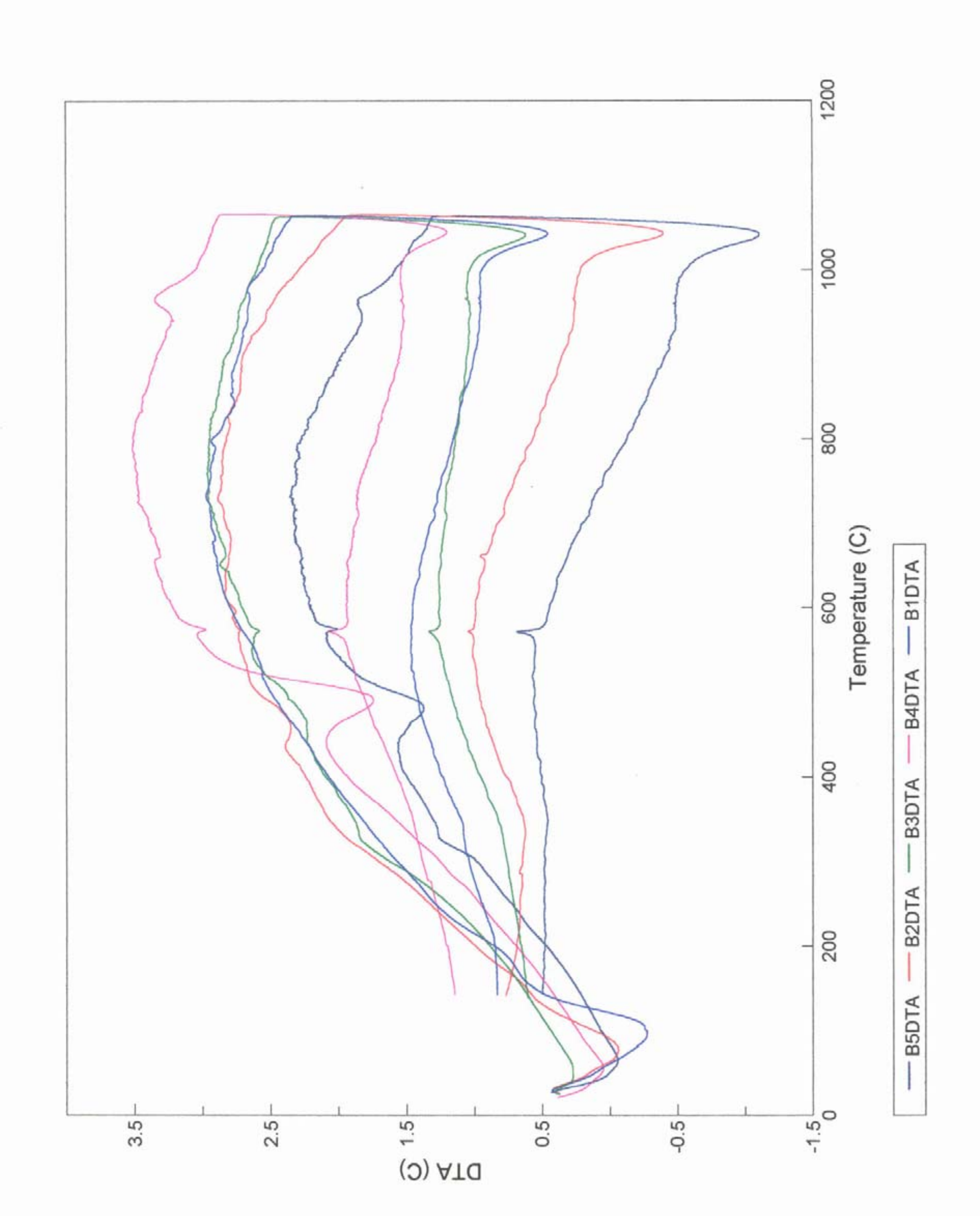


Figure B-1. DTA results following treatment of soils with SPPs

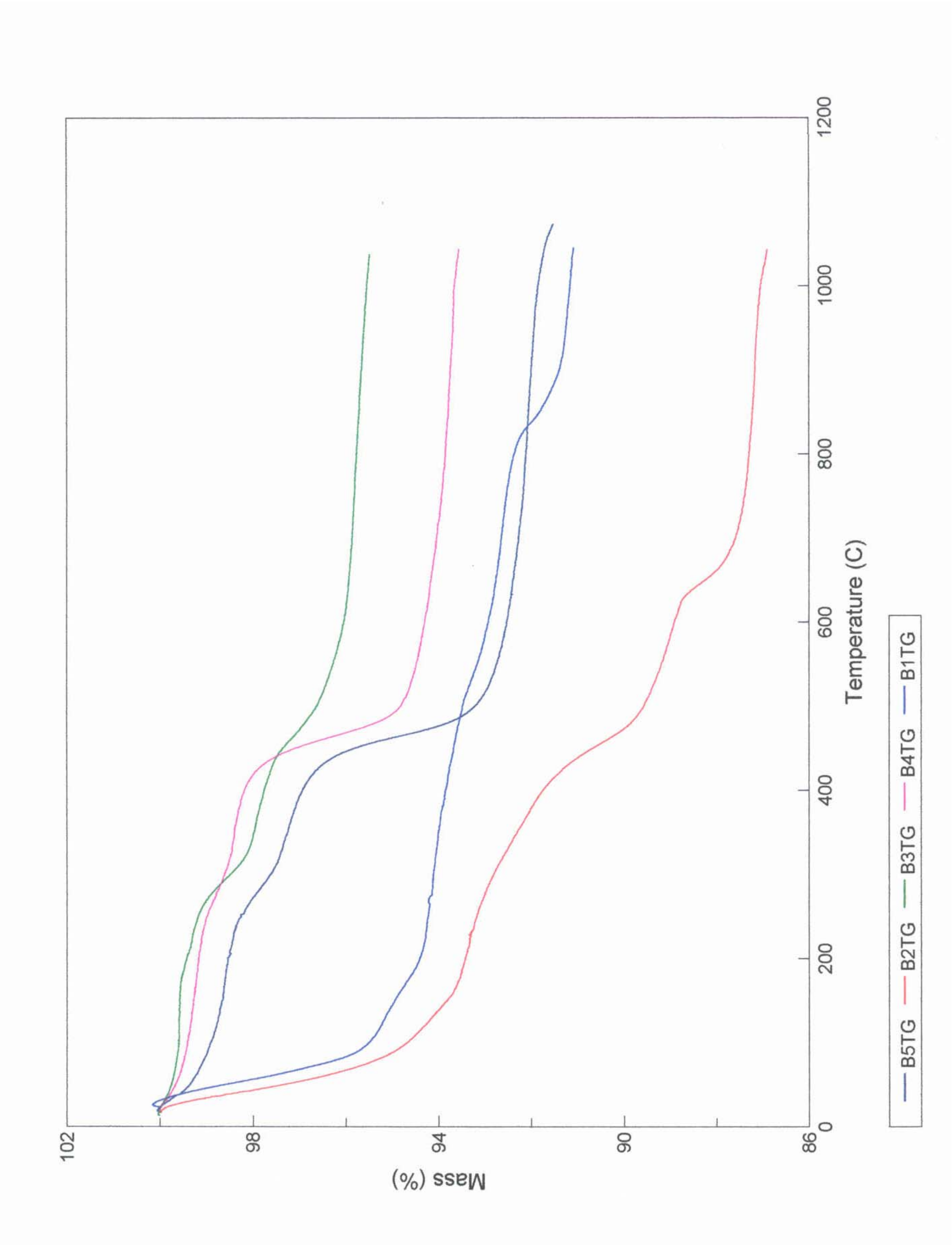


Figure B-2. TGA results following treatment of soils with SPPs

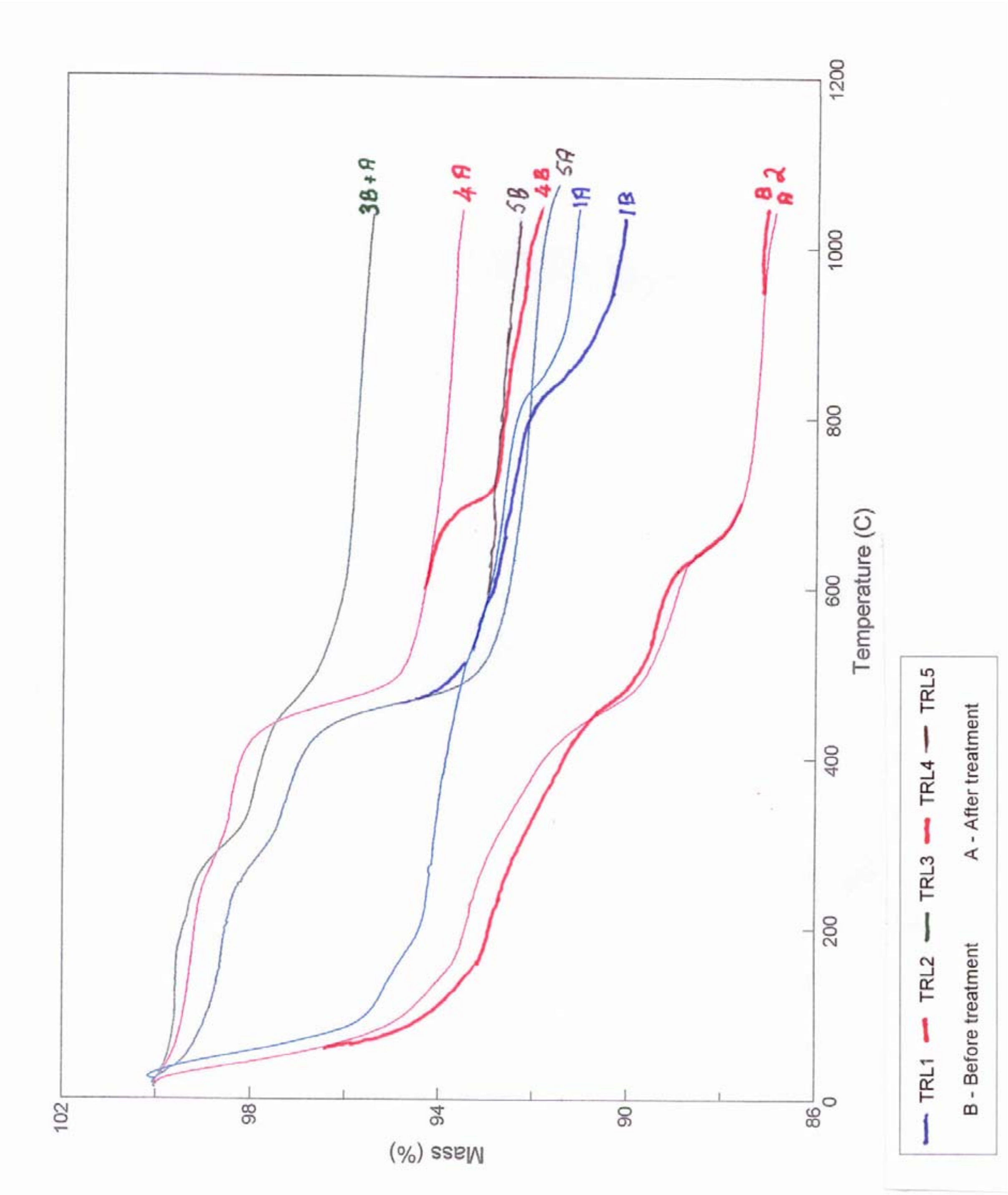


Figure B-3. Comparative TGA results before and after treatment of soils with SPPs

Annex C: Selected case studies

The following brief descriptions of published case studies have been located in the literature. In most cases, the documents have been prepared by journalists associated with the periodical and the scientific validity and credibility of the statements is taken in good faith in this report.

Johannesburg Athletics Stadium

During construction of the Johannesburg Athletics stadium, a clayey soil with a moisture content of 29 per cent affected mobility on a 1:6 ramp over which scrapers were to remove 86 000 m^3 of cut to fill. Con-Aid was applied to 150 mm of the material by hand using watering cans, blade mixed with a grader and left for 5 days. It was then mixed again and compacted. A second 150 mm Con-Aid treated layer was placed over this and after a week the ramp was operational. Over the next four weeks, 7 166 loads were carried (60 tonne scrapers) and "no deformation whatsoever" (sic) was observed. The CBR before treatment (and presumably drying and compaction) was two. After four weeks the in situ CBR (measured with a DCP) was 62. (Note: Much of the increase could probably be attributed to drying and compaction.) The site agent was, however, very happy with the result.

Heilbron, Ladybrand, Standerton and Meyerton

Successful reports of the use of Con-Aid have been reported by the Town Engineering Departments for unsealed and sealed municipal roads in Heilbron and Ladybrand (Free State), Standerton (Mpumalanga) and Meyerton (Gauteng). The in situ heavy clay materials have been treated with Con-Aid and the resulting roads have required significantly less maintenance than normal when unsealed. In one case a treated road has required sealing after 15 years, although the treated base is still "*in excellent condition*" (sic).

Swaziland

Following the successful use of Con-Aid on various sugar estates in Swaziland, the Government upgraded two local roads constructed with fine, high plasticity materials (70-90 % < 2 mm and PI .17). The chemical was applied by a contractor inexperienced with chemical stabilisation, during a period of very heavy rainfall, and the roads soon became impassable. The suppliers were called in and the roads reconstructed according to their standards and within two months the in situ CBRs were in excess of 200 per cent. The roads were then sealed with a single seal and have apparently performed well. The importance of proper construction and adhering to the suppliers requirements were clearly exhibited in this project.

Forestry and sugar industries

The successful treatment of a forestry road to reduce dust, slipperiness and potholes has been described. The article was written 5 months after construction and very little technical information is provided. The Forester in charge of the forest praised the treated road highly.

The treatment of roads on two sugar estates in Swaziland is also described. Little technical information is provided but significant reductions in dustiness and maintenance requirements were observed and improvements in passability, rideability and road durability are discussed. A common problem with SPP treated materials was also highlighted - protrusion of larger aggregates above the general level of the road occurred and these were held so well in the soil matrix that "*severe damage to the grader would have resulted"* (sic) had a grader tried to blade the road.

It was also stated that an airstrip constructed with Con-Aid was reported to be the only one in the area that is serviceable during wet weather.

Cracking of black top surfacing

The case of a badly cracked black top surfacing due to movement in the lower layers is reported. Chem Road was ripped 150 mm into the lower layers (sic) eliminating further cracking of the black top surface "*due to its stabilising ability. Further tests revealed that the chemical reaction had worked its way down to a depth of 1 m".*

Black clay subgrade in a township

The in situ material in a low cost housing development consisted of a plastic black clay (PI 21 to 28) with soaked CBR values of between 3 and 5 per cent. A laboratory investigation showed that treatment with 0.03 P/m^2 of ISS chemical stabiliser reduced the Cation Exchange Capacity significantly (33-64 me/100 g before treatment and 6 to 17 me/100g after treatment. On the basis of these results the in situ clay was treated to a depth of 200 mm and imported material was used for the base and subbase. A single bitumen-rubber surfacing was used to seal the pavement. Six months after construction the pavement was evaluated. The surfacing was in perfect condition and no problems were observed. Samples of the treated subgrade showed significant changes in the clay properties with a reduction in PI from more than 20 to 5 per cent and an increase in grading modulus from 0.63 to 1.04.

The effectiveness of the **chemical was evident within 24 hours of application. Prior to application it was not possible** to work the material with a grader due to passability and cohesion problems but within 24 hours the material was completely workable.

Roads in Tanzania

Various projects in Tanzania are described by Knowles. The materials utilised had PI values between 9 and 14 per cent and CBR values between 9 and 36. After treatment the CBR values ranged between 24 and 46 per cent. The roads were not sealed and significant reductions in gravel loss were recorded after 6 months. In general, savings of between 20 and 25 per cent were calculated.

Tests in the United States and Puerto Rico

Scholen summarises eleven case studies from various states in the USA and one in Puerto Rico using a range of chemical stabilisers. Definition of the specific stabilisers is not clear but ISS was certainly used. Although little information about the specific materials is provided, in most cases the performance was described as good.

Black cotton soils in Kenya

This paper summarises the results of laboratory studies on two samples of black cotton soils removed from two sites about 126 km apart. The properties of the materials were similar to those of sample TRL2, if not slightly poorer (PI - 34-37%; P425 - 75-84%; MDD - 1378-1665 kg/m^3). Extensive testing, including curing for up to 7 days, indicated that the plasticity was positively affected but CBR strength development did not show increases with curing time.

Success has been achieved with the treatment of black clays (see Swaziland and township case studies above) and it was expected that TRL2 would be the material most likely to benefit from treatment. Despite testing after treatment with various chemicals no success was achieved during the Transportek investigation. No reason for this could be found.