A laboratory study of soil stabilisation with a urea-formaldehyde resin

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The aim of this paper is to present laboratory results on the effectiveness of a proprietary urea-formaldehyde (UF) resin as a soil stabiliser. The Indirect Tensile Strength (ITS) was used to characterise the soil stabilising properties of the resin. A brown shale gravel with an ITS dry strength of 160 kPa was used as test soil. Treated samples were compacted at the optimum moisture content (OMC) of the soil (ca 9,5%) using the Marshall apparatus. Dry strength was evaluated after the samples were left to air-dry for 7 or 21 days. The wet strength was determined following a 24-hour water-soak of the air-dried samples. In this system, cement and lime were ineffective soil stabilisers even at the 6% dosage level. In contrast, the addition of 2% UF resin was sufficient to raise the dry strength to 340 kPa but wet strength was still poor. This problem was solved by a further addition of a suitable bitumen emulsion. At a 2% dosage it increased both the wet and dry strengths to ca 450 kPa. Unconfined Compressive Strength (UCS) measurements on this as well as other soil types confirmed the soil stabilisation utility of the UF resin. These tests also showed that the system performed better in siliceous than in calcareous aggregates.

Keywords: urea, formaldehyde, resin, soil, binder, stabiliser, stabilisation

INTRODUCTION

Soil stabilisation is the treatment of earth-based road building materials in order to improve their engineering properties. The stabilised road material must offer sustained resistance to deformation under repeated loads in both wet and dry conditions (Ballantyne & Rossouw 1989). Desired soil property improvements include increased workability during application, and also strength, durability and dimensional stability in the end-use situation. Cement, lime, bitumen and tar are well-established soil stabilisers with proven track records.

Factors that influence the effectiveness of a soil stabiliser include the following:

- *The soil:* The type, composition, pH and grading of the soil affect its properties and hence influence the performance of the stabiliser (Road Research Laboratory 1952). The soil moisture content has a direct effect on strength but can also have an effect on the stabilising agent.
- *The stabiliser:* The dosage levels and the use of modifying agents must be optimised.
- *The application method:* Proper mixing is necessary to ensure homogeneous dispersion of the stabiliser in the soil. Ultimate strength is also highly dependent on the degree of compaction that is achieved. The time allowed between application and compaction and between compaction and trafficking also affects performance.

Resins based on formaldehyde condensation products are widely used as binders in industry (Diem & Matthias 1986). These polymers could provide commercially viable alternatives to traditional soil stabilisers (Ebdon et al 1990). However, their widespread use in this application must await extensive testing and evaluation in order to establish their effectiveness as well as their effect on the environment. The aim of this laboratory investigation was to assess the technical suitability of a proprietary, cold-setting urea-formaldehyde (UF) resin as a soil stabiliser for various soils. The indirect tensile strength (ITS) was used as a measure of soil stabilisation efficiency in a brown shale gravel (soil A) for resin optimisation studies. Thereafter the unconfined compression strength (UCS) was used to confirm the results on additional soil samples that included calcaraceous and siliceous aggregates. The resin was evaluated in combination with other additives such as cement, lime and bitumen emulsion. The effect of factors such as stabiliser dosage level and soil moisture content on stabilisation performance was evaluated.

EXPERIMENTAL PROCEDURE

- *Materials and conditioning:* The stabiliser tested in this study was a proprietary urea-formaldehyde resin formulation. It was used in combination with a 60% anionic bitumen emulsion to SABS 309. The properties of the test soils are presented in the Appendix. Soil A, a brown shale gravel, was used for initial resin optimisation experiments. It was classified as a G7 material according to the grading, Atterberg limits and CBR in terms of TRH 14 (1985). The moisture content of the soils was maintained by storing them in sealed plastic bags. All the experiments were carried out at a

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constant temperature of 23°C. The dosage levels of resin and bitumen emulsion are reported on an add-on basis, ie the mass of the corresponding undiluted liquid used as a percentage of the dry soil mass.

- *Sample preparation:* A typical test sample preparation procedure was as follows. The liquid stabiliser system was diluted with the required amount of water to ensure that the final mixture would be at the optimum moisture content (OMC) for compaction. The diluted resin was then added to approximately 1 kg of soil and mixed thoroughly to ensure good distribution of the reagents throughout the soil phase. Cylindrical test briquettes were prepared using the Marshall apparatus according to TMH1 Method 2C (CSRA 1990). Standard moulds with an internal diameter of 101,6 mm were used. Compaction was achieved using 50 blows on each side of the sample. The compacted samples were air-dried for a specified number of days. The Indirect Tensile Strength (ITS) was determined according to TMH1 Method A16T (CSRA 1990). Unless stated otherwise, the ITS dry strengths were determined using samples that were initially air-dried for either 7 or 21 days. Similarly, the wet strength was determined after soaking the air-dried samples in water for a further 24 hours.
- *Optimisation of the sample preparation procedure:* The effects of compaction soil moisture content, degree of compaction, drying time and soak time were investigated. The UF resin-bitumen emulsion combination was used throughout with both additives dosed at the 2% level. The compaction soil moisture content was varied from 7,5% to 13,5%.
- *Experiments with cement and lime as binder:* Soil binding experiments with cement and lime were conducted according to TMH1 Method A13T (CSRA 1990). Instead of the air-drying, the compacted samples were kept in a high humidity cabinet for seven days to allow for curing. This was followed by 24 hours of air-drying before measuring the dry strength. Wet strength was measured after soaking such samples in water for 24 hours. In all cases the cement used was Portland cement type CEM 1 42,5 to SABS ENV197-1.
- *Unconfined compressive strength (UCS):* Tests on the other soils were carried out using the UCS as a measure of the soil stabilisation efficiency of the UF resin. The samples were all prepared according to TMH1 Method A13T (CSRA 1990). They were air-dried for 21 days before the UCS was determined according to TMH1 Method A14 (CSRA 1990). In the case of soil B the effect of compaction level was evaluated at various resin dosage levels. For all the other soils the samples were compacted to 100 % of Modified AASHTO.

RESULTS

- *Optimisation of sample preparation procedure:* Preliminary experiments showed that both the dry strength and soil density peaked at a compaction moisture content near the OMC value. It was therefore used in all further tests. The results obtained with the compaction experiments showed that the dry strength and sample density stabilised, ie remained constant after 50 blows per side had been applied. For samples containing bitumen, long drying times (>21 days) were necessary to reach ultimate strengths. Such long drying times are often unacceptable in practice. It was therefor decided to also evaluate the strength after seven days of drying. TMH1 Method A13T (CSRA 1990) prescribes a soak time of 1 hour. However, the bitumen emulsion treated samples reduced the water penetration rate to such an extent that it was decided to increase the soak times to 24 hours.
- *Screening of stabiliser systems:* Table 1 shows the effect of the various soil stabilisers on the wet and dry strength of soil A after 7 days of air-drying. The low values for lime suggest that it is not an effective soil stabiliser for this soil. The cement and the UF resin are effective provided the correct sample preparation method is used. The results obtained with the UF resin-bitumen emulsion combination (using TMH1 Method C2) show synergism, especially with respect to wet strength. It was therefore decided to study this system in more detail.

  Similar trends were observed with cement and UF resin samples that were cured for 7 days in a humidity cabinet in accordance with TMH1 Method A13T (CSRA, 1990). With 2% UF resin negligible strength development occurred whereas the dry strength with 6% cement reached 325 kPa. The combination of 2% UF resin with 6% cement resulted in a dry strength of 287 kPa and a wet strength of 124 kPa.
- *Optimisation of resin dosage level:* Figure 1 shows the effect of resin dosage level on the soil strength of soil A. The bitumen emulsion dosage kept constant at 2% (mass basis). The results reveal an antagonistic interaction at low resin dosage levels. It is particularly severe in the case of wet strength where mechanical integrity is completely lost at the 0,5% resin dosage level. With further resin addition, the ITS recovers and reaches a plateau level above a resin level of 2 to 3%. Figure 1 also shows that long drying times are beneficial for strength development.

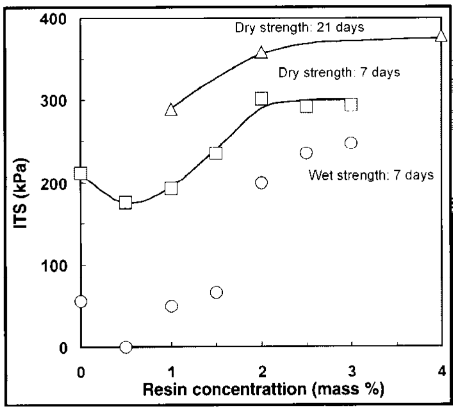

Figure 1 The effect of resin concentration on strength development of brown shale gravel (soil A) containing 2% bitumen emulsion

- *Optimisation of bitumen dosage level:* The effect of bitumen emulsion dosage was determined at a fixed 2% resin level for soil A. The ITS strengths were measured after a 7-day drying period. Figure 2 shows that adding the bitumen emulsion improves wet strength but has no effect on the corresponding dry strength.
- *Drying time:* The effect of air-drying time was studied using soil A stabilised using 2% resin with and without an addition of 2% bitumen emulsion. Figure 3 shows that in the absence of bitumen, the UF resin develops negligible wet strength, even after prolonged drying. Wet strength is

Table 1 Effect of treatments on ITS soil strength (in kPa) after a 7-day air-drying period for the brown shale gravel (soil A)

	TMH1 sample preparation method			
Indirect Tensile Strength Measurement:	Method A13T[1]		Method C2[2]	
Treatment (dosage)	Dry	Wet	Dry	Wet
None	–[3]	–	160	0
Lime (4%)	7	14	41	~5
Cement (6%)	325	262	68	35
Bitumen emulsion (2%)	–	–	210	55
UF resin (2%)	–	–	300	15
UF resin (2%) plus lime (2 - 6%)	–	–	100	30
UF resin (2%) plus cement (4%)	–	–	290	170
UF resin (2%) plus cement (6%)	287	124	334	230
UF resin (2%) plus bitumen emulsion (2%)	–	–	435	270

1 Compaction 4 hours after mixing of stabiliser, curing in a high humidity cabinet for 7 days.
2 Compaction immediately after mixing of stabiliser, air-drying for 7 days.
3 – indicates that the measured values were too low to be meaningful.

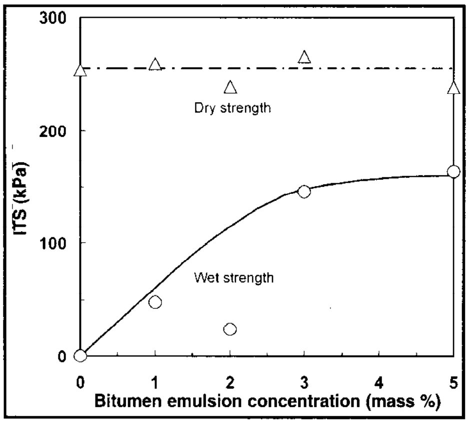

Figure 2 The effect of the bitumen emulsion dosage on the strength of a brown shale gravel (soil A) after drying for 7 days. Resin dosage was kept constant at 2%

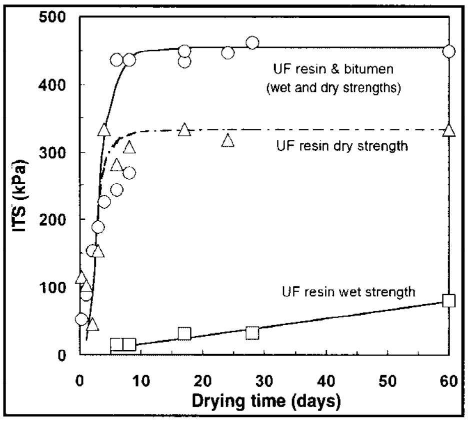

Figure 3 The effect of the drying time on the strength of brown shale gravel (soil A) stabilised with 2% UF resin with and without 2% bitumen emulsion

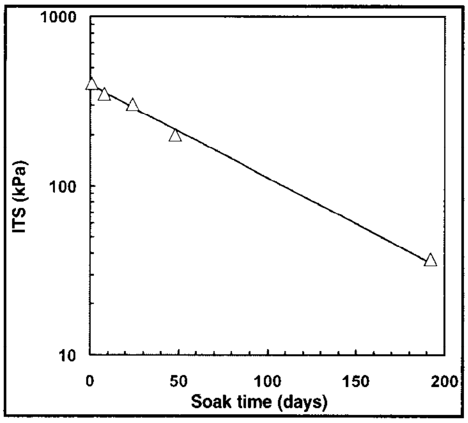

Figure 4 The effect of the soak-time on the wet strength of a brown shale gravel (soil A) stabilised with 2% each of UF resin and bitumen emulsion. Soil samples were dried for 7 days before soaking

improved significantly by adding bitumen. When such UF resin-bitumen emulsion combinations are dried for longer than 6 days, wet and dry strengths become indistinguishable. Figure 3 also shows prolonged drying (>7 days) is necessary to achieve ultimate strengths. Further measurements revealed that strengths exceeding 400 kPa were only achieved when the residual moisture content of the soil

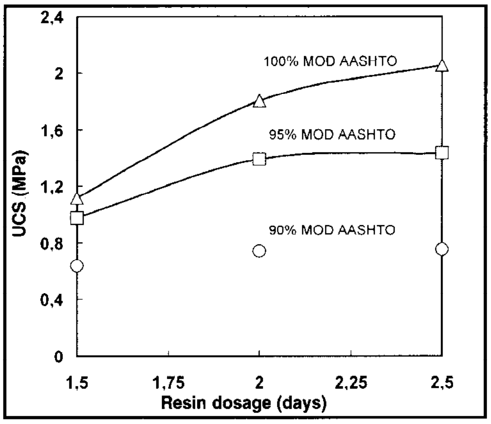

Figure 5 The effect of compaction and UF resin dosage on the 21-day dry strength of a calcrete (soil B). The resin was used in combination with 2% bitumen emulsion

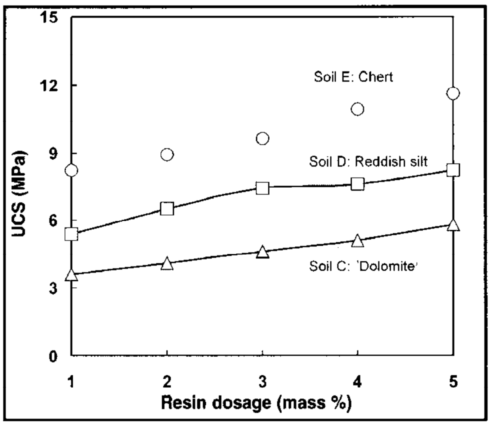

Figure 6 The effect of resin dosage on the 21-day dry strength of soils compacted to 100 % of Mod AASHTO. The resin was used in combination with 2% bitumen emulsion

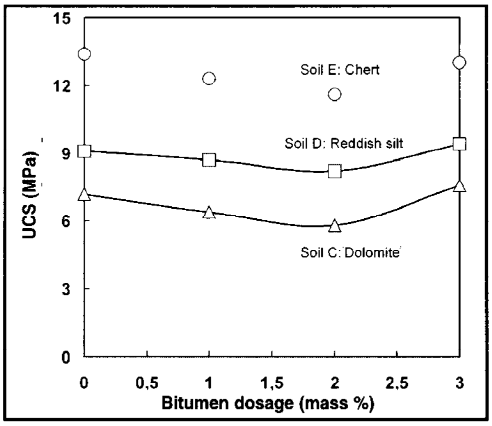

Figure 7 The effect of bitumen emulsion dosage on the dry strength of soil samples (C, D, E) compacted to 100 % of Mod AASHTO and dried for 21 days. The bitumen emulsion was used in combination with 5 % UF resin

was reduced to below 2,5%.

- *Long-term wet strength*: The influence of prolonged water soaking on soil strength was determined using samples of soil A stabilised with 2% each of resin and bitumen emulsion. The samples were dried for 7 days before proceeding with soak tests. Figure 4 shows that the wet strength followed an exponential decay over time with a half-life time of approximately 50 hours. This suggests that the urea-formaldehyde-bitumen stabilisation system is fundamentally unstable in the presence of water.
- *Compaction:* A calcaraceous aggregate (soil B) was used to study the effect of soil compaction on ultimate unconfined compressive strengths (UCS). It was treated with 2% bitumen and various percentages of resin. The UCS was determined after a 21-day drying time. The results are reported in figure 5 and it show that, as usual, proper soil compaction is essential for achieving high UCS values.
- *Effect of resin and bitumen dosage levels on the strength of other soils:* Figures 6 and 7 respectively show the effects of varying either resin or bitumen dosage levels on the compressive strength of three additional test soils: two silty soils (soils C and D) and a chert (soil E). At a constant 2% bitumen emulsion dosage, an increase in resin level leads to a linear increase in compression strength. When the resin level is pegged at 5%, an increase of bitumen dosage initially decreases compression strength. However, when the bitumen level reaches ca 3%, the initial compression strength is recovered. Comparison of the UCS values for soil B (figure 5) in relation to soils C, D and E (figure 6) also shows large differences for the same bitumen emulsion content and corresponding resin content. For the one sample of each tested, the performance of the UF resin-bitumen system decreased in the series: chert > reddish silt > 'dolomite' > calcrete

The compression strengths obtained with chert and calcrete differed significantly. This illustrates the important effect of soil type on the performance of specific soil stabilisers (Ingles & Metcalf 1972). Care should therefore be taken when attempting to extrapolate results presented here to other soil conditions.

DISCUSSION

The synergistic interaction between the cement and UF resin might be explained in terms of differences with respect to water requirements during curing. The chemical cure reaction of the UF resin releases water. Removal of the water is necessary in order to drive the reaction to completion. This is confirmed by the observation that full strength development, in UF resin stabilised soil, requires removal of free moisture. In contrast, the curing of cement involves hydration reactions that consume water. These opposing needs might be better satisfied when the two additives are used together in suitable proportions. The cement, by absorbing the excess moisture, causes local dehydration and thereby contributes to more efficient curing of the UF resin. On the other hand, the UF resin cross-linking reaction releases additional water to help cure the cement.

Bitumen emulsions are widely used in road construction and maintenance as a binding and waterproofing agent. It is therefore not surprising that it provided a degree of soil stabilisation by itself. However, the large, positive interaction between the resin and the bitumen, with respect to indirect tensile strengths, was not anticipated. It is not clear what gives rise to this synergistic interaction. It could be related to improved wetting of soil particles, reactions between the resin and bitumen components or even a plasticising effect of the bitumen on the resin.

Early investigations into resin treatment of soils focused on reducing water absorption (Road Research Laboratory 1952). However, bacteria and fungi attack most resins and this has limited their application. It is noteworthy that Otake *et al* (1995) found no evidence of biodegradation of urea-formaldehyde resin buried under soil for over 32 years. This implies that the UF resin has an intrinsic resistance to soil-borne bacteria and fungi. Further work is required to reduce the health hazard associated with the use of urea-formaldehyde resins in open work environments.

CONCLUSIONS

Indirect tensile strength measurements on a brown shale gravel (Soil A) were used to optimise the application of a proprietary urea-formaldehyde soil stabiliser. Dry strengths were measured on compacted soil samples that were air-dried for either 7 or 21 days. Wet strengths were measured by soaking such samples for at least one hour in water. Comparing the results with the properties of the natural soil, showed that, under these conditions:

- Cement and UF resin are effective provided the appropriate soil preparation procedure, as described in table 1, is used.
- 2% UF resin addition doubled the soil dry strength but showed no significant improvement in wet strength.
- Addition of 6% cement to the 2% UF resin stabilised system gave a similar dry strength and improved the wet strength considerably.
- The highest strengths were obtained with a combination of UF resin (2%) and bitumen emulsion (2%). The 21-day dry strength was almost trebled,
- When soaking this latter system in water, the strength decreased exponentially with a half-life time of approximately 50 hours.

The compression strengths obtained using different soils showed large differences. Excellent UCS strengths (up to 12 MPa) were obtained for a chert (soil E) but values for a calcrete (soil B) were almost an order of magnitude lower. It is concluded that urea-formaldehyde resins may hold promise as soil stabiliser in dry climates only since the strength of the soil decreases during long exposure to moisture. It is also essential that application conditions are optimised with respect to the soil to be treated and that adequate time is allowed for drying.

Acknowledgement

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APPENDIX: Test soil properties

Material*		Soil A	Soil B	Soil C	Soil D	Soil E
Screen analysis	(% pass)					
	37,5 mm	100	100	100	100	100
	26,5 mm	100	100	95	95	100
	19,0 mm	100	100	88	89	96
	13,2 mm	95	85	85	85	95
	4,75 mm	61	76	78	81	89
	2,0 mm	60	55	75	74	80
	0,425 mm	49	39	67	56	65
	0,075 mm	13	15	44	39	39
Constants	**Units**					
Liquid limit		19		37	26	24
Plasticity index		5		18	9	9
Linear Shrinkage	(%)	1,5	9,3	4	4	
Classification - TRB		A-1-b(0)		A-4(3)	A-4(0)	A-(0)
Classification - TRH14		G7	G7	G7	G7	G7
Classification - Unified	GM, GC	–	GC	SC	SC	
Mod AASHTO	**Units**					
Max dry density	(kg/m³)	1985	2169			
Optimum moisture content	(%)	9,6	7,2			
CBR / UCS values						
100 % Mod AASHTO		59				
98 % Mod AASHTO		46				
97 % Mod AASHTO		40				
95 % Mod AASHTO		31				

*Soil descriptions: A: Dark brown shale with a quantity of sand stone and fine gravel; B: Orange calcrete; C: 'Dolomite' (dark brown silty soil); D: Reddish silty soil; and E: Chert (dark reddish silty soil).