Cemented Materials: Accounting for Compaction Delays and minimizing Strength Loss with Time

S.J. Bredenhann
South African National Roads Agency, Cape Town, South Africa

P. Paige-Green
CSIR, Pretoria, South Africa

K.J. Jenkins
Stellenbosch University, Stellenbosch, South Africa

ABSTRACT: In South Africa extensive use is made of cement stabilized materials in the structural layers of both new construction works and pavement rehabilitation. The construction process plays a role in the ultimate strength obtained for the material, especially with regard to the time taken to mix and compact the material. Mix designs of cemented materials should therefore be done in such a way that any potential loss in material strength is compensated for. In this paper results are provided that assess strength (UCS and ITS) with compaction time, from laboratory-based research. The study then evaluates the actual strength results achieved for field mixes during the construction process. An investigation into the accelerated test methods used in quality control is also reported.

1 INTRODUCTION

In South Africa extensive use is made of cement stabilized materials in the structural layers of both new construction works and pavement rehabilitation. The construction process plays a role in the ultimate strength obtained for the material, especially the time taken to compact the material. Mix designs of cemented materials should therefore be done in such a way that any potential loss in material strength is compensated for during construction and the construction process is clearly specified to ensure that the material produced conforms to the required standards. In this paper, the relationships between strength and time to compaction from a laboratory study are presented and then the actual strength results obtained during the construction process are assessed.

The investigation consisted of various experiments using different stabilizers, classified according to South African specifications. The experimental design is shown in Table 1~~Table 1~~.

Table 1. Experimental design

Experiment	Stabilizing Agent
1	CEM II A-L 32.5R
2	CEM II A-M 42.5N
3	Lime
4	70 % CEM II A-L 32.5R + 30 % GGBS?
5	50 % CEM II A-L 32.5R + 50 % GGBS?
6	50 % CEM II A-L 32.5R + 50 % Lime
7	Delay time to Compaction
8	CEM II A-L 32.5R + Additional 10 % Fines
9	CEM II A-L 32.5R + Additional 15 % Fines

Two types of cement, CEM II A-L 32.5R and CEM II A-M 42.5N, were used as stabilizing agents and also blended with GGBS. Lime was also used as a stabilizing agent on its own and in a blend with the CEM II A-L 32.5R. The main aim with these blends was to investigate the reduction of reactivity of the stabilizing agent due to the addition of an extender to the cement.

2 MATERIAL PROPERTIES

2.1 *Material properties based on indicator tests*

The properties of the material treated in the experiment are summarised in Table 2. The material was obtained from borrow pits used on a road rehabilitation project on the National Road N1 near Colesberg in South Africa. Two gravel materials were blended (60 % decomposed dolerite and 40 % sand stone) with typical material properties shown in Table 2~~Table 2~~.

Table 2. Material properties from indicator tests

Description	**Results**
Grading:	
% passing 2 mm	42
% passing 0.425 mm	13
% passing 0.075 mm	3
Grading Modulus	2.42
Liquid Limit (%)	-
Plasticity Index (%)	NP
Linear Shrinkage (%)	-
Mod. AASHTO MDD (kg/m³)	2 194
Mod. AASHTO OMC (%)	5.0

Due to a lack in fines, especially the 0.075 mm size, fine material from a borrow pit was added to investigate the affect the addition of fines will have on the strength results.

2.2 *Grading analysis of material used in experiments*

The grading analyses of the material used in the experiments are shown in Table 3~~Table 3~~.

Table 3. Grading analysis of material used in experiments

Experiment	**Agent**	**Sieve sizes (mm)**									**GM**
		53.0	**37.5**	**26.5**	**19.0**	**13.2**	**4.75**	**2.00**	**0.425**	**0.075**	
1	CEM II 32.5 AL	100	100	93.8	87.0	80.0	65.0	44.2	13.4	3	2.39
2	CEM II 42.5 AM	100	100	94.4	84.0	74.8	59.0	40.0	11.4	2	2.46
3	LIME	100	100	96.4	90.8	83.4	68.6	49.4	17.0	3	2.30
4	70/30 CEM/SLAG	100	100	93.2	84.8	76.4	59.8	40.8	12.4	2	2.44
5	50/50 CEM/SLAG	100	100	93.2	85.0	75.8	59.8	40.6	11.8	2	2.45
6	50/50 CEM/LIME	100	100	94.4	87.6	79.8	66.4	47.8	15.2	3	2.34
7	+10 % FINES	100	100	93.6	85.6	78.8	64.6	46.0	20.4	7	2.26
8	+15% FINES	100	100	93.4	86.0	78.8	65.0	46.8	20.6	10	2.22

In general, for the material used in the experiments, the percentage passing the 2 mm sieve is high with a low -0.075 mm fraction.

2.3 *Maximum dry density and optimum moisture content of natural and stabilised material*

The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the natural and stabilized materials are compared in Table 4~~Table 4~~.

Table 4. Natural and stabilized MDD/OMC

Experiment	60/40 Blend		CEM II A-L 32.5 @ 2 %		CEM II A-L 32.5 @ 3 %	
Number	**MDD**	**OMC**	**MDD**	**OMC**	**MDD**	**OMC**
1	2 194	5.0	2 072 (-122)	5.7	2 155 (-39)	7.1
2	2 228	4.8	2 146 (-82)	7.5	2 144 (-84)	6.5
3	2 220	5.2	2 140 (-80)	7.7	2 096 (-124)	8.7
4	2 225	5.0	2 238 (+13)	6.9	2 223 (-2)	8.4
5	2 220	4.5	2 230 (+10)	6.3	2 220 (0)	8.8
6	2 225	5.0	2 150 (-75)	5.7	2 187 (-38)	8.1
8	2 200	5.8	2 150 (-75)	7.5	2 170 (-30)	7.9
9	2 218	5.5	2 160 (-58)	9.3	2 142 (-76)	8.6

Manual M5 (DoT, 1987) warns against a MDD difference of more than 200 kg/m^3 after stabilization. With differences of more than 200 kg/m^3, excessive rutting can occur when the stabilized material eventually reverts back to the material's natural state (equivalent granular state (TRH 13, 1986). A study (Paige-Green and Netterberg, 2004) showed that there is no strong trend between the density decrease and the cement type used.

3 LABORATORY TESTING

Laboratory testing comprised the determination of the initial consumption of cement, determining the effect of conditioning time (or the influence of delay on compaction), influence of type of stabilizing agent on strength parameters (UCS and ITS) and the influence of the addition of soil fines. These items are discussed in more detail below.

3.1 *Testing conditions*

The experiments were conducted during the winter when cold temperatures were experienced at times. The following measures were therefore implemented in the study:

- Municipal water was used and heated to 25°C.
- COLTO/SANRAL requirements were used in sample preparation and testing.
- Laboratory personnel used were trained on site by the consultant's senior laboratory technicians and had two years' experience at the time of the experiment.
- Supervision was done by an experienced Assistant Resident Engineer who also acted as the Laboratory Manager throughout the contract.
- MDD compaction was done with a mechanical compactor.
- UCS and ITS briquettes were compacted manually by the same operator who prepared the MDD samples in an effort to reduce operator error.
- Solid moulds were used and briquettes were extruded as split moulds were not available on site.
- Curing was carried out at ambient (winter) temperatures, approximately 15ºC minimum during night time and 22ºC during daytime.

The importance of temperature with regards to setting time and curing was noted by Paige-Green and Netterberg (2004). Further, the UCS and ITS values reported are not at the same mould compaction levels, i.e. no adjustment was made to UCS and ITS values to report at 100% compaction as in the past.

3.2 *Initial consumption of cement*

The Initial Consumption of Cement (ICC) was determined at an earlier stage of the project and the results are shown in Figure 1~~Figure 1~~. No repeat ICC tests were done as part of this study.

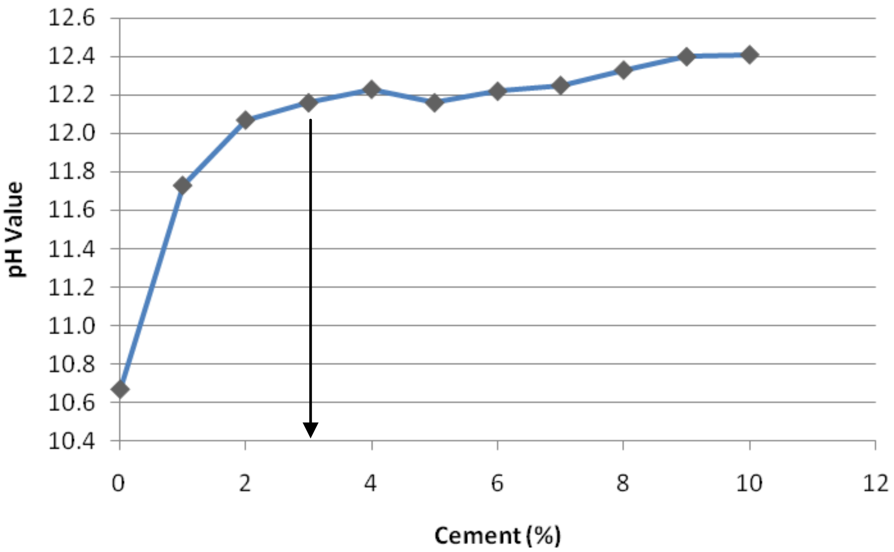

Figure 1: Initial Consumption of Cement of Decomposed Dolerite

From Figure 1~~Figure 1~~ it is deduced that the ICC of the whole sample is 3 %. It is well known that, for an ICC of 3%, more than 3 % stabilizing agent must be added to affect any strengthening due to cementation. Some practitioners argue that the ICC of only the 0.425 mm fraction (in this case ICC = 0.6 % based on a 0.425 mm fraction of 19%) must be used, as only the fine fraction reacts with the stabilizing agent. This should hold true for crushed stone but not for natural gravel derived from decomposed basic crystalline rocks. Further research in this regard is necessary, but falls outside the scope of this study. Current practice includes the use of ICC with a more representative sample and for this reason the gravel ICL (on material passing the 19 mm sieve) was developed. The method is reported in Ballantine and Rossouw (1989) and is also applied to cement (ICC). Some confusion however, still exists with the determination of the ICC.

The most important conclusion from the above discussion is that between 0.6 % and 3 % of the cement added to the decomposed dolerite/sandstone blend is used for the initial consumption of the cement by the material. It must therefore be kept in mind that not all of the cement added during stabilization is available for cementation.

3.3 *Effect of conditioning time*

The conditioning time is the time taken from when the cement comes into contact with the material until the final compaction takes place. The purpose of this test was to simulate the situation where the material is mixed in the field, sampled and then transported to the laboratory to be compacted at a later stage. The result of tests to determine the influences of conditioning time on the ITS values are shown in Figure 2~~Figure 2~~.

From Figure 2~~Figure 2~~ it is clear that the conditioning time plays an important role. The ITS strength reduces by approximately 70 % within three hours of mixing in the water. Any delay in compaction is therefore critical, firstly in terms of strength obtained in the field and secondly, and perhaps more importantly, in terms of the time differential between field and laboratory compaction. With a large time difference between laboratory and field compaction, the reference values used for quality control bear no resemblance to the actual field values.

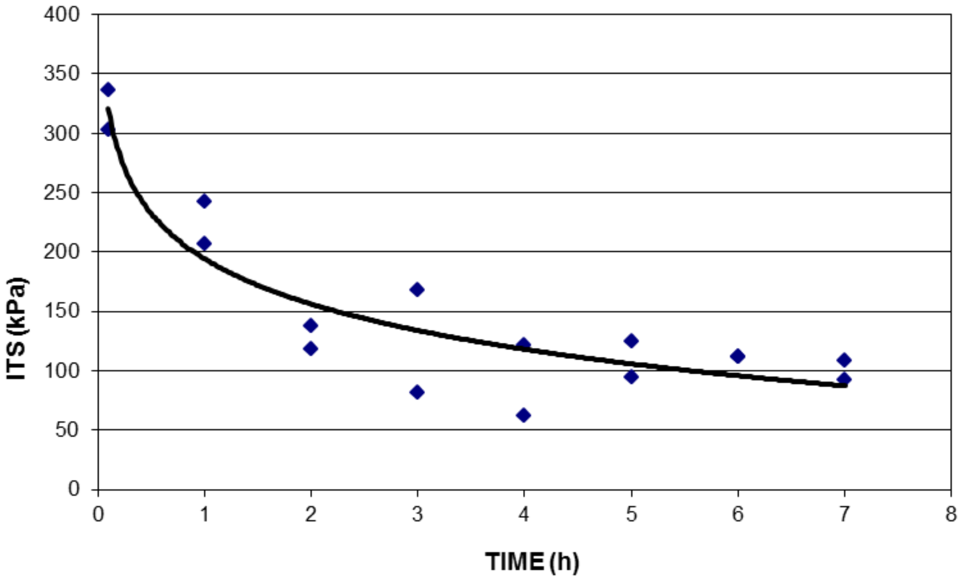

Figure 2. Influence of compaction delay on ITS (2 % CEM II A-L 32.5R)

In conclusion, the influence on the strength parameters, UCS and ITS, due to conditioning time should be monitored on two fronts:

- firstly, the time taken to construct the layer, and
- secondly, the time taken to sample material, transport it to the laboratory and to eventually compact it in the laboratory.

Delays on site will result in reduced strength, while delays with sampling and preparation of quality control samples will result in false reports. The influence of conditioning time on different granular / stabilizing agent combinations should be determined during the design stage so that appropriate limits can be specified.

Actual delays in the compaction of samples taken from site was monitored at another site and the ITS values measured in the laboratory versus distance from the laboratory is shown in Figure 3~~Figure 3~~ and compared with the time delays in Figure 4~~Figure 4~~.

The trend, although not very clear, is that ITS values from samples taken close to the laboratory, and therefore having very short delays before compaction in the laboratory, showed the normal spread in results. Al samples were taken to the laboratory within an hour limit where sensitivity due to time delay on ITS is the highest.

As the construction activities move further away from the laboratory the time delay in the compaction of the samples in the laboratory becomes more variable and longer with sampling times between one and four hours. Due to the much lower sensitivity of the ITS to time delay in this region the ITS values then show less variation.

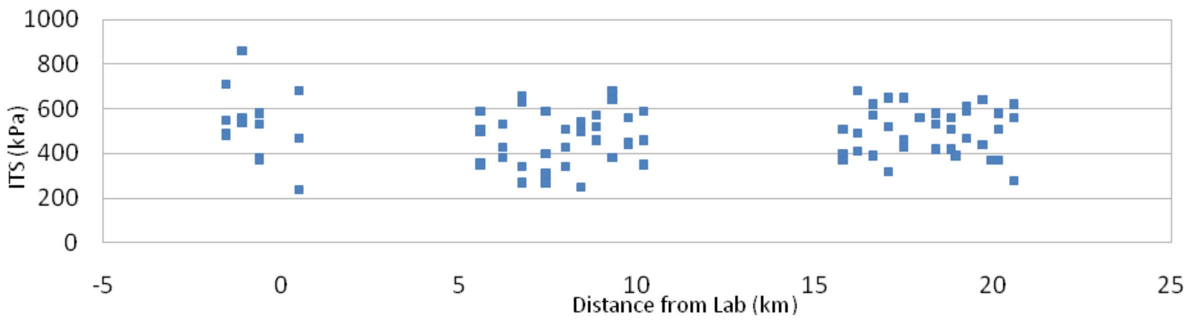

Figure 3: Variation in ITS with travel time from laboratory

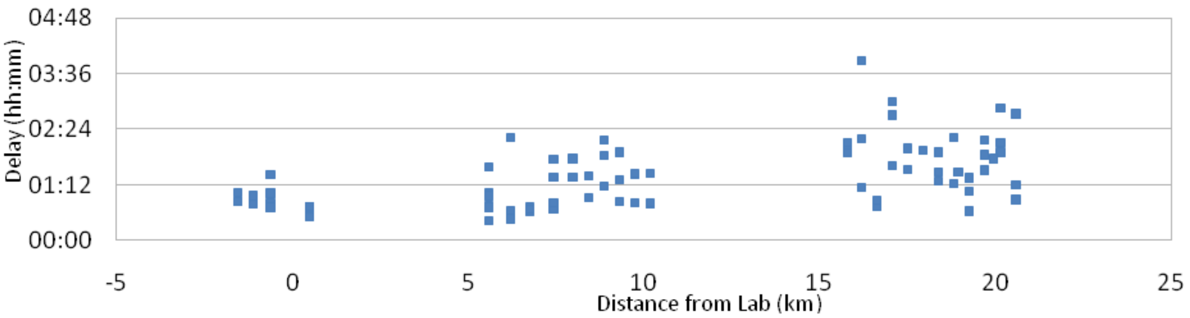

Figure 4: Variation in compaction delay with distance from laboratory

3.4 *Influence of type of stabilizing agent and curing method*

The results from the use of cement, lime, cement/lime and cement/slag blends on the UCS are shown in Figure 5~~Figure 5~~ and Figure 6~~Figure 6~~ for different stabilizer contents.

Figure 5~~Figure 5~~ shows that only the CEM II 42.5 A-M and the 70/30 cement/slag blend conform to the UCS specification at 2 % stabilizer content.

A further, somewhat disturbing, deduction made is that the relationship between the 45 hours rapid curing and 7 days curing at ambient temperature do not correlate well. The 7-day strength is also not always a good indicator of 28-day strength. It should be considered that slag and lime normally show a slow initial increase in strength which may explain some of the anomalies. Research is required in this regard as it seems that the 28-day / 45-hour curing condition correlation for strength is material dependent. It is recommended that the correlation is confirmed or revised during the design stage.

Figure 6~~Figure 6~~ shows that only the CEM II A-M 42.5N cement conforms to the ITS specification at a 2 % stabilizer content while the CEM II A-L 32.5R cement and cement/slag blends all require 3 % stabilizer. The same weak correlation between the 45 hour rapid curing and 7 day curing at ambient temperature is observed.

Considering the above it is clear that the required stabilizer content lies between 2 % and 3 %. These tests confirm the trend observed during construction i.e. it is easy to achieve the UCS specification (lower limit), but it is necessary to exceed the upper UCS limit in order to achieve the ITS specification (without the addition of fines, which will be discussed later).By carefully studying Figure 5~~Figure 5~~ and Figure 6~~Figure 6~~ it can be deduced that increasing the stabilizer content is not always the solution. Sometimes strength parameters reduce with the addition of more stabilizers.

From the results so far it is deduced that the different stabilizer blends do not give any significant advantage over the CEM II A-L 32.5R cement. Based on cost and availability factors the CEM II A-L 32.5R was therefore selected as the stabilizer agent. 2 % stabilizing agent will satisfy the UCS specification (1.5 MPa to 3.0 MPa), while 3 % stabilizing agent is required to satisfy both the UCS and ITS (> 250 kPa) specifications.

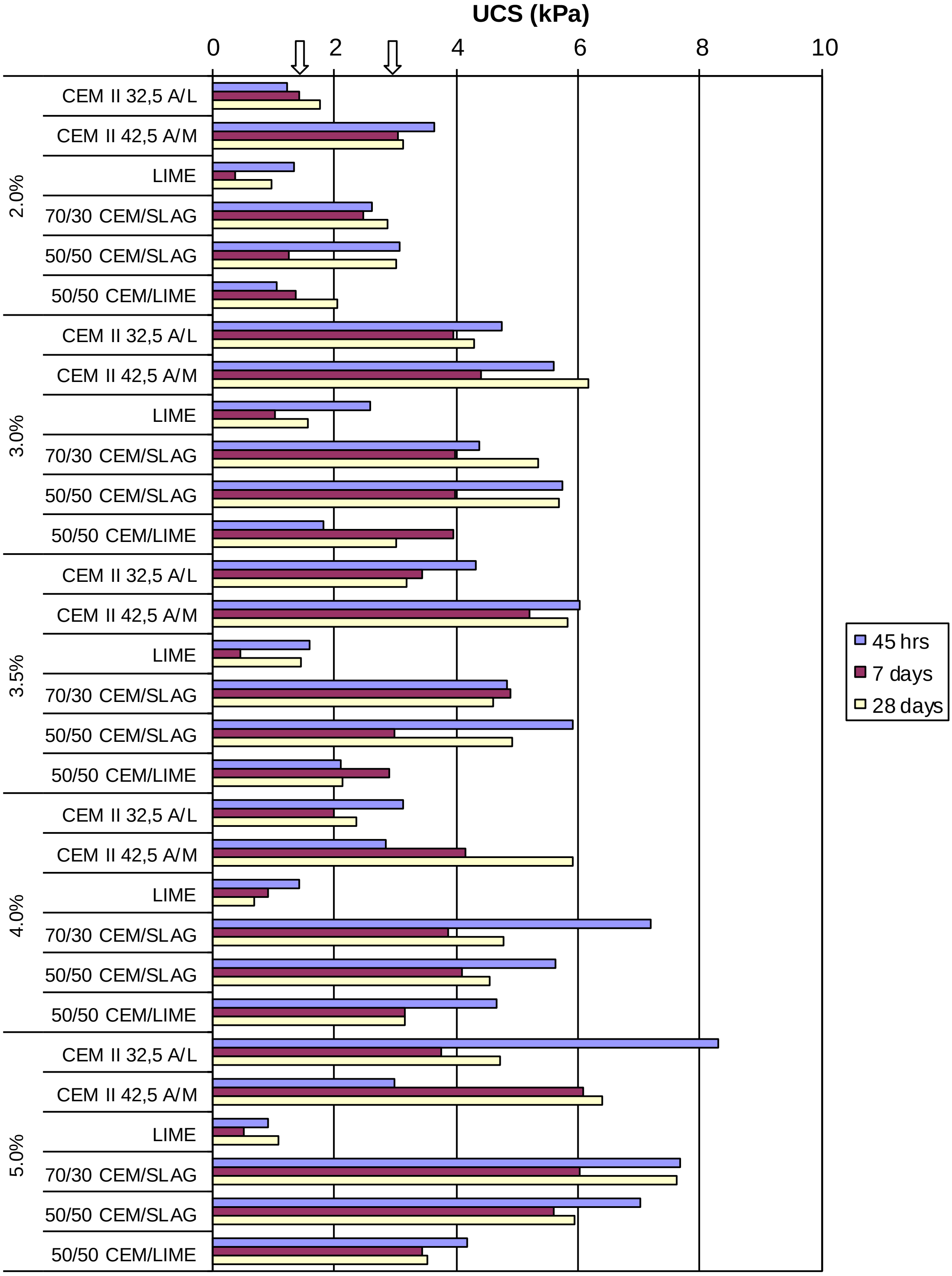

Figure 5. Comparison of influence of different stabilizing agents on UCS

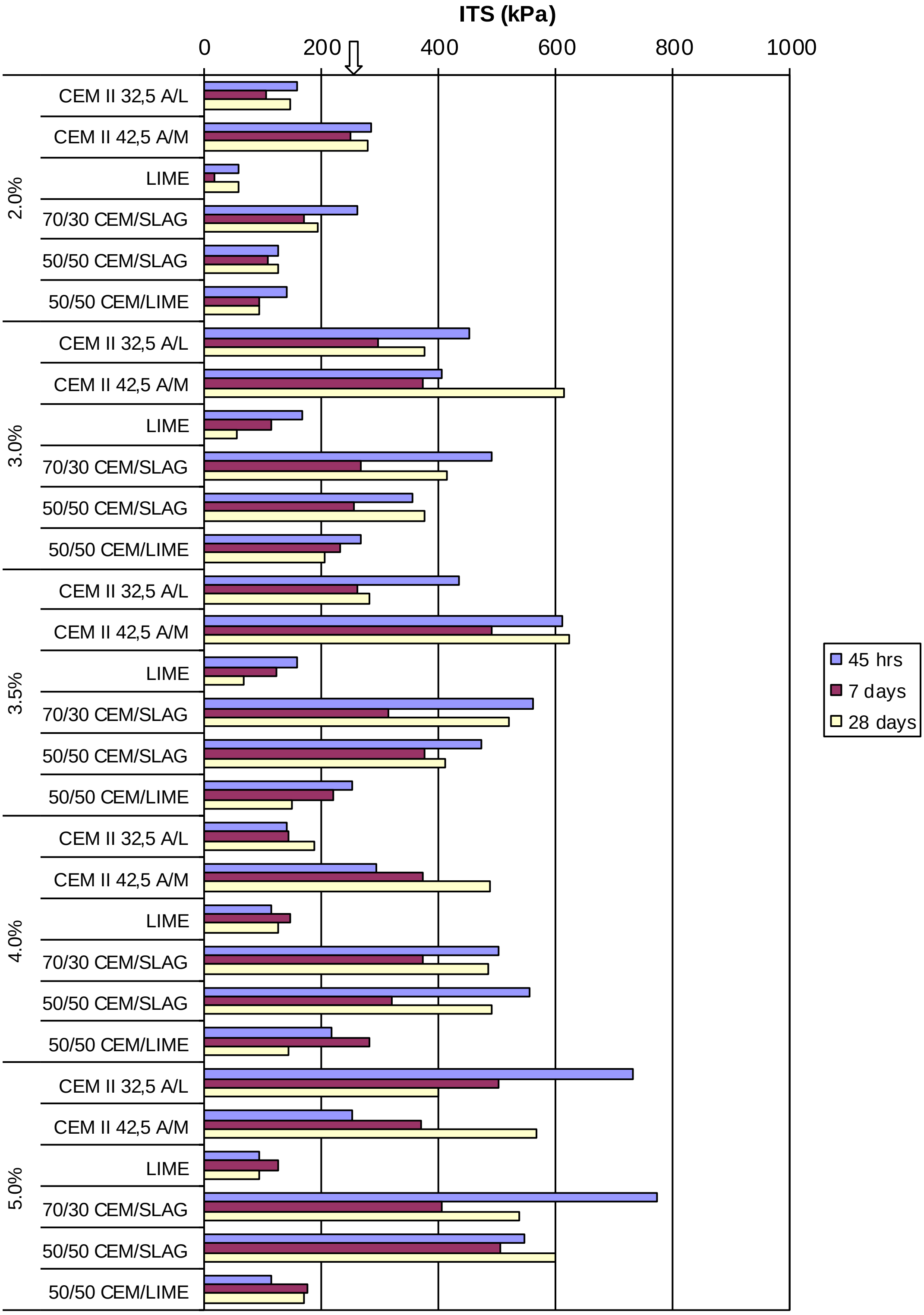

Figure 6. Comparison of influence of different stabilizing agents on ITS

3.5 *Addition of soil fines*

The possible benefit to be obtained with the addition of soil fines was investigated and the UCS and ITS values for materials with added fines are shown in Figure 7~~Figure 7~~ and Figure 8~~Figure 8~~ respectively.

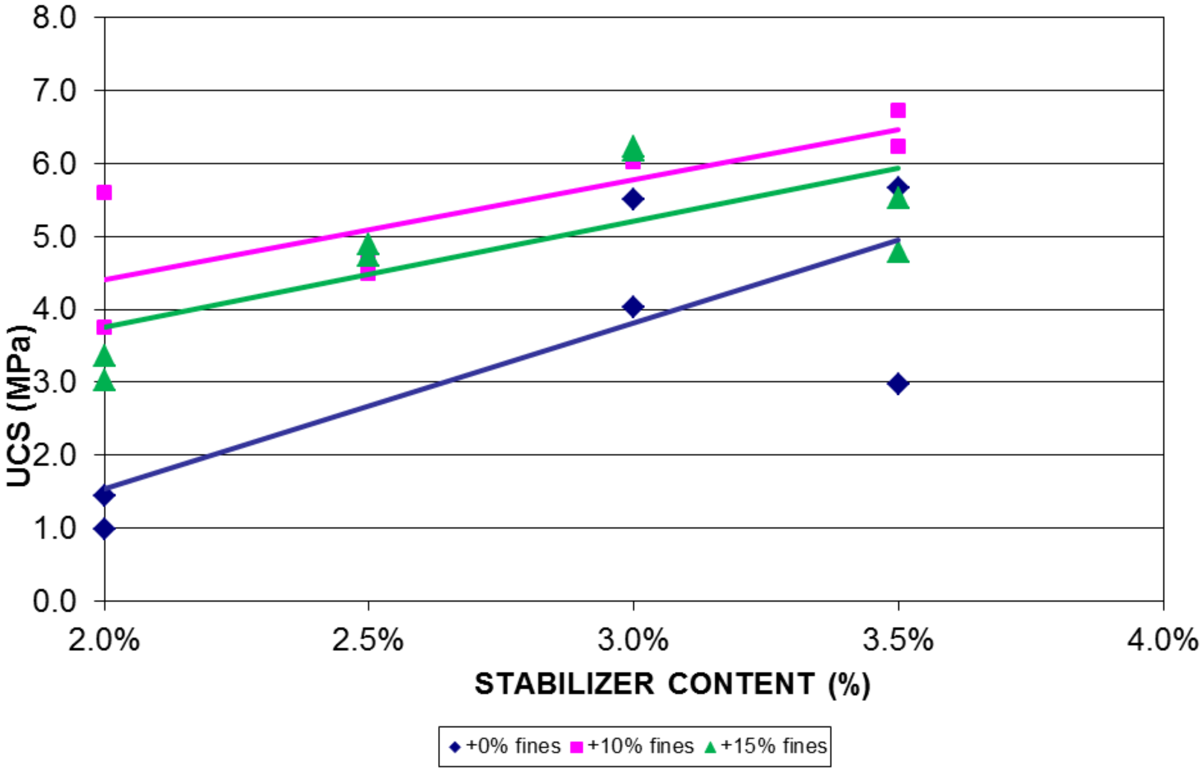

Figure 7. Influence of additional soil fines on the UCS with CEM II A-L 32.5R

Figure 7~~Figure 7~~ shows that the addition of 10% soil fines brings the UCS to exceed the upper limit of the specification at 2 % stabilizer content. The addition of 10 % fines renders higher strengths than 15 % fines, which indicates that 10 % fines may be the optimum and that the addition of more fines will actually reduce the shear strength as the grading is pushed further from the optimum Nijboer grading.

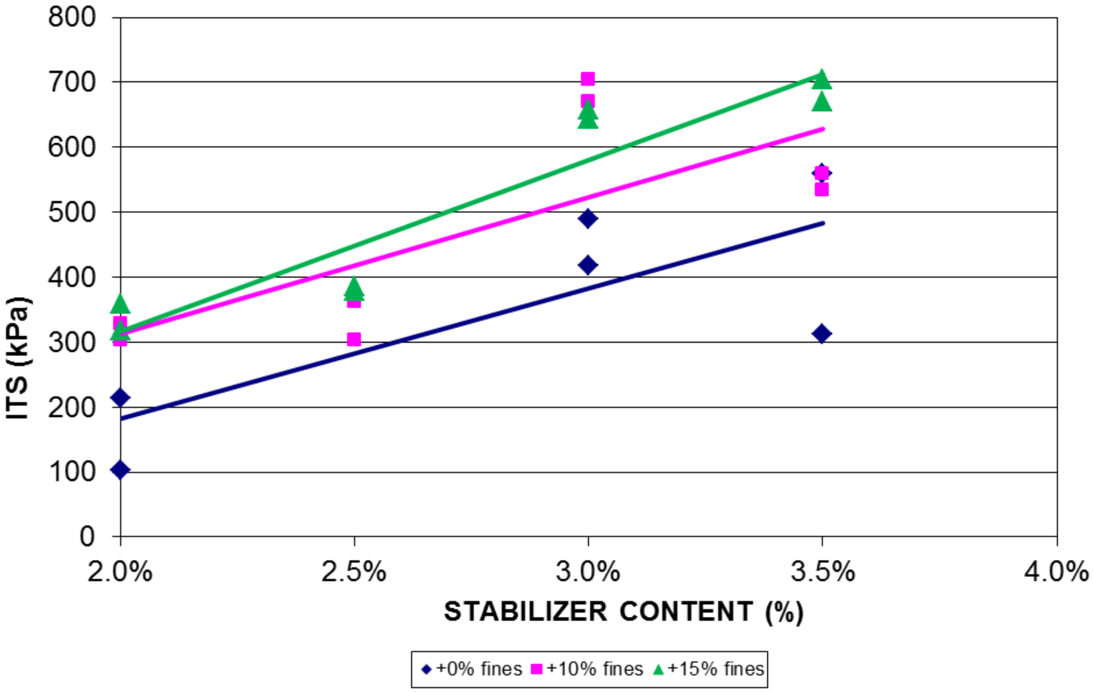

Figure 8. Influence of additional soil fines on the ITS with CEM II A-L 32.5R

Figure 8~~Figure 8~~ confirms that the addition of 10 % soil fines to the CEM II A-L 32.5R cement now produces a stabilized material that conforms to both UCS and ITS specified values with only 2 % stabilizer content. The addition of the fines brings the micro-grading (< 2mm) closer to the Nijboer grading [%P = (d/Dmax)^n x 100] with n=0.45 coefficient i.e. closer packing of particles and reduced voids in the mineral aggregate. Both chemical behaviour and mechanical behaviour are at play when adding fines.

It should be noted that the CEM II cement used was an R-cement (ie giving high early strength) and the implications of this compared with a conventional N-cement are not assessed in this paper.

4 SPECIFICATION ISSUES

Only the ITS specification will be discussed here with special reference to the interpretation of the minimum specification in the absence of a statistical judgment plan.

The contract that was investigated used a specification of a minimum ITS of 250 kPa implying that the average ITS on a construction section (typically 300 m or a day's production), shall not be less than 250 kPa. The ITS values obtained with 2 % and 3.25 % stabilizer contents are demonstrated graphically in Figure 9~~Figure 9~~ and Figure 10~~Figure 10~~ respectively.

It is clearly shown in Figure 10~~Figure 10~~ that adding 3.25 % stabilizing agent will result in a higher probability of achieving specified results and therefore also a lower risk on the strength of the road, especially considering that the ICC is now satisfied.

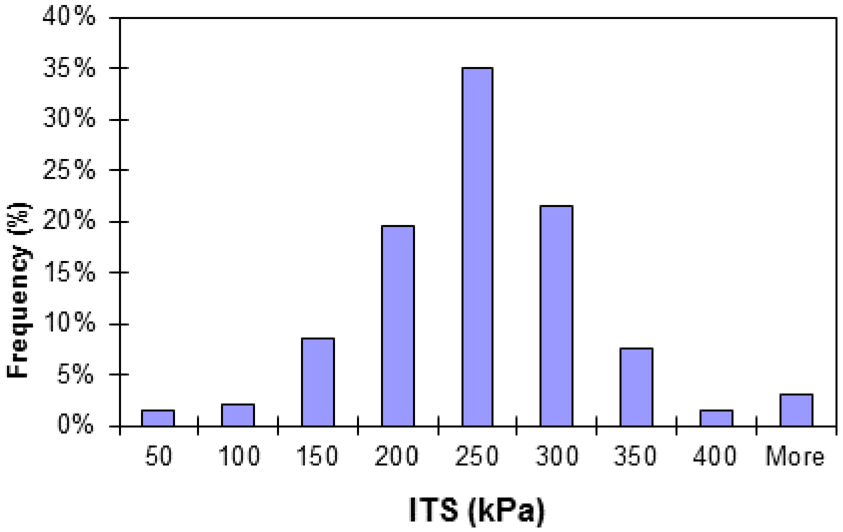

Figure 9: ITS values at 2 % stabilizer content

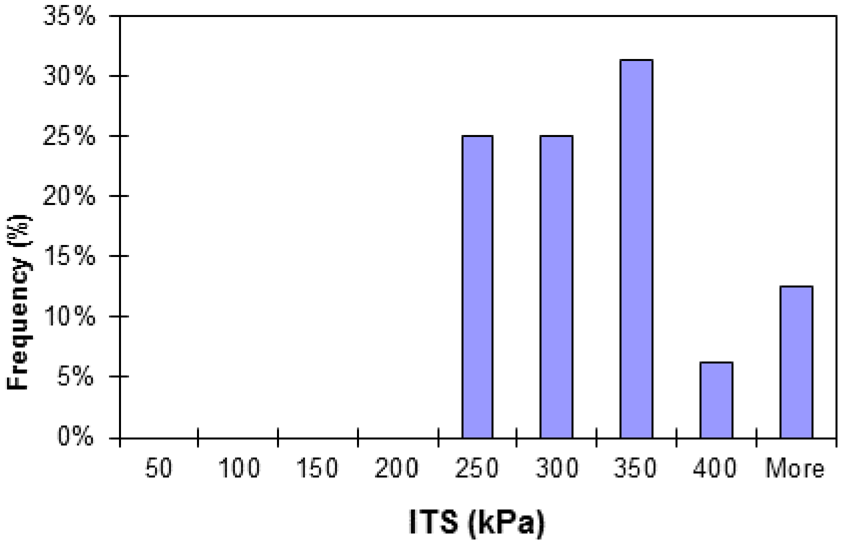

Figure 10: ITS values at 3.25 % stabilizer content

There is an on-going debate regarding whether the ITS or the UCS test is more critical when selecting the design stabilizer content and which should take precedence. In many cases the ITS is not met although the UCS is easily attained. In order to obtain the required ITS, an increase in stabilizer content (or change in type) usually results in the required minimum ITS limit being achieved. However, the fear is then that the accompanying higher UCS (often exceeding the specified upper limit) is indicative of potentially excessive cracking. It has been postulated that, especially when making use of marginal materials that are prone to carbonation, the specified ITS is necessary to avoid disintegration of the layer as the lime is converted to calcium carbonate (during the carbonation reaction) and its volume increases (Paige-Green, 2009). The specified ITS is considered necessary to counteract cracking due to the expansive strains generated during the volume increase. The overall philosophy is that it is easier to manage the potential cracking (with programmed crack sealing maintenance) than it is to manage disintegration of the layer due to carbonation.

The 3.25 % section was monitored over a six year period and no excessive cracking was observed.

5 CONCLUSION

Although stabilization is an established practice and used in construction since Roman times, there are still some concerns and uncertainties that must be addressed thoroughly, especially during the design stage. Stabilizing designs must be done extensively before the contract starts and must be revisited throughout the duration of the contract, especially when material sources change. In particular, the following aspects require attention:

- Significant reduction in the strength of cement stabilised materials results from longer mixing and compaction times e.g. 50% reduction in ITS can result from a 4 hour delay until final compaction. This trend needs to guide the allowable construction time specifications
- Cement type, temperature, moisture content and other factors influence the quantum of strength loss. But these factors cannot, however, be manipulated to reduce the strength loss to levels that render the influence of construction time to be insignificant.
- Specification issues exist that must be addressed, especially the incompatibility of lower and upper bounds for the UCS with lower bound for ITS and a restriction on moisture content.

Further research is required to increase the pool of knowledge, incorporate later developments and to address changes in specifications such as the cement specifications. In this manner, the understanding of the behaviour of cemented layers in the pavement structure could be enhanced drastically.

6 ACKNOWLEDGEMENTS

The South African National Roads Agency is thanked for permission to publish this paper. The work done by site staff on the Colesberg and Leeu-Gamka sites with the main author is also acknowledged.

7 REFERENCES

Bredenhann, S.J. 2004. Report on experiment on influence of stabilizing agents on the decomposed dolerite. South African National Roads Agency. Cape Town. April 2005.

Paige-Green, P. 2009. A reassessment of problems affecting stabilized layers in roads in South Africa. 3rd International Symposium, Treatment and Recycling of Materials for Transport Infrastructure (TREMTI), 18-20 November 2009, Antigua, Guatemala. (On CD)

Paige-Green, O and Netterberg, F. 2004. Cement stabilization of road pavement materials: Laboratory testing programme Phase 1. Contract Report CR-2003/42, CSIR Transportek, Pretoria.