

# **A REASSESSMENT OF PROBLEMS AFFECTING STABILIZED LAYERS IN ROADS IN SOUTH AFRICA**

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## **ABSTRACT**

During the early 1980s a number of problems related to the loss of stabilization and disintegration of stabilized layers in roads (lime and cement) were reported in South Africa. This led to many comprehensive investigations and it was shown without any doubt that the problems were related to carbonation of the stabilized materials. A paper was presented at the TREMTI Conference in Paris in 2005 indicating that many of the problems in South Africa that were attributed to carbonation, were actually caused by “water driven reactions” and were thus material related and not construction related. This paper assesses the fundamental principles of each of the processes and draws conclusions as to their likelihood and the increasing occurrence of stabilization problems. It is concluded that, although there is indubitable proven field and laboratory evidence for carbonation of stabilized layers, there is no solid scientific evidence for the occurrence of the “water driven reactions” in soil stabilization for roads.

## **KEY WORDS**

STABILIZATION / LIME / CEMENT / PAVEMENT RECYCLING / DURABILITY.

## **1. INTRODUCTION**

During the early 1980s a number of problems related to the loss of stabilization and disintegration of stabilized layers in roads (lime and cement) were reported in South Africa. This led to many comprehensive investigations (De Wet and Taute, 1985; Netterberg, 1987; Netterberg et al, 1987; Paige-Green, 1984, 1991; Paige-Green et al, 1990; Sampson et al, 1987; Bagonza et al, 1987) and it was shown without any doubt that the problems were related to carbonation of the stabilized materials during their curing and after construction as a result of the attack on the hydroxides and stabilization products by carbon dioxide from the atmosphere and the soil air. This problem has subsequently been observed by the author in a number of countries. Although the process of carbonation was a fundamental feature related to the chemical properties of lime and lime based stabilizers (reversal of the production reactions), it had never been a major problem with roads previously although similar effects were reported from a project in California (Alexander, 1976) and attributed at that time to “carbonation of the lime or the lime being flushed out by water application”.

A paper was presented at the TREMTI Conference in Paris (Botha et al, 2005) indicating that many of the problems in South Africa that were previously attributed to carbonation, were in fact caused by “water driven reactions” and were thus material related and not construction related. It has since resulted in a number of cases of stabilization problems caused by poor construction (primarily over-rolling and ineffective curing procedures) being attributed to unsuitable materials by contractors and a consequent increase in large contractual claims.

The current paper assesses the fundamental principles of each of the processes and, based on laboratory and field investigations, draws conclusions as to their likelihood and their role in the increasing occurrence of stabilization problems.

## 2. CARBONATION

Between 1981 and 1990 significant research regarding the detrimental carbonation of stabilized materials was carried out in South Africa and abroad. This was written up in a comprehensive Project Report (Paige-Green et al, 1990). It should be noted that no reference has been recorded in the literature relating to beneficial effects of carbonation in road stabilization. Ballim and Basson (2001) describe carbonation as one of the major factors in the deterioration of concrete – “... loss of stabilizers by their conversion to the corresponding carbonates results in a lowered pH and destabilization of the silicates”. Certain researchers, however, indicate that the effect of surface carbonation (and the related volume increase) on concrete has the effect of filling surface voids and thus decreasing the porosity and permeability of the concrete. This has the effect of slowing the carbonation of the concrete.

The effect of carbonation on the structure of much weaker stabilized materials in roads would be considerably greater than the effect on the structure of concrete, a high quality engineered material.

### 2.1. Chemical background

Carbonation can affect both lime and cement (and any other pozzolanic) stabilized material. This has been seen and proven in the laboratory and the field, where the strength and pH of stabilized material using a range of stabilizers under controlled and uncontrolled conditions has been observed (and measured) to decrease (Paige-Green, 1991). Although the fundamental principles of lime and cement stabilization are similar, the production techniques and reaction processes for the two materials differ significantly. The major difference in behaviour is that lime requires the presence of clay minerals in the material being stabilized before any cementation reactions will occur. Cement contains all of the necessary individual ingredients to react (hydrate) in the presence of water and form standard cementitious products.

Road lime is produced simply by the burning at high temperatures (about 900°C at 1 atmosphere pressure) of calcium carbonate rich materials (mostly limestones). This produces quicklime (CaO) which is hydrated with water at the production plant to produce the equally reactive but much safer calcium hydroxide (Ca(OH)<sub>2</sub>). This material, when pure has a pH of 12.4 at 25°C.

The addition of calcium hydroxide to a material containing clay minerals in the presence of moisture leads to various reactions. These are described as rapid and long-term reactions (Ballantine and Rossouw, 1989). It should be noted that all of the relevant reactions only take place in the aqueous phase, ie, the pore water system. The first thing that happens is a physico-chemical reaction in which ion exchange takes place resulting in flocculation of the clays and a change in the fundamental properties of the material, mainly plasticity and friction. The long-term reaction is the result of the pH of moisture in the pores of the material increasing rapidly as the calcium hydroxide is dissolved in the pore water. This causes the solubility of alumina and silica in the clay minerals to increase. These two elements react with the calcium in the lime to form calcium aluminate hydrate and calcium silicate hydrate.

The production of cement is a far more complex process, requiring the burning of limestone at between 800 and 1000°C to produce lime (CaO) followed by clinkering in a hotter part of the kiln (1400 - 1450°C) where the carefully controlled mixture of lime, clay or shale (containing silica and alumina), and iron oxide forms the cement clinker (calcium silicates and aluminates). The clinker thus formed is then finely ground with gypsum to produce cement.

Unlike lime stabilization, the addition of water to cement initiates hydration of the cement (no other materials are essential for the hydration of cement). The same calcium aluminate hydrate reactions as for lime occur although gypsum is added to the cement to control the rate of these reactions. Hydration of the calcium silicates forms calcium silicate hydrates, the dominant cementing material. A critical component of these reactions is the generation of calcium hydroxide during the hydration of the di-calcium and tri-calcium silicates. The reaction generates/releases about 20% calcium hydroxide, which is essential to keep the pH above at 12.4.

## 2.2 The carbonation reaction

Both lime and cement are produced at high temperatures from limestone (CaCO<sub>3</sub>), essentially producing lime which is only stable under a partial pressure of CO<sub>2</sub> (P<sub>CO2</sub>) of less than 3 x 10<sup>-14</sup> atmospheres. The lime is thus inherently unstable under normal environmental conditions (P<sub>CO2</sub> = 3 x 10<sup>-4</sup> atm) and absorbs carbon dioxide from the atmosphere (in the presence of pore water) to revert to the more stable phase, calcium carbonate (Paige-Green et al, 1990; Engelsen et al, 2005). This is accompanied by a significant increase in volume (10% in the case of calcite (pure CaCO<sub>3</sub>) and 14% in the case of the metastable vaterite, which is likely to be a transition phase between lime and calcite).

Carbonation is not an unexpected problem and is widely known in the concrete industry (Lagerblad, 2005). Despite this, little has been published on the carbonation of stabilized road materials. The majority of the following background discussion is therefore based on concrete work, in which the fundamental principles are identical. The behavioural characteristics, however, differ as a result of the basic differences between concrete and stabilized materials (ignoring cement/lime differences). These are summarised in Table 1 and can affect the results of carbonation.

Table 1 –Differences between concrete and stabilized road materials

Concrete	Stabilized materials in roads
High binder (cement) content (about 8%)	Low stabilizer content (2 – 4%)
Dense mix (low interconnected voids)	Porous material (more interconnected voids)
Low permeability	Relatively high permeability
High tensile strength	Low tensile strength

Measurements of the carbon dioxide (CO<sub>2</sub>) content in pavement layers have identified values regularly in excess of 4% and as high as 13%. As the atmosphere has values of 0.035%, it is clear that the decomposition of vegetation, transpiration of plants and respiration of insects allows the build up of CO<sub>2</sub> in road pavement structures, particularly under relatively impermeable bituminous surfacings, providing an adequate source of CO<sub>2</sub> for the reactions.

One of the results of the carbonation of lime is the gradual decrease in pH of the material from about 12.4 for lime to about 8.3, that of calcium carbonate (CaCO<sub>3</sub>). As this occurs,

other hydrate phases in the hardened cement or lime stabilized material successively break down (Lagerblad, 2005). Essentially the lime dissolves (solubility =  $9.95 \times 10^{-4}$ ) and  $\text{CaCO}_3$  (solubility =  $0.99 \times 10^{-8}$ ) precipitates. This continues until all of the lime is consumed, when the pH decreases and the calcium ion concentration in the pore solution drops. In order to maintain equilibrium between the solid and the pore solution, compensation occurs by the release of calcium ions from the calcium silicate hydrates resulting in a lower calcium:silica ratio. When this ratio drops to less than 1 (pH would be about 10) the calcium silicate hydrates transform to silica gel with some calcium.

The carbonation reaction depends on the solubility and diffusion of the components. The diffusion is controlled by the concentration differences and is an inward diffusion of  $\text{CO}_2$  gas and carbonate ions (Lagerblad, 2005). The gas diffusion is much faster than ion diffusion. Thus the rate of reaction is controlled by the humidity in the material, i.e., how much liquid fills the connected pore system. In dry material, the  $\text{CO}_2$  can penetrate well but there is insufficient water for the reaction to take place. In the saturated condition, only the carbonate ions move and carbonation is slow. Typically, the reaction is most likely and rapid at humidities of 40 to 70 % (Lo and Lee, 2002; Ballim and Basson, 2001; Gjerp and Oppsal, 1998).

The diffusion is a two way operation – carbonation lowers the calcium ion content in the pore solution, which results in the dissolution of lime and diffusion from the interior of the carbonation front where the concentration of both components will be low due to the low solubility of calcium carbonate. The speed of carbonation depends on how fast the carbon dioxide and/or carbonate ions move into the stabilized material and react with the free lime and cement paste following Fick's first law (Lagerblad, 2005). Ficks' second law gives the depth of carbonation and not the amount of material affected.

The volume changes associated with carbonation (expansion between lime and calcite and shrinkage on carbonation of cementitious products) cause a disruption of the cemented matrix and consequent loss of strength. This is not as critical in concrete where the material has considerable tensile strength, but in most stabilized materials, the strains associated with the expansion and shrinkage easily exceed the tensile strength resulting in microcracking within the materials.

There is some debate as to whether carbonation is necessarily detrimental. In the case of concrete, the closure of pores and decrease in permeability has been shown to retard the rate of carbonation. However, ultimately, concrete will deteriorate to a mixture of carbonates together with ferrite, silicate and aluminium hydroxide phases (Lagerblad, 2005). Cases have been observed in carbonated stabilized materials where the carbonation has not been detrimental, probably as a result of high tensile strength developing prior to carbonation.

In summary, although the carbonation process is chemically rather simple, it is fairly complex in physico-chemical terms. There is, however, no doubt that this is a natural and extremely common process, and all the theory described in the literature and above fits into what has been observed in the field.

### **3. WATER DRIVEN REACTIONS**

Botha et al (2005) describe an alternative cause of the loss of strength of stabilized layers. The basic premise of this paper is that the loss of strength is due to a “water-driven reaction”. The process is described by Botha et al (2005) as follows:

“During ion exchange  $\text{Ca}^{++} + 2(\text{OH})^- + \text{H}_2\text{O} + 2\text{Na}^+ = 2\text{Na}^+ + 2(\text{OH})^-$  is formed in the reaction of  $\text{Ca}(\text{OH})_2$  with the clay minerals. The NaOH is relatively soluble and can be transported to just under the surface of a sealed road due to hydro-genesis. Furthermore, the NaOH is relatively hygroscopic and thus it will attract water once formed, which will increase the ability to migrate.”

“The ion exchange reaction if all the clay has not reacted is indicated by  $\text{Ca}^{++} + 2(\text{OH})^- + \text{H}_2\text{O} + 2\text{Na}^+$  and forms  $2\text{Na}^+ + 2(\text{OH})^-$  (Foster, 1953). The NaOH then aggressively attacks the aluminosilicates and fine-grained quartz, destroying the cementitious bonds. This reaction can take place in the absence of  $\text{CO}_2$ . If more  $\text{Ca}^{++} + 2(\text{OH})^-$  is available, new calcium silica hydrates (CSH) and calcium silica aluminates (CSA) can form that can destroy the existing cement matrix by expansion. The pH could also drop due to depletion of the  $\text{Ca}^{++} + 2(\text{OH})^-$  and  $\text{H}_2\text{O}$ . Due to the high solubility of NaOH and its ability to migrate to the interlayer between the base and the surfacing, the surfacing layer may still maintain a relatively high pH.”

This description, although rather vague and difficult to understand is fraught with unsubstantiated statements, contradictions and errors. It does, however, resemble to some extent the typical alkali silica reaction common in concrete.

The first assumption in this theory (it has never been proved by rigorous scientific method or laboratory investigation) is that there is sufficient sodium (NaOH) in the materials to displace the calcium to form sodium hydroxide. This sodium can only be obtained from the materials being stabilized, from the cement (where this is used and not lime) or possibly from the water used for compaction and/or to hydrate the cement/lime reaction. In general, the earth's rocks contain between 0 and 3.5% of sodium oxide (compared with 0 - 20% calcium oxide). The exchangeable sodium in most South African soils (other than dispersive or coastal soils) is less than about 5 or 6 meq/kg soil and South African cements typically have less than 0.3% sodium oxide (Paige-Green and Netterberg, 2004). The chances, therefore, of sodium being available in sufficient quantities to cause problems are small. It should also be noted that many of the problems encountered have been associated with weathered dolerites and calcretes, both of which are specifically lacking in sodium (i.e., they are calcium rich materials).

Although there are certain misconceptions in the above statements such as the unproven belief that sodium exists in all clays in which the problem has been encountered, the principle expounded is fundamentally flawed.

Foster (1953) notes that a 0.5 N solution of NaOH is necessary to dissolve the free silica which makes up the silica phase of the silicates in clays. This takes place in a steam bath over a period of 4 hours. It should be noted that only fine amorphous silica and not pure quartz is dissolved by NaOH. This NaOH also dissolves the alumina phase from clay minerals. The concentration of NaOH in a typical soil with an exchangeable sodium content of 5 meq/kg of soil and a moisture content of 10% would be equivalent to a 0.05 N solution, one tenth of the required concentration. Sodium hydroxide essentially attacks the fine components of the material, specifically particles less than 2 micron in diameter, a size which includes the clay minerals, by definition.

The reaction correctly assumes that calcium will replace any exchangeable sodium ions attached to the clay. These would remain in solution as a weak source of NaOH. In a sealed road, these could possibly move to the surface under the influence of

hydrogenesis. However, the majority of cases of carbonation have been observed in roads prior to sealing, during construction, where hydrogenesis is unlikely to occur. It is also probably likely that the weak NaOH solution would be equally if not more susceptible to carbonation than the  $\text{Ca}(\text{OH})_2$ .

As stated by Botha et al (2005), NaOH is hygroscopic and will absorb (attract) water. However, when sodium hydroxide is in solution, as it would be while taking part in any of the reactions described by Botha et al, the hygroscopic effects would be essentially nil. It is also stated by Botha et al (2005) that the NaOH aggressively attacks the aluminosilicates and fine-grained quartz destroying the cementitious bonds. No research appears to have been done in this respect and although it is likely, the work by Foster (1953) only addressed clay minerals and not cementitious reaction products. This statement is thus an incorrect quote from Foster and only an unsubstantiated assumption. Similarly, the assumed increase in volume destroying the existing cement matrix by expansion when new calcium silicate hydrates form is an assumption, as little is known about such volume changes and it is unlikely that the cemented matrix would be stiff enough to be disrupted at this early stage in its crystallization: the predominant components would be gels in the early stages. The formation of calcium silico aluminates (CSA) resulting in expansion is also referred to: however, calcium silico aluminates are not commonly referred to in the cement chemistry, and in fact are even rarer in clay mineralogy.

One of the fundamental premises of lime/cement stabilization is the dissolution of the silica and alumina under the high pH conditions (about 12.4) produced by the  $\text{Ca}(\text{OH})_2$  (Ballantine and Rossouw, 1989). The proposal by Botha et al (2005) relies on the dissolution of these elements by NaOH, with a pH of 14 at a concentration of 1.0 M and a pH at 0.05 M concentration of 12.7. As there is essentially little difference between the dissolution conditions of the two highly caustic hydroxides, there seems to be no scientific basis for the sodium hydroxide to attack the clays preferentially over calcium hydroxide.

Botha et al (2005) also state that carbon dioxide acts as an accelerator dissolving calcium hydroxide in the presence of water. The theoretical basis for this statement is unclear.

Botha et al (2005) describe the dry-layer (alkali aggregate) reactions. This reaction as described involves the "alkaline solution secreted from the hardening cement eroding the aluminosilicate-glass". Generally alkali aggregate reaction involves the reaction between the alkaline pore solution of concrete and any aggregate and is commonly referred to in the concrete industry as alkali-silica reaction (Oberholster, 2001). Alkali aggregate is relatively uncommon, being limited to about 10 of the hundreds of rock types present in South Africa. As was the case for carbonation, existing information on this problem is restricted to aggregates for concrete and little, if any, work has been done in relation to stabilization of road construction materials. Several techniques and standard tests have been developed to identify potentially alkali reactive aggregates, but these were not applied in the work by Botha et al (2005).

The alkali silica reaction takes place between the alkaline pore solution in concrete (or possibly compacted stabilized material) and metastable forms of silica such as opal, tridymite, cristobalite and volcanic glasses, which produce expansive alkali-silica gels (Oberholster, 2001). Alkali silicate reaction has also been described to cover possible reactions between certain clay minerals and alkalis, but no evidence for this has ever been found (Oberholster, 2001). This is the reaction described by Botha et al (2005), ie, the reaction between alkalis and aluminosilicate-glass and appears to be highly unlikely.

A case is made for the water-driven reaction reported from Heidelberg, Mpumalanga (sic – actually Gauteng) and apparently incorrectly referenced by Botha et al (2005). This project was in fact a foamed bitumen recycling project and the cement was added as an active filler with the foam bitumen and not for cement stabilization *per se*. The discussion regarding this project by Botha et al (2005) is, therefore, irrelevant and incorrect.

This does, however, lead on to discussion regarding the drop in pH illustrated by the extended Initial Consumption of Lime (cement) (ICL/ICC) test. It should be noted that this test was originally developed to determine the amount of lime required to provide sufficient calcium to satisfy the instantaneous (defined as within one hour) reactions (Eades and Grim, 1966). They pointed out that under the high pH conditions, the clays will be attacked, freeing silica and aluminium which react to form calcium silicates (no mention is made of alumina silicates) as long as the high alkalinity is maintained. They also explicitly explain that "lime requirements for this continued reaction could be determined under varying conditions of time and temperature" (Eades and Grim, 1966). They illustrate this with a record of the pH of two samples (one at room temperature and one at 140°F (60°C)) for 3 years, where the stabilization reaction continues. In this experiment, the pH drops to between 10.75 and 10.9 after about 22 days and then decreases slowly to 10.55 and 10.8 after 3 years.

This method was modified by Clauss and Loudon (1971) to develop what is now known as the Initial Consumption of Lime (ICL) test. This has subsequently been improved to the gravel ICL test (Ballantine and Roussow, 1989), which analyses the entire material and not just the fines and subsequently to the Initial Consumption of Stabilizer (ICS) test (Gautrans, 2004). In retrospect, it may be considered this latter proposal has moved away from the original concept of the initial lime consumption.

The extended ICL/ICC discussed by Botha et al (2005), has little relevance to the problem under discussion, particularly when carried out using cement. Firstly, the initial consumption of lime after one hour (and probably of cement) would be indicative of the early cation exchange and flocculation reactions. After this, the cement would hydrate, normally in the paste or slurry condition. The sealing of the sample during this test observed in the laboratory would typically reduce evaporation but not eliminate carbonation at the surface, leading to a reduction in pH over time. Botha et al (2005) state that "enough evidence is available to prove that the detrimental water reactions can generally be controlled" based on two cases of carbonation failure that were corrected using bitumen emulsion. This is highly debatable. Lime/cement stabilization and bitumen emulsion stabilization are totally different techniques. In the former, chemical reactions occur and new products are formed. In the latter, the fine particles are essentially bonded together with the theoretical advantage of allowing some water-proofing of the material.

They also state that carbonation "is more strength gaining than strength reducing". Previous work into this aspect has been carried out (Paige-Green, 1991) and it was proved that even after 7 years of controlled curing of four different stabilized materials, the strength of the specimens after a 24 hour period in a 100% carbon dioxide atmosphere was reduced by between 50 and 75%. It should be noted that the hardness of calcite (CaCO<sub>3</sub>) on Mohs Hardness Scale is 3. The pure mineral is thus very soft and can in no way contribute to a material with a strength of several MPa. What it can do (certainly in concrete) is to fill surface voids and reduce the potential for water to enter them and thus increase the material strength.

## 4. LABORATORY AND FIELD INVESTIGATIONS

### 4.1 Carbonation

#### 4.1.1 Laboratory evidence

In cases where field evidence for carbonation has been observed, samples of uncarbonated material from the field can be rapidly carbonated in the laboratory. In addition to this testing, many samples of stabilized materials have been compacted in the laboratory and subjected to various tests, including accelerated carbonation. In this test, the samples are placed in a pressure cell under vacuum and the cell is then filled with carbon dioxide for 24 hours. The strengths and visible evidence of carbonation is investigated. In all cases where sufficient stabilizer was added to satisfy (and exceed by 1%) the Initial consumption of stabilizer (ICS) requirement, full carbonation could not be achieved. On those samples where the ICS was not satisfied, the entire sample carbonated within 24 hours.

In order to confirm the conclusions based on field and laboratory investigations both uncarbonated and carbonated materials have been studied using a Scanning Electron Microscope (SEM). The uncarbonated specimens were dried in a desiccator with soda lime (a standard absorbent of CO<sub>2</sub>) during their preparation and the “carbonated” material was left to dry on an office shelf. The matrix of the lime stabilized material in the uncarbonated specimen was clearly observed to be intact while that in the carbonated specimen showed significant micro-fracturing, associated with a significant decrease (70%) in shear strength (UCS = 1.319 MPa and 0.397 MPa respectively). This was associated with a decrease in the pH from 12.4 to less than 8.5.

Spot chemical analyses using the Energy Dispersive X-ray analysis (EDX) system attached to the SEM show that the relative heights of the Ca/C and O peaks before and after carbonation indicate that there is relatively more carbon than calcium. It is also seen that the second calcium peak is more than double the height of the first one. It can thus be concluded that the peak at 0.25 keV contains significantly more carbon, indicating the addition of carbon to the material. This can only be in the form of calcium carbonate (CaCO<sub>3</sub>).

#### 4.1.2 Field evidence

The primary field evidence is the presence of a weak layer of stabilized material that shows no (or little) positive reaction with phenolphthalein but a strong reaction with dilute hydrochloric acid. In nearly all cases the material can be “scratched loose” using a finger and the in situ pH is less than 10. Carefully executed Dynamic Cone Penetrometer (DCP) tests generally confirm the weak nature of the carbonated layer. This layer is usually found on the upper surface of stabilized base and subbase layers as well as in the lower layers of stabilized subbase layers (Sampson et al, 1987). Changes in the degree of the effervescence with hydrochloric acid can be traced through the layer and related directly to the degree of phenolphthalein reaction.

### 4.2 Water driven reactions

#### 4.2.1 Laboratory evidence

There is currently little laboratory evidence of these reactions. Attempts to simulate the work of Botha et al (2005) using granitic materials (assumed to have higher sodium contents) have produced little evidence of the reaction. Even the addition of a material identified as being potentially dispersive (having a higher exchangeable sodium content)



when added to a typical granite material showed no evidence of being affected by “water driven reactions”. No evidence of any sodium (alkali) reaction was visible using a SEM on these materials after curing, despite specific attempts to identify such reactions.

#### 4.2.1 Field evidence

Following publication of the paper by Botha et al (2005) this potential problem has been specifically investigated during a number of investigations into stabilization problems. The presence of the “water driven reaction” should be verifiable by a dry weak material with a high pH, resulting from the presence of sodium hydroxide. In no case has a dry soft layer with pH values in excess of 10 been observed by the author. Where weak upper layers were located the materials either had low pH values (< 10) or where the pH values were in excess of 10, the material was visibly wet. The original project on which Botha et al (2005) based their hypothesis was investigated independently by the author and little evidence of high pH values in the weak upper layers of the road was recorded. Even where the virgin material does not contain carbonate materials, increasing effervescence with hydrochloric acid is seen as the pH decreases with time.

### **5. DISCUSSION**

The reactions described for the carbonation reaction are all standard reactions quoted in any concrete or chemistry text book. All of the components required for these reactions are standard constituents of the conventional stabilization reaction, i.e., water, lime, calcium silicate hydrate reaction products and there is a ubiquitous presence of carbon dioxide and water in the atmosphere.

The reactions required for the “water-driven” reaction are not all standard chemical reactions, although some of these (disregarding obviously erroneous ones) are described in documents related to alkali silica reactions. The primary constituent necessary for these reactions is sodium. In no case quoted by Botha et al (2005) has the actual presence of sodium been identified or has the quantity of sodium been determined. The practice of curing stabilized materials under moist or wet conditions has been used since stabilization was first introduced and was probably based on the need to cure concrete under similar conditions (to ensure complete hydration of the reaction products). No problems using moist curing techniques for stabilized materials appear to have been reported in the literature prior to the late 1970s (Alexander, 1976). The question must thus be asked “Why has water suddenly become a destructive agent in stabilization reactions after many years of prescribing it as a necessary component to facilitate the curing of stabilized materials?” as proposed by Botha et al (2005).

Discussions regarding this so-called “destructive reaction” with a number of highly experienced cement chemists indicate that, although the reactions are theoretically possible, they are highly unlikely in road stabilization practice. A unique set of circumstances would need to be present for these reactions to progress to the extent necessary to cause the problems described.

There has been considerable debate on the merits of the two stabilization deterioration processes for some time. The testing carried out has indicated that carbonation generally results in significant decreases in the strength of the material. No significant weakening of the upper surface of beams as described by Botha et al (2005), however, has been detected, except for the material compacted to the much lower density (90% Mod AASHTO) as expected.

One of the ubiquitous problems with this type of investigation is the control of moisture during testing. Small changes in moisture result in a major effect on the progression of the hydration reactions, but also on the strength and performance of the stabilized materials. The impact of this is seen on the obvious moisture differences (visible and confirmed by the moisture content determinations) between the specimens that are cured and treated in different ways.

Cyclical changes in moisture content also promote carbonation (Ballim and Basson, 2001) and in small samples, these moisture changes are very difficult to control. Carbonation of small samples has been observed in the laboratory (usually the humidity is controlled to 50%, the optimum for carbonation) seen to be very fast. In addition, the carbon dioxide in even small containers is often enough to initiate carbonation.

## **6. CONCLUSIONS**

Based on a thorough review of the evidence, it is concluded that, although there is indubitable proven scientific, field and laboratory evidence for the carbonation of stabilized road construction materials, there is no solid scientific evidence for the occurrence of the “water driven reactions” in soil stabilization for roads as hypothesised by Botha et al (2005). In fact, the evidence manifested at many sites is contrary to the presence of these reactions.

This mechanism should be considered as a possible cause of any problems only when the “water driven reactions” can be conclusively proved to have occurred on site (primarily by testing for sodium and the presence of the detrimental reaction products).

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