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The Durability of Stabilized Materials

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ABSTRACT: With the increasing scarcity of good quality materials for the construction of roads and the demand for recycling of existing pavement structures, the need for more chemical stabilization will increase. These issues are compounded by the rapidly increasing traffic loading. Chemical stabilizers are frequently used to improve sub-standard materials. However, it is necessary to ensure that the long-term durability of the stabilized material is sufficient to provide the structural capacity required over the design life. Experience gained over the past 25 years has shown that many failures of stabilized materials are the result of a lack of understanding but can be overcome using existing knowledge.

Aspects that need to be considered include:

- Is the correct stabilizer being used?
- Is sufficient stabilizer being added?
- Is the material sufficiently stabilized to provide the necessary strength?
- Is the material durability sufficient to withstand the prevailing environmental conditions?
- Has the stabilized layer been correctly constructed?

This paper discusses these questions in turn, with answers based on the evidence of many years of laboratory and field investigations. Based on the information provided, failures of properly designed and constructed stabilized layers (other than problems resulting from uncontrolled overloading) should be rare.

1 Introduction

As good road construction materials become scarcer and their location becomes more difficult and costly, the need to improve marginal quality materials using chemical stabilization is becoming more important. The recycling of existing pavements using chemical stabilization in an attempt to conserve non-renewable gravel resources is also becoming more prevalent. Compounding these problems, the trend of increasing axle load limits, increasing tyre inflation pressures and the general increase in traffic dictate significantly higher structural capacities of road pavements. In order to satisfy these needs, stronger and more durable construction materials are required.

Despite many years of experience with the stabilization of materials for use in road construction and comprehensive specifications based on this experience, a noticeable increase in problems related to road material stabilization is taking place in southern Africa, resulting in serious cost increases, claims and the author has even been involved in two arbitration cases.

Chemical stabilization in the context of this paper includes the improvement of materials by cementation producing a tensile strength (as opposed to modification of the material properties to reduce plasticity or improve grading). This is done using lime, cement, ground granulated blast-furnace slag (GGBS), flyash or combinations of these usually in quantities of 2 to 4 per cent by mass. The use of bitumen or less common proprietary chemical stabilizers based on surfactants, enzymes or various inorganic compounds is not considered in this paper.

The aim of this paper is thus to highlight the types of problem that are occurring with conventional chemical stabilization and make recommendations on means for overcoming such problems.

2 The chemical stabilization process

In order to understand the problems that can occur with chemical stabilization it is important to clarify the chemical processes involved. These are generally the formation of mainly calcium silicate hydrates (or Tobermorite minerals as found in conventional concrete technology) by the reaction between water and calcium silicate under high pH conditions. Various other compounds such as calcium aluminate hydrates, calcium aluminate sulphate hydrates, calcium alumino-ferrite and hydrogarnet (calcium alumino ferrite silicate hydrates) are also produced and contribute to the early strength development but make little contribution to the long-term strength. Although the end products using lime, cement, GBBS or flyash are all similar (ie, calcium silicate and calcium aluminate hydrates), the processes differ significantly.

In cement stabilization, all of the components needed for cementation are included in the cement. The addition of water results in the hydration of all of the components, but it is hydration of the calcium silicates that form the strong calcium silicate hydrates (various forms occur), which cements the soil or aggregate particles together. As all of the cementing materials are added within the cement, it is not necessary for the soil being treated to have any specific components, although certain materials such as gypsum and soluble salts can interfere with the successful formation of the cementation products by forming such minerals as ettringite and thaumasite, with their accompanying expansion or inducing a "flash-set" of the material should excessive chlorides be present.

Calcined calcium carbonate in the form of lime, which can be either hydrated (slaked) as calcium hydroxide ($Ca(OH)_2$), or less commonly remain unslaked as calcium oxide (this can have serious safety problems resulting from the strong exothermic reaction with water) is used in lime stabilization. Lime stabilization involves two "reaction" processes. The first (or modification reaction) is very rapid (Ballantine and Rossouw, 1989) and involves ion exchange and flocculation of the clay minerals. Both of these processes result in a lowering of the plasticity of the material and the production of a more friable material. The second stabilization reaction (cementation) is much slower and involves the reaction between the calcium in the lime and silica and alumina in the clay minerals (soluble under high pH conditions caused by the addition of lime) to form calcium silicate hydrates and calcium aluminate hydrates similar to those formed during the hydration of Portland cement. However, it is essential for these reactions to occur that a suitable clay component is present.

In materials with insufficient clay to react effectively with the lime, the addition of silica and/or alumina from pozzolanic materials such as flyash or GGBS can provide the necessary components to react successfully. It should be remembered that lime is a standard chemical with a relatively fixed composition prepared for industrial use, including road stabilization. Cement on the other hand, is prepared primarily for the construction of buildings and large concrete structures, and different cements are synthesised to fulfil the necessary requirements for the concrete industry. Its use in road stabilization is relatively minor and not of sufficient concern to warrant adaptation of production cements for road stabilization.

3 Is the correct stabilizer being used?

As summarised above, for successful stabilization the material to be stabilized must have the required components in the necessary quantity. This usually requires knowledge of the base material properties (Atterberg limits, grading and mineralogy) but must be confirmed by determining the effects of different stabilizers under laboratory conditions. Although various "rules of thumb" exist such as materials with a Plasticity Index of less than 10% should be stabilized with cement and those higher should use lime (DoT, 1986), these are not necessarily always good indicators. Other aspects such as high amorphous silica concentrations may result in low plasticity materials reacting well with lime. Table 1 shows the unconfined compressive strength (UCS) and plasticity results of testing a weathered gneiss/migmatite with a plasticity index (PI) between 8 and 11 % after treatment with 2% of different stabilizers (using the South African test methods (TMH, 1986) which are based on the equivalent ASTM methods).

Table 1: Effect of the addition of 2% cement and lime on the UCS and PI of a weathered gneiss/migmatite

Stabilizer type	UCS [kPa]	PI after treatment [%]
CEM II B-L 32.5 R cement	2862	4.0
CEM II B-L 32.5 N cement	3558	7.0
Hydrated lime	1834	5.0

It is clear that all of the stabilizers produce the required design strength (750 kPa in this case), but their effect on the plasticity index of the material varies from minimal (decrease from between 8 and 11% to 7% for 32.5N cement to 4% for 32.5R cement). Of particular interest in this case is that none of the stabilizers rendered the material non-plastic, despite providing sufficient strength.

It is thus recommended that the material to be stabilized be tested in the laboratory using a nominal quantity of different stabilizers (say 2 or 3%) and the stabilizer that produces the optimum strength (usually Unconfined Compressive Strength (UCS) or Indirect Tensile Strength (ITS)) should then be selected for additional testing. Only high quality and fresh stabilizers should be used. The effect in reducing the plasticity should also be noted. The costs of the stabilizers should not be assessed at this stage, as the purpose is to assess which stabilizer is technically the best. However, where equal quantities of, for example, cement and lime yield similar strengths and have similar effects on the plasticity, their costs and availability should be considered as an additional factor.

It must be noted that a wide range of cements is available and each of these could have different effects and stabilization potential on different materials. It is, however, recommended that cements with strength classes higher than 32.5 according to EN 197-1 (CEN, 2000a) should not be considered, and neither should rapid hardening (R) cements.

Lime and cements with high extender contents (classified as B under the EN 197 specification) often provide less early strength allowing more time for construction. Where available, hydraulic road binders complying with ENV 13282 (CEN, 2000b) may often be the best stabilizer choice.

Where excessive amounts of chemical stabilizer are found to be necessary to achieve the required properties, the technical and economic feasibility of using other stabilizers such as bitumen emulsion or foamed bitumen can be considered.

4 Is sufficient stabilizer being added?

A good stabilization design will include an investigation into the optimum stabilizer content. This will normally be carried out at the same time as the identification of the best stabilizer type, during which the stabilizer content that provides the required design strength (and that will be available for use on the project) is identified. This is done by determining the strengths of representative specimens at various stabilizer contents, using the best identified stabilizer. The consideration of a number of other factors, however, should accompany this decision.

To ensure that the proportion of active stabilizer is not unacceptably diminished by the early cation exchange and flocculation reactions described in Section 2, it is customary to determine the “Initial Consumption of Lime” or ICL. This is carried out in most countries using the Eades and Grim (1966) test, now specified as BS 1924-2 (BSI, 1990). This test essentially determines the quantity of stabilizer that will be used up during the early cation exchange and flocculation reactions. Subsequent work by Clauss and Loudon (1971) indicated deficiencies in the method and a revised method was proposed. However, research over the years has led to further improvement of this method (Ballantine and Rossouw, 1989) in which a lager sample covering a wider grading is used. The main problem with the ASTM/BS tests was that the ICL is determined at the lime content at which a pH of 12.4 is reached. Experience has shown that the end point is not always 12.4, with other factors affecting the ultimate pH. It is thus necessary to continue the test until the further addition of lime results in no increase in the pH.

In order to ensure that sufficient stabilizer is added to allow for completion of the early reactions and to have adequate stabilizer remaining to promote effective cementation, it is recommended that at least an additional 1% of stabilizer more than the ICL be taken as the nominal stabilizer content, subject to the design strengths being attained. Many engineers also request that an additional 0.5 to 1% be added to allow for variability in the properties of the materials on site and variation in spreading and mixing. These details all need to be considered by the design engineer.

If insufficient stabilizer is added, the design strength will not be achieved in the field and premature failure of the project is likely. It should always be remembered that the strengths and other test results obtained in the laboratory are achieved under almost perfect conditions which are unlikely to be encountered in the field as discussed below.

5 Does the material have the required strength?

The stabilization design will determine the best type of stabilizer and the required stabilizer content to provide the design strength. This strength will be determined during the pavement design to provide the necessary structural capacity of the layer for the pavement, bearing in mind that the individual layers should be evaluated holistically in terms of the total pavement structure.

It should be noted that the likelihood of the material achieving the strengths determined in the laboratory after construction in the field is relatively low. In the laboratory, the stabilizer and soil is combined with the exact quantity of water to ensure the material is at its optimum water content, it is thoroughly mixed such that it is evenly distributed through the material, it is then compacted to the required density after controlled conditioning periods at a standard temperature, perfectly cured under controlled temperature and humidity conditions and carries no load until curing is completed. In the field the achievement of any of these states is often doubtful and to make matters worse, construction traffic (even water spray tankers) often makes use of the layer within hours of compaction.

The determination of the material strength is typically difficult. In practice, a sample of the material is usually removed from the road during compaction, taken to the laboratory and compacted (to a specified density) for controlled curing, soaking and testing. The laboratory strength is then determined and this is assumed to represent the field strength. The deficiencies related to this process should always be borne in mind when assessing problems in the field. The only solution to obtaining actual field strengths is by removing cores from the road (dry coring is necessary) and testing these in the laboratory. This can only be done once adequate cementation has occurred to obtain intact cores from the layer.

6 Is the material durability adequate?

A good stabilization design should produce a material that will provide the required stiffness over the design life of the road. It is generally accepted that stabilized layers change their properties with time, going from an intact material (pre-cracked), through a microcracked phase in which the material consists of small blocks of stabilized material rather than a continuous layer (post-cracked) and then reverting almost to the original unstabilized layer (equivalent granular phase) (DoT, 1986). However, it has also been proven over the last 25 years that many of the problems related to stabilization durability result from the reaction between the residual lime in stabilized materials and carbon dioxide in the atmosphere (Paige-Green, 1991; Paige-Green et al, 1990).

Although for control purposes, most testing is carried out after 7 days, the strength of stabilized materials increases over an extended period, sometimes even years (Paige-Green, 1991). This appears to vary for different materials and stabilizers and no standard estimate of the long-term strength from the 7 or 28 day strength appears to be in general use.

It is essential that early curing is carried out under controlled conditions. Moisture is necessary to ensure the continued hydration of the cement components. If the surface of the road dries out, cementation ceases and other problems are initiated.

It has been shown beyond doubt that stabilized materials can be seriously affected by carbonation (Paige-Green, 1991; Paige-Green et al, 1990). In lime treated materials, unreacted lime is required to maintain the pH of the material above about 12 and ensure that the reaction products remain stable. In cement stabilization, the hydration of the calcium silicates releases lime (about 20 to 25% by mass), which similarly keeps the pH of the material above 12. Should the pH decrease to below about 10 as a result of the carbonation, the calcium silicate hydrate reaction products become unstable and decompose. Movement of water through this material can leach the calcium leaving weak silica gels. Carbonation of the material involves the reaction between the lime and carbon dioxide in the air to form calcium carbonate. This reaction is accompanied by a significant increase in volume (at least 12%). Should the expansive forces generated exceed the tensile strength of the material that has built up, weakening and/or disintegration of the stabilized material will occur. If the tensile strength developed in the material exceeds the expansive forces, no detrimental action will occur. This accounts for the observation that carbonation is not necessarily always detrimental to the material. However, it is also true that the calcium silicate hydrates forming the cementation become unstable as the pH of the material decreases (below about 10) and the material's strength may thus decrease with time (Paige-Green, 1991) to a point that it is insufficient to perform its structural requirements.

This process was recognised as a significant problem in southern Africa in 1981 (Netterberg and Paige-Green, 1984), following which an accelerated carbonation test was developed (de Wet and Taute, 1985). Experience with this test has shown that where the stabilizer content does not exceed the ICL by at least 1% (Sampson and Paige-Green, 1990), the material is fully carbonated and weakens: where the ICL is exceeded, the material does not carbonate fully and the residual strength exceeds the nominal design strength.

The standard prescribed durability testing in South Africa is the wet/dry brushing test. This is based on the original PCA test (PCA, 1971) (also specified as ASTM D559-03 and AASHTO T 135-97(2004)) but has been modified to more closely simulate the compaction levels utilised in South Africa (98% of heavy compaction versus 93-95% in the US test). The variability in the original test caused by hand brushing has been eliminated by using a mechanical brushing technique (Sampson, 1988) (figure 1).

Figure 1. Mechanical wet/dry brushing device

Observations during a typical series of wet/dry brushing tests indicate that the oven drying step in the test procedure causes carbonation of the exposed surface of the specimen. Depending on the degree of carbonation, deterioration of the material occurs and a higher proportion of the material is brushed off. The test, thus, probably fortuitously, takes the carbonation durability into account to a significant extent.

The durability of the material can also be affected by other material properties or in situ conditions such as salinity, acidity (Netterberg, 1979) and possibly even alkali silica type reactions. These potential problems are, however, usually identified timeously and the necessary precautions taken.

7 Has the layer been constructed properly?

A good stabilization design is essential before construction begins: no matter how well constructed a stabilized road is, poorly designed stabilized materials will not provide the expected performance. However, many of the problems investigated by the author over the past 25 years or so can be attributed to poor construction techniques.

7.1 Spreading and mixing

Conventionally, chemical stabilizers are spread from individual pockets by hand or by bulk tanker. When done under proper supervision, there is probably little difference between the two techniques, provided the correct calculations are done. In the past, mixing was done using a motor grader (or less frequently equipment such as “pulvimixers” or “Rotavators”. Again, provided this was done by experienced personnel under proper supervision, problems with distribution were seldom encountered. More recently, the use of recycling machines has increased – there is no doubt that the control on mixing is now better. However, this improved mixing is mostly in the vertical and forward direction. Lateral mixing appears to be not as well done and it is therefore essential to ensure that lateral spreading is even and the overlap between runs is carefully controlled.

One of the problems with quality control of stabilizer distribution is that the percentages added are so small. The normal chemical techniques to assess the stabilizer content involve the determination of the calcium ion in the material before and after stabilization. Although various techniques are available (these are chemically sound analysis techniques), the natural variation of the calcium within the soil or gravel material tends to be greater than the quantity of calcium ions added. The testing is thus of limited value. Generally, by spraying an exposed vertical surface of the layer with a phenolphthalein solution, a good qualitative indication of the stabilizer distribution can be obtained. Provided the records of the quantity of stabilizer added to the known volume of material tally and the distribution appears even and to the correct depth, it can be assumed that mixing was sufficient.

During the cutting of the final levels, it is essential that no dry or untreated material is cut across the road to fill depressions or sags. This will not cement and result in weak and permeable areas that will disintegrate rapidly, usually during brooming before application of the prime or during rolling of the aggregate during sealing.

7.2 Time of construction

Experience and laboratory investigations have shown that lime is a much slower reacting material than cement. For this reason, most specifications allow a much longer period for the construction of lime stabilized materials (12-24 hours) than that allowed for cement stabilized materials (2- 8 hours).

It is essential that the same make and classification/type of stabilizer that was used for the stabilization design is used on the project. Should there be a change in stabilizer type the stabilization design must be repeated to confirm that the behaviour and timing is similar.

With cement stabilization in particular, construction should be carried out as quickly as possible, as the initial cementation reactions can be very rapid. Once initial bonds start developing, additional compaction is necessary to break these down in order to achieve the specified density. This extra compaction requires additional time, which can result in the destruction of a lot of the early cementation. It must also be remembered that the rate of chemical reactions is proportional to temperature (a rule of thumb is that reaction rate doubles for every 10°C rise in temperature), and the high temperatures often encountered in the field can result in marked reductions in allowable construction time.

It is thus important to determine the allowable working time for any material/cement combination before use so that the Contractor can ensure that excessive compaction is not necessary to achieve the required density. This is best done in the laboratory under simulated field conditions (particularly temperature) as described by Vorobieff, 2006).

A common procedure carried out by Contractors and observed on numerous sites in South Africa is to roll the layer “lightly” (ie, without vibration) at the end of the day to smooth the surface and improve its visual appearance. This should not be done as heavy rollers can damage the upper surface should it have dried out at all since final cutting and rolling.

7.3 Curing

For the successful formation of cementation products in stabilized materials, the continued hydration of the fundamental components (mostly calcium silicates) is essential over the short to medium term. Experience has shown that the stabilized material must be kept in a moist condition for at least 7 days. This is difficult on site and various techniques are usually specified for this. These include periodic water spraying, covering with plastic sheet or spreading the next layer and keeping it moist, priming (preferably with a bitumen emulsion that forms a skin), etc (COLTO, 1998). The main objective is to minimise moisture variations as carbonation is most detrimental at a relative humidity of about 50% - unless the material is kept continuously moist, wetting and drying during the course of the day causes this situation to be encountered each time the layer is sprayed or dried. Experience has shown that stabilized layers are generally sprayed with water twice a day, which does not necessarily keep the continuously moist and results in problems. Placing a moist layer of material on the completed stabilized layer has been shown to be one of the most effective techniques for reducing moisture changes and encouraging proper cementation.

8 Conclusions

As chemical stabilization is being increasingly used to improve the quality of sub-standard materials and to recycle old pavement materials, the number of problems seems to be increasing correspondingly. These can often be attributed to inexperience on the part of the designer and failure to take the full design, construction and service conditions into account.

In order to ensure the durability of chemically stabilized road pavement materials over the service life of the pavement, the entire stabilization design and construction process must be carefully controlled. Deficiencies in any area along the way can significantly affect the performance of the final stabilized later. However, provided the engineer has a full understanding of the stabilization process and requirements, there is no reason why a marginal or sub-standard quality material cannot be effectively improved for use as a structural layer in a road by chemical stabilization.

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