The geology and petrology of road construction materials revisited

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ABSTRACT: As the need for road construction materials increases with urban and rural development, their availability is decreasing. They are becoming more costly, their extraction usually has serious environmental implications and many of the most suitable materials have been depleted. Significant work on the engineering petrology of construction materials was carried out in South Africa in the late 1960s but this has not been continued and reported on an ongoing basis and subsequent problem materials have not been described or reported in a single document. In addition, the quality of geological training provided to undergraduate civil engineers (and even geologists) appears to have reduced in recent decades. This paper reviews the geological and petrological inputs into road construction material usage, highlighting recent developments and summarizing areas that need greater attention during the investigation of potential construction materials. Improvements in investigation and analysis techniques as well as research into problems associated with specific rocks and minerals are discussed. Appropriate examples are used to illustrate relevant aspects.

1 BACKGROUND

Although geology was an important input into the civil engineering industry in South Africa prior to the 1960s, there was an unprecedented growth and synergy between geologists and civil engineers from the mid 1960s onwards (Clauss et al 1969). This resulted in the formation of various associations and institutions among the geological fraternity and closer cooperation with the civil engineering industry. One area of particular growth was in road development (Clauss et al 1969).

In 1969, it was estimated that there were about 350 practicing civil engineers and about 25 geologists with a particular interest in geotechnics (Clauss et al 1969). The current estimate is about 320 civil (geotechnical) engineers and 155 engineering geologists.

In the intervening period, there have been a number of economic booms and downturns in South Africa, each one resulting in fluctuation in these numbers. In addition, the prevailing socio-political environment in South Africa has resulted in a "brain-drain" on one hand, primarily through emigration, and a poor response to replacement of these individuals on the other. This has resulted from the poor science and mathematics background associated with the former education systems for the majority of South African students.

The fluctuations in numbers of professionals, research and development funding and infrastructure development have all had an impact on developments in the industry. This is manifested by the reduction of important publications and the failure to implement new technologies on a large scale.

During the period from about 1960 to 1987, numerous landmark journal articles and books were published in South Africa. Many of these were groundbreaking developments related to geology and petrology, whilst other synthesized the new and important developments for everyday use. Subsequently, very few comparable publications have been produced. This reduction in published work coincided with the move from primarily Government funded research to predominantly contract research in South Africa. One of the results of this was that much of the research carried out was privately funded and thus not available for general publication.

At about the same time, the South African road construction industry came under enormous pressure to recover a significant maintenance backlog, while attempting to expand the infrastructure to deal with a significantly increasing vehicle population. The legal axle limit has recently been increased by about 10 per cent, and there has been a marked increase in average tyre inflation pressures on trucks. The increasing use of marginal and treated materials in road construction requires a better understanding of the geology and petrology in order to minimize problems. This is unfortunately not always provided and material problems afflict many projects.

This paper briefly summarizes the important works published prior to 1987, highlights some of the more important aspects, identifies techniques and tools related to these, discusses shortcomings in the current situation and makes suggestions to improve the situation.

2 LANDMARKS REVISITED

Probably the most significant early work in the road construction materials arena in South Africa was carried out by Weinert (1964, 1965). In an investigation to determine why certain weathered dolerites performed well as a construction material and others did not, the climatic N-value was developed. This related the formation of various clay minerals to the prevailing environment (in terms of rainfall and evaporation).

This work led onto durability studies in a wider context culminating in an engineering classification of southern African rock types based on their durability and performance in roads (Weinert 1968, 1969). This work grouped all of the typical southern African road construction materials into nine groups and all the work was published in an important book (Weinert 1980). This book is still the only comprehensive reference to road construction materials in southern Africa available and is used extensively in the industry.

Petrology is a key component of Weinert's book, although it is simplified to a point that the recognition and identification of quartz is the only requisite for classifying materials. Reference to thin section preparation only for the estimation of the quantity of secondary minerals is made. The importance of deleterious minerals such as nepheline, reactive silica, sulfides, muscovite and clay is highlighted in one chapter. A great deal of emphasis is placed on the smectite clay group, the primary cause of problems in his Basic Crystalline Rock group.

The importance of geomorphology, particularly the erosion cycles affecting southern African construction materials since the Cretaceous Period was developed primarily by Partridge (1975), being summed up in a major work by Partridge and Maud (1987).

Other landmarks include work on individual material types such as that by Netterberg (1971) on calcretes and by Venter (1980) on mudrocks. Findings from these works have been included in recent specifications (eg, COLTO, 1998). Specific problems related to geological materials such as soluble salt damage (Weinert and Clauss, 1967; Netterberg, 1979) and alkali silica reactions (Semmelink, 1981) also contributed significantly to the industry.

The culmination of the work carried out between the 1960s (and even earlier in some cases) and 1985 was a series of four volumes on the engineering geology of South Africa published between 1979 and 1985 (Brink, 1979, 1981, 1983, 1985). These volumes were systematic reviews and assessments of as much engineering geological information as was accessible at the time supplemented with stratigraphic and relevant geological and petrological data. Brink compiled the last three books, with inputs from competent experts. Numerous case histories were included.

Although numerous papers and articles have been published by geotechnical experts since 1985, no significant books particularly related to materials in the South African road construction industry have been forthcoming. It is also notable that all of the aforementioned books are currently out of print.

3 ROAD CONSTRUCTION MATERIALS - STATUS QUO

Materials for the construction of pavement layers in roads are generally selected on the basis of their engineering properties as defined for the different material usage classes in standard specifications (COLTO, 1998). These are primarily related to grading, plasticity, CBR strength and various other parameters such as aggregate shape and strength for base course materials. Until the revision of the COLTO specification in 1998, little attention was paid to durability, with the soaked to dry ratio of the 10 per cent Fines Aggregate Crushing Value (10%FACT) being a proxy for the assessment of durability.

As increasing use is made of more marginal materials (in order to reduce costs and environmental impacts), particularly for lighter pavement structures (typically Category C in TRH4: 1996), the risk of premature distress increases. The practice of in situ recycling of existing pavement materials is becoming more popular and often involves the blending of shoulder base and subbase materials, of significantly differing quality.

In order to make optimum use of the available materials, it is necessary to predict their behaviour and long-term performance or durability. This requires accurate material identification and a sound understanding of their geological history, mineralogy, petrology, rock weathering and clay formation as well as the conditions and forces prevailing in pavement structures. Clear differentiation between mineralogical changes related to weathering and those due to alteration is also necessary. A well-prepared engineering geologist is best suited to provide this information.

4 TRAINING

It is the observation and opinion of the author that the geological knowledge of recent civil engineering diplomates and graduates (particularly but not only) in South Africa appears to be diminishing. Geology has always been a course viewed with marginal interest by many civil engineering students. This is probably the result of the course composition (particularly the practical aspects) as well as the aspirations of the students.

Geology courses for civil engineering students are frequently biased towards the recognition of uncommon minerals and rocks, crystals and the interpretation of small-scale geological maps and cross sections. Geology is typically studied early in the diploma or degree course (second or third year), at which stage most students are unaware of their likely field of specialization. If geology were studied at a later stage, the students would have a much greater appreciation of the importance and impact of geology on the designed structures, whether they are roads, dams buildings or any other structure.

Of greater concern is the field material recognition capability and knowledge of the mineralogical composition of relatively common rock and pedocrete materials of many recent geology graduates and diplomates. No systematic logical process of rock identification appears to be followed. It is felt that fieldwork is generally conducted in relatively close proximity to their universities and the local materials dictate the primary practical knowledge levels, which is often not as relevant in other parts of the country. The importance of field observation and field relationships in geology has been highlighted by Partridge (1998).

5 TECHNIQUES

Numerous techniques, although not necessarily new, have been used and shown to provide information that can assist in predicting the behaviour and performance of geological materials in roads. Many of the older techniques have become easier to use and interpret and are more cost effective than they were two or three decades ago.

Typical examples of these are thin section preparation for assessment under the polarizing microscope, X-ray diffraction analysis and electron microscopy. The preparation of thin sections is now mostly automated. Their production is thus rapid and the thin section thickness is much better controlled. X-ray diffraction (XRD) too, is almost fully automated with the interpretation being quickly done using computerized comparisons with standard traces. Similarly, the quality of Scanning Electron Microscope (SEM) images has improved significantly and useful information, particularly with respect to problem solving can be clearly seen.

All of these techniques, however, do have potential shortcomings as discussed in Section 8.

6 SPECIFIC MINERALOGICAL PROPERTIES AND PROBLEMS

A number of aspects and problems related to the primary rock forming mineral groups and other specific minerals are discussed individually below. Many of these almost fundamental issues are not known to graduates entering the road construction field

6.1 Silica

Silica in rocks is primarily in the form of silicate minerals and quartz. The silicates are described individually later in this paper. Quartz, being the last mineral to crystallize from magma is the most stable mineral under normal environmental conditions, does not weather and is essentially inert as a construction material. Amorphous or cryptocrystalline forms of quartz, as well as quartz showing evidence of significant strain, however, react with the alkaline pore solution of a concrete to form expansive alkali-silica gels with serious consequences.

Thin section studies of potential concrete aggregates are excellent means of screening materials prior to carrying out laboratory testing for identification of the potential reactivity of aggregates with cements. This procedure has been clearly outlined by Oberholster (2001).

The presence of significant quantities of amorphous silica in a material can also result in the rapid development of cementation in lime treated materials, with concomitant compaction and density problems. X-ray diffraction techniques (or wet chemical analysis) are best for identifying this possible problem.

6.2 Feldspars

Feldspars tend not to give problems in road construction aggregates. In wet areas, the calcic plagioclases weather to smectite clays, usually in association with more mafic minerals (Weinert, 1980). X-ray studies of various basalts and dolerites indicate that the formation of kaolinite and/or sericite is equally possible. Smectites produced by the alteration or weathering of the mafic minerals probably cause the major problems, however.

The in situ weathering of feldspar particles, particularly in granites, dirty sandstones and arkoses produces a potentially collapsible soil structure (Brink, 1979). Although extremely important in road construction, this aspect is not specifically relevant to this paper.

6.3 Micas

Warnings regarding the compaction of micaceous materials have been repeated since the 1960s (Weinert, 1980). These have generally been restricted to muscovite micas with no problems being attributed to biotite. However, compaction problems caused by a partly weathered biotite (visually identified as biotite but shown as smectite clays by XRD) have recently been reported (Paige-Green & Semmelink 2002).

It was suggested in 1980 that as long as the muscovite content of a material does not exceed 10 per cent, present as particles larger than 0.5 mm, problems are unlikely (Weinert, 1980).

6.4 Pyroxenes, Amphiboles and Olivines

Alteration (usually deuteric) or weathering of these minerals typically results in the formation of smectite clays, with their accompanying expansive potential. Moisture changes within the smectites will result in deterioration of the host rock. It is postulated that the rapid degradation of rocks such as mudrocks, tillites, some calcretes and basic igneous rocks on exposure to the atmosphere is a result of these volumetric changes.

This degradation may take the form of disintegration or slaking and will occur if the stresses induced by the volumetric changes exceed the tensile strengths of the material. The nature and form of the deterioration will depend on the texture, fabric and isotropy of the material.

6.5 Feldspathoids

The feldspathoids are relatively uncommon minerals in southern Africa but care must be taken if they are likely to occur. Their predominant occurrence is in certain undersaturated lavas and intrusions. The predominant representative of this mineral group in South Africa is nepheline. Nepheline will, under fluctuating temperature conditions alter to analcime, with a considerable swell.

The consequences of this are the same as those originating from water induced swell of smectite clays.

6.6 Phyllosilicates

The phyllosilicates include all of the clay minerals. These materials have low shear strengths and are mostly volumetrically unstable. Their presence in road construction materials is generally indicated by the plasticity index of the material but the relationship between the type and the quantity of the clay is also important. Two materials, one with a high component of low plasticity clays (eg, kaolinite) and one with a low component of high plasticity clays (eg, smectite) could have the same plasticity index, but would behave differently in service. The Activity of the clay (ratio of plasticity index to clay-sized (<0.002 mm) fraction) tends to indicate this better than other properties, but it is recommended that the actual clay minerals are identified, generally using XRD techniques as discussed in Section 8.2 of this paper.

6.7 Soluble salts

Problems related to the presence of soluble salts in road construction materials encouraged significant research in South Africa between 1967 and 1980 (Netterberg 1979). Very little additional work has subsequently been carried out in South Africa.

Recent international work (MoWTC, 2001) has indicated that the whisker form of sodium chloride appears to be particularly deleterious, but this nature of crystallization appears to be restricted to very fine-grained materials. In general, sodium chloride has not been a significant problem in South Africa.

6.8 Sulfides

The presence of sulfide minerals in rocks has led to serious difficulties in road construction. This is a particular problem in South Africa with its extensive mining industry and the prevalence of sulfides in the majority of mineral deposits. The processes involve oxidation of sulfides to sulfates resulting in soluble salt problems as discussed above as well as sulfate attack on stabilized layers. This involves the reaction between sulfates and calcium and alumina to form calcium sulfoaluminates. Typically, the calcium is derived from the cement while the alumina can be derived either from the cement or from partial dissolution of clays in the material. Ettringite and to a lesser extent Thaumasite are the primary troublesome minerals, with their formation being accompanied by large volume increases and fracture of the stabilized material. Their influence on compacted materials with low stabilizer contents has not been fully quantified – it is possible that the voids in conventional stabilized soils may be sufficient to cater for the expansion, although loosening of the surface is likely.

Netterberg (1979) provided guidance on the limitation of sulfates to minimize the risk of sulfate damage to stabilized materials. Little new information has been added to this since 1979. It is apparent, however, that changes in cement compositions since adopting the EN 197-1 specification and the use of lower quality coal in the calcining process has resulted in an increase in the C_3A component of South African cements. The possible effect of this may be that sulfate-related problems could be expected to increase in future.

7 SPECIFIC PROBLEMATIC ROCK GROUPS

7.1 Basic igneous rocks

The durability problems associated with basic igneous rocks have been highlighted for more than half a century. Problems related to the development of clay minerals (and an increased plasticity index) in the road layer were attributed to in situ chemical decomposition of the material (Weinert, 1980). Wylde (1982) developed the "Texture Factor", which correlated well with pavement performance and indicated rearrangement of the fines in the matrix of road materials under traffic loading.

South African evidence suggests that this texture change can be taken one step further to include release of fines from the altered rocks. Most basic igneous materials in southern Africa are deuterically altered and contain appreciable amounts of smectite or interlayered smectite/chlorite clays. Recent studies indicate that decomposition of these rocks in situ is unlikely, but the existing clays in the altered rock appear to be released under traffic loading and internal volumetric changes could cause their disintegration.

One of the critical aspects with extrusive and to a lesser extent hypabyssal basic igneous rocks is the quantity and composition of any vitreous groundmass. Devitrification of this glassy material usually results in the formation of smectite together with other less deleterious clays.

The use of ethylene glycol to accelerate the effects of smectite clays on the rock has become almost routine practice in South Africa (Van Rooy & Nixon, 1990; Van Rooy & Van Schalkwyk, 1993; Bell & Jermy, 2000). No standard test method, however, has been developed and implemented yet. This aspect needs research as the degree and type of disintegration vary considerably with time. Test results from different sources are thus not comparable.

7.2 Arenaceous rocks

The importance of the type of cementation material in arenaceous rocks has been highlighted (Holleman, 1975: Weinert, 1980, Brink, 1983). Materials cemented with silica are considerably stronger than those cemented with, for example, calcite, clays or iron oxides. No additional work on these materials has been carried out in South Africa although an investigation into the failure of a number of basecourses, including sandstones, in the Cape Province of South Africa (Sampson et al, 1985) indicated that a number of sandstones complying with the standard engineering tests failed in service. The investigation showed that the sandstones either disintegrated severely in service and/or released plastic fines. No petrologic assessments were done prior to construction but it is likely that this would have shown the presence of clays and the interparticle bonding.

7.3 Mudrocks

Venter (1980) investigated the use of mudrocks in road construction, with particular emphasis on their durability. This resulted in a classification system based on the degree and nature of disintegration/slaking, which have subsequently been incorporated into the standard specifications in South Africa (COLTO, 1998).

Although, petrographic studies of each material were done, no direct comparison between these and the slaking characteristics of the materials were carried out.

No subsequent work has been reported on, despite a number of questions being left unanswered.

7.4 Diamictites

Like mudrocks, certain tillites (diamictites class of rock), have given durability problems in South Africa. An investigation into these problems (Paige-Green, 1984) allowed the formulation of specifications for the durability of tillites, part of which have been incorporated into the standard specification (COLTO, 1998).

Petrographic work on tillites is difficult because of the fine clayey nature of the matrix. However, X-ray diffraction studies are useful in revealing the composition of the matrix, although full treatment to differentiate between the individual clay minerals is necessary (Paige-Green, 1980).

7.5 Pedocretes

South Africa has a large range of pedocretes including calcrete, ferricrete and gypcrete. Extensive work has been carried out on ferricretes in many tropical countries, but little has been done in South Africa. Calcretes on the other hand have been comprehensively researched (Netterberg 1971). The primary clays in calcretes are rather unusual (sepiolite and palygorskite) although smectites and other clays do occur. The smectites can result in swelling and disintegration of the particles.

Rapid setting of some lime-stabilized calcretes was attributed to the presence of amorphous silica in the form of microfossils, primarily diatoms (Netterberg, 1971). This type of problem would be easily identified during detailed petrographic examinations.

Petrographic analyses were carried out on silcretes and calcretes used in surfacing aggregate trials in Botswana to identify the mineralogy associated with engineering test results on the materials (Woodbridge & Slater, 1995).

8 TESTING AND INTERPRETATION

Good engineering testing and interpretation of test results is paramount to successful road construction projects. Significant work has been carried out in this respect, but insufficient attention is still paid to the geological aspects of most road building materials. Engineering testing can be time consuming and expensive, especially good durability testing, and the use of preliminary geological assessments can assist significantly with sample screening and selection. Important aspects pertaining to this type of testing and interpretation are summarized below.

8.1 Petrology

The use of thin sections for road construction materials is seriously underrated. Rocks that have undergone any weathering or alteration, particularly those likely to contain smectite group minerals must be examined by a competent geologist, experienced in thin section investigations. The cost of preparing thin sections is still very reasonable and comprehensive interpretations can usually be obtained from Government Geological Survey Departments or Universities. In many cases, the cost of thin section preparation includes an analysis of the slide.

Although the use of thin sections, especially for secondary mineral counts was strongly recommended by Weinert (1980), these are still seldom used on a routine basis.

Apart from the mineralogy and material textures and fabrics, aspects such as alteration and weathering are usually clear, the nature of interparticle boundaries can be readily assessed and the presence of internal microcracking can be seen in thin sections. Minerals such as sulfides that can be problematic under certain conditions can be identified in thin or polished sections.

In addition, selective staining of individual minerals can be very useful. Benzidine, for example is absorbed by montmorillonite, staining it blue while nontronite turns green. The use of basic igneous rocks as road construction materials in southern Africa without careful thin section studies should be considered as foolish.

8.2 X-ray Diffraction

X-ray diffraction facilities are readily available at universities, agricultural research facilities and at many commercial laboratories and provide a quick, excellent means of identifying minerals, particularly clay minerals. The trend these days is to carry out unoriented powder diffractograms and have the results interpreted by computer. This is not recommended for road construction material, however. It is almost essential that oriented and treated powder scans are made and the results are interpreted manually. Where computer interpretation is used, the results should also be carefully assessed manually. Quantitative assessment using XRD is difficult and although the techniques are constantly improving, the results should be taken as estimates at best.

The use of XRD is considered essential during the assessment of basic igneous materials for road use and desirable in soluble salt investigations. However, it is important that the sample preparation and treatment for soluble salt analyses does not affect the hydration state of the salts causing the damage.

8.3 Scanning Electron Microscopy

Scanning electron microscopy can be particularly useful for the investigation of problems and for specific investigations such as potential salt damage and stabilization reactions. The alteration of minerals to clays can also be assessed. Modern SEMs have the facility to carry out energy dispersive X-ray analyses (EDX) on small spots within the SEM view. These show immediately the elemental composition of minerals, reaction products and crystals, which when combined with the shape and form of the minerals, allow conclusions to be drawn that cannot easily be obtained any other way.

8.4 Sample selection

Road construction utilizes large volumes of material. Typically, a road would consist of at least three layers of selected materials, each 150 mm thick and at least eight metres wide. This equates to about 3 600 m^3, or about 6 850 tonnes of material per km of road. To extrapolate the results of thin section or XRD analyses on one or two "randomly selected samples" to the entire material in a borrow pit or quarry seems to be rather ambitious. This is where the experience and geological knowledge of petrology and field relationships is so important.

A competent engineering geologist should be able to assess the variability of the material source, identify appropriate strata/material units and select a range of representative samples that can be used to determine the required properties and expected performance. The material units would need to be manageable for final material production.

9 CONCLUSIONS

It has been clearly demonstrated that, despite the availability and access to improved identification and analysis techniques, very little development in petrology for road materials has developed in South Africa since the mid 1980s. Significantly more use should be made of petrology and mineral identification when assessing rocks, and marginal materials in particular, for use in road construction. It is important that all the minerals in a rock, including alteration and weathering products and accessory minerals be identified to avoid potential later problems. Recent experience has shown that visual inspection of rocks alone is insufficient to characterize the mineralogy and predict the future performance. Close inspection of the mineralogy will assist in identifying the most appropriate engineering tests.

This paper is primarily a review document and does not pretend to include a lot of new information. It does show, however, that little research and development findings regarding petrology has been published since the mid 1980s. This, together with the increased use of new construction techniques such as in situ recycling, has resulted in more and more construction problems. A better understanding of the geological and petrological background to the materials would certainly assist in reducing the problems. These investigations are generally carried out at present only after problems are encountered.

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