THE GEOLOGY AND ENGINEERING GEOLOGY OF ROADS IN SOUTH AFRICA

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ABSTRACT

This paper briefly summarises the geological and geomorphological history of South Africa. This history is then related to various problems affecting the construction of roads in South Africa. These problems need to be identified early and countermeasures taken to ensure that premature and costly road failures do not occur. The major problems discussed include those related to expansive, collapsible, dispersive, erodible and very soft soils as well as material durability and slope stability. It is interesting, but somewhat worrying, to note that little development in these areas has taken place since the hey-days of research between the mid 1960s and the late 1980s.

1. INTRODUCTION

South Africa has one of the oldest and most complex geologies of any country on earth, with fine examples of classical geological features, many unique minerals and, of course, significant riches in the form of exploitable industrial and precious minerals.

The geology and related mineral and mining industry resulted in the economic development of South Africa, which is still a significant contributor to the South African economy. The income from minerals and mineral products comprises about 16 per cent of the South African Gross Domestic Product (GDP) and the industry directly employs about 550 000 people [1].

However, together with the benefits of the mineral wealth of the South African geology, many geological problems related to the infrastructural and engineering development of South Africa have also been encountered. This has led to the need to develop innovative and practical solutions to these problems, in many of which South Africa is a world leader.

This paper presents a brief review of the geological history of South Africa and the associated engineering geological problems related to this geological history.

2. GEOLOGY

Dating of the oldest rocks in South Africa has provided an age of about 3.7 billion years[2]. Like many of the oldest dated rocks on earth, these are sedimentary rocks, indicating that the source rocks were even older.

The South African geology is based around a cratonic nucleus (Kaapvaal Craton) centered in the northern and north-eastern one third of the country surrounded by various metamorphic mobile provinces.

All significant geological activity was associated with the Kaapvaal Craton between the formation of the oldest rock types and up to about 1800 million years ago, when orogenesis, metamorphic activity and associated igneous intrusions initiated adjacent to the Craton. This occurred in the Natal

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and Namaqualand metamorphic provinces and continued over a period of about 800 million years, during which time little activity affected the Kaapvaal craton.

During the last 570 million years, a chain of basins formed along the southern margin of the craton/metamorphic belts and into these basins, vast thicknesses of sediments were deposited. This deposition continued into Karoo times (300 to 140 million years ago) during which a range of environments from glacial to tropical forest resulted in the deposition of tillites, sandstones, coal and mudrocks with a rich assemblage of marine and terrestrial fossils. The Karoo period ended with a vast outwelling of lavas covering the majority of southern Africa. The lavas are more than 1350 metres thick in places and consist of numerous individual flows of primarily basaltic material. Karoo deposits currently cover more than half of South Africa, although evidence suggests that a significantly larger area was covered in the past.

Since Cretaceous times, various erosion cycles have produced significant sediment that has been deposited mostly on the south and east coasts of South Africa, with a large central deposit of sands (Kalahari desert). More recent reworking of the sediments in the coastal areas has resulted in extensive deposits of loose wind-blown and dune sands. Also during this period, various diamond-bearing kimberlite pipes were intruded.

The mineral resources of South Africa occur in some of the oldest (asbestos and gold in the 3.5 billion year old Onverwacht Group) rock formations as well as some of the youngest (diamonds in the 20 to 80 million year old kimberlites and in the more recent alluvial and marine gravels).

3. GEOMORPHOLOGY

The geological origins of South Africa provided the original “hard” rock surface. The effects of the environment (climate) on the rock surface results in weathering and alteration of these rocks to form “soils” followed by erosion transportation and deposition. Engineering structures on the surface are typically founded in these materials although tunnel and mine engineering are mostly associated with the hard rock occurring deeper.

As mentioned previously, the climatic conditions have varied over geological time from extreme glacial to extreme desert conditions, with numbers of these conditions and everything in between affecting the land. Even today, although not as extreme, the climate varies from hot, dry desert conditions to periodic, cold and icy (not glacial) conditions in the mountain highlands (Drakensberg). Each condition has specific characteristics with regard to the ongoing geomorphologic evolution, in terms of rock weathering and generation of material for erosion and deposition.

Geomorphology is defined as the study of landforms, each different landform being related mostly to geology and climate. The topography seen today is a result of long periods of geomorphic activity, but the most important aspects are probably related to activity in the past 150 million years or so. This period is related to the separation of the Gondwanaland supercontinent into its individual continents during the early Cretaceous, about 125 million years ago.

Simply, nature’s geomorphologic objective (or equilibrium condition) is to flatten all topography to sea level, by eroding uplands and depositing the resulting debris in the oceans. Erosion is therefore primarily controlled by sea levels. Sea levels are, however, not constant, fluctuating significantly over time. These fluctuations are mostly related to the quantity of water held as icecaps or vertical movement of landmasses.

South Africa has undergone at least 5 erosion cycles during the last 135 million years [3], which have left evidence of planed surfaces, many over relatively limited areas. The African surface, however, developed over a period of about 80 million years ending about 20 million years ago. This left a vast, flat and deeply weathered plane, remnants of which are visible over an extensive area of southern Africa. Since then relative movements of the South African landmass to sea-level up to about 900 m have resulted in the relatively rugged topography, often with thin soils towards the coastal areas.

In relatively recent times, soil-forming processes (pedogenesis) have resulted in extensive, but usually thin, deposits of pedocretes ranging from ferricretes to calcretes, silcretes, gypcretes and others. These are extremely important road construction materials, with unique properties making their use, even when outside traditional specifications, highly cost-effective [4,5].

4. ENGINEERING GEOLOGY

Engineering geological characteristics are related to the basic geology, the geomorphology and the prevailing environmental conditions. The geological and geomorphological history of South Africa has resulted in a range of materials that produce significant engineering problems. These require early identification during the execution of projects and careful consideration in the engineering design.

It was noted in the early 1960s that many basic igneous rocks, particularly Karoo dolerites, performed well in certain areas and poorly in others [4]. Although the boundary between those materials performing well and poorly appeared to be linked to climate, none of the existing climatic indices discriminated between the two materials. This led to the development of the N-value [4], where a value of 5 differentiated between regions in which material decomposition to form smectite clays (montmorillonite) predominated ($N < 5$) and disintegration predominated ($N > 5$). Additional relationships between the formation and breakdown of other clay minerals at N values of 1, 2, and 10 were developed. This was used as the basis for defining the behaviour of basic igneous rocks.

Subsequent investigations indicated that all geological materials in South Africa could be subdivided into ten groups, in which the materials within each group, when assessed in relation to the climatic N-value, had consistent weathering and performance properties.

These groups are:

- Decomposing rocks
  - Basic crystalline rocks
  - Acid crystalline rocks
- Disintegrating rocks
  - High silica rocks
  - Arenaceous rocks
  - Argillaceous rocks
  - Carbonate rocks
- Special groups of rocks
  - Diamictites
  - Metalliferous rocks
  - Pedogenic materials
  - Soils

This classification is based purely on the engineering geology/performance of the materials and is independent of the geological origin or genesis. The performance of the materials within each of the groups in roads has been extensively described and the relationship of the durability of the materials within the groups to climatic N-value developed [4].

5. SPECIFIC PROBLEMS

As a result of the geological and geomorphic past, one or more of various engineering problems related to road design and construction prevail over most of southern Africa. Early awareness of these problems and appropriate counter-measures can save significant time and costs during road construction projects. All of these problems have been fully described in many publications and in this paper are only introduced for awareness with limited referencing. An intensive review will produce many tens of references on each topic.

5.1 Rapid Weathering Dolerites

The alteration of basic crystalline materials to smectite clays during the weathering process and the effect of these expansive clays on the performance of the materials is an international problem, which has warranted extensive research. In South Africa, many of the dolerites and basalts of the Karoo Supergroup were subjected to deuteric alteration (caused by a residual hot volatile phase in the cooling lava) during their crystallisation, resulting in the formation of smectite clays [6,7]. Conventional durability testing does not always identify the potential of such basic crystalline materials to degrade in service and considerable research has been devoted to appropriate test methods.

There is no doubt that the immersion of samples of basic crystalline materials containing smectite in ethylene glycol results in accelerated degradation. Various test techniques using ethylene glycol have been developed, however, no test accurately quantifies the breakdown and durability of the material as a road construction aggregate. No specification relating the performance of a material to the glycol durability (breakdown) results has been developed.

In the interim, it is recommended that any basic crystalline material is subjected to the Durability Mill Index test [8] as well as soaking of a representative sample of the plus 19 mm aggregate in ethylene glycol be carried out. Any breakdown of the material in the ethylene glycol after 7 days should preclude use of the material as a surfacing aggregate and in excess of 10 per cent breakdown should preclude its use as an unstabilized base course aggregate.

5.2 Expansive Clays

Advanced weathering of basic crystalline materials results in the formation of highly expansive black clays (often called cotton soils or turf). Many other materials including mudrocks, tillites and varvites of the Karoo Supergroup and various transported soils are also potentially expansive. A wide area of South Africa is thus susceptible to subgrade problems resulting from expansive materials.

The state-of-the-art regarding expansive soils generally was fully documented in 1985 [9] and a recommendation pertaining to low volume roads specifically was prepared in 1988 [10]. Although a limited amount of research has subsequently been carried out in this field, few new developments are being implemented.

The recognition of potential problem materials is usually based on visual evidence of the area and adjacent structures, past experience, basic indicator tests, maps and observation of the soil profile. Many techniques are available for the prediction of the likely heave, most of them giving disparate predictions. As a result, more than one technique is usually used and a likely predicted heave based on the results proposed.

Testing to predict heave may be based on both disturbed and undisturbed samples. The latter would generally be considered to give a better result but the samples tested are generally too small to represent the soil profile adequately and no sampling technique will produce a totally undisturbed specimen. The natural variability of soil materials and moisture movements in the soil is such that accurate modelling of these is very difficult. Nevertheless, double oedometer tests can give good estimates of the likely heave when designed and assessed by experienced engineers.

Assessment of heave based on the testing of undisturbed samples typically relies on standard indicator tests. Many methods and models have been developed both locally and internationally. Van der Merwe [11] developed a heave prediction method based on indicator test results and depth factors to account for the increasing overburden pressure with depth. This is probably the most commonly used method but must be interpreted with caution.

Brackley [12] developed the following model for the potential swell (in %):

$$\text{Swell} = (5.3 - 147e/PI - \log_{10}p) \times (0.525\,PI + 4.1 - 0.85W_o)$$

where e = original void ratio
p = external load (kPa)
W_o = original moisture content
PI = plasticity index of whole sample

Weston [13] later developed the following heave prediction model, specifically for roads:

$$\text{Swell } (\%) = 0.000411(w_{LW})^{4.7}\,(P)^{-0.386}\,(w_i)^{-2.33}$$

where w_{LW} = weighted liquid limit of whole sample
P = total vertical pressure (kPa)
w_i = initial moisture content (%).

Although the models are in many respect similar, as discussed earlier, the estimation of moisture contents and assumptions such as the uneven equilibration of moisture at different depths all introduce problems. However, by assessing the results form the different models, a realistic estimation of heave for design purposes can be obtained.

The two most serious problems related to expansive subgrades under roads are:
- Differential heave
- Longitudinal cracking associated with seasonal moisture variations

The former problem typically results from variations in the quality and depth of expansive material and is often associated with leakage at culverts and/or ponding adjacent to the road. A now almost routine practice is to partially remove the expansive material (typically 600 to 750 mm depth) and replace it with a more stable material. Other techniques [10] utilised include the use of a pioneer layer (100 to 200 mm of permeable sand, gravel or rock fill), pre-wetting, the application of impermeable membranes or combinations of these. Various countermeasures to minimise differential heave at culverts have been proposed [13], predominantly related to ensuring that leakage does not occur from the culverts and ponding is minimised by ensuring good side drainage that is well maintained.

Longitudinal cracking is best minimised by flattening side slopes along the road, typically using the subgrade material that was replaced by the more stable imported material.

5.3 Collapsible Soils

Collapsible soils are those that can withstand relatively large imposed loads with small settlements when dry but undergo a decrease in volume (at the same load) when wetted up [14]. This is typically the result of the material being composed of a framework of hard quartz particles with adhering colloidal coatings [15]. The addition of moisture results in weakening of these coatings and collapse of the soil structure. Where these materials form the subgrade of roads and are not specifically treated to remove or significantly reduce the collapse potential, trafficking of the roads under poorly drained or excessively wet conditions can result in rapid and severe rutting. It is also not unusual for severe differential settlement of roads to occur when a collapsible subgrade becomes saturated, solely under the load of the fill and pavement structure.

Many transported soils and residual granitic and sandstone materials are collapsible (other soils may occasionally also have collapsible structures). These materials need to be timeously recognised. Unlike expansive materials, the presence of collapsible soil structures is not easily evident from the indicator test results. However, silty or sandy soils with a low clay content and plasticity are likely to be more prone to collapse than more clayey, plastic materials although this "rule" is not exclusive. Collapsible soils often have a low bulk density (900 to 1600 kg/m^3) but other materials with high bulk densities could collapse and not all low-density materials do collapse. Typically single or double oedometer tests are required to identify potentially collapsible soils as highlighted in a state-of-the-art document prepared in 1985 [14].

Various methods to remove the collapse potential from potentially collapsible subgrades have been utilised, but essentially heavy compaction of the wet material is necessary. Many of these collapsible materials, however, are present in arid areas where it is often not possible or too costly to apply the required quantities of water to the collapsible materials. I these cases, the rolling should take place during the wet season where timing permits. The use of high energy impact compaction can obviate the need for this water as has been utilised on various projects in South Africa [16] and Botswana [17].

5.4 Dispersive and Erodible Soils

Although local problems related to the use of dispersive materials in dams are widespread in South Africa, their impact on roads is relatively small. However, localised problems have been encountered where piping and tunnelling adjacent to and beneath roads has resulted in the need for significant maintenance and repair.

Dispersive soils contain clays with high exchangeable sodium percentages, which allow the fine (colloidal) fraction to go into suspension in pure water (due to high surface electrical repulsive forces). This material can then be removed from the soil in flowing water leading to the development of channels. The process and associated problems have been fully described by Elges [18].

Dispersive soils should be differentiated from purely erodible soils, which lack the cohesion to resist the flow of water over the surface. The surface manifestation of the two problems is very similar, but erodible soils seldom show any internal piping or tunnelling, unless associated with the flow of water along old roots in the soil mass.

The identification of these materials requires careful chemical testing of the exchangeable cations backed up by laboratory testing using the pinhole test [18]. One particular highly dispersive material investigated by the author showed none of the typical test results related to sodium ions. However, a lithium bearing mica (lepidolite) was observed in the area and a high lithium content in the residual soil was determined – as lithium is even more active than sodium, this was identified as the cause of the problem.

Dispersive soil subgrades and its use in fills should be avoided as far as possible. Where this is not possible, treatment with a small amount of gypsum (0.2 to 0.5 per cent) can be beneficial. As high a degree of compaction as possible should be applied in order to minimise the permeability of the material.

5.5 Soft Clays

The geomorphological history of South Africa (resulting from the fluctuating sea-levels) has resulted in wide lagoon environments with deep channels where many of the larger rivers meet the sea. These channels reflect the past stream locations as well as the flood plains and are often filled with thick deposits of very soft clays. These clays typically have plasticity indices between 20 and 35 per cent and in situ moisture contents in excess of their liquid limits [19]. Undrained shear strengths seldom exceed 25 kPa. The materials are highly compressible (m_v between 1.0 and 2.0 m^2/MN).

The construction of high-class roads in the coastal areas necessarily requires high fills across these estuarine deposits, with the concomitant settlement and low subgrade bearing strengths. Site investigations thus require accurate delineation of the soil profile, identifying drainage paths, high quality "undisturbed" soil sampling and good laboratory testing. Inevitably, construction needs to be programmed to permit incremental fill construction and loading of the subgrade allowing time for pore water dissipation, prior to the next layer being constructed. The pore-water pressures are monitored using piezometers. The use of drains to accelerate consolidation has also been used.

Differential settlement is often a problem and needs to be assessed, as does the stability of the fill against deep-seated base failure [20]. These clays also have a major impact on water-crossing structures, which need to be placed on piles, often founded at significant depths.

5.6 Dolomites

Various dolomite and limestone formations have been deposited in southern Africa over geological time. These vary in extent and thickness but the Malmani Dolomites of the Transvaal Supergroup cover wide areas of the central portion of South Africa, where they are up to 1900 m thick [15].

Typical of carbonate rocks (karst terrains), the Malmani dolomites can be dissolved by atmospheric water (a weak carbonic acid solution) resulting in the formation of dolines, sinkholes and highly irregular sub-surface rock/soil interfaces with high pinnacles approaching the surface [15,21]. These obviously result in significant founding problems for structures although, provided potential sinkhole and doline areas can be identified, precautions during road construction (avoidance is the best) can be taken.

Identification of potential sinkhole problems is still difficult, with gravity techniques currently being the most useful other than direct methods such as core logging and profiling.

Various guidelines have recently been produced for the development of townships on dolomitic areas [22] and these should be used as a basis for designing roads in these areas.

5.7 Slope Stability

The stability of excavations or cuts for roads is an international problem. In the interests of economy, the volume of the cut is usually minimised, resulting in as steep a slope as possible. Typically, the natural slope is in the equilibrium state for the prevailing or worst past geological, topographical and climatic regime, and any modification of this can result in unstable conditions. The conditions in South Africa are similar to those occurring internationally, although the thin soil profiles generally prevailing in South Africa typically result in more complex types of failure [23].

Most deep cuts in South Africa will be predominantly in partly weathered to fresh rock and the stability will thus be joint (or bedding plane) controlled. A good knowledge and experience in carrying out and interpreting joint surveys is essential to

Prior to analysis of any slope, it is essential that the geological structure, the expected mode of failure, the appropriate material strengths and the expected water levels, sources and flow paths are adequately understood to ensure a stable and safe design [24].

6. CONCLUSIONS

The geological and geomorphological history of South Africa has had a significant impact on the local road construction industry. Many of the impacts are negative but a number of positive aspects have resulted in the ability to develop thin pavement structures using local material, the cost savings incurred probably being in excess of the extra costs involved in catering for the problem materials. It is, however, interesting to note that very few of the references relate to work carried out since 1990, indicating that the enormous amount of research carried out between the mid 1960s and late 1980s has not been followed up.

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- Technical audits of roads and forensic investigations
- Environmental impact assessments

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