TECHNOLOGY TRANSFER OF ROADS TECHNOLOGY (NANO MODIFIED EMULSION TREATMENT) TO ENGINEERED RAMMED EARTH HOUSE CONSTRUCTION

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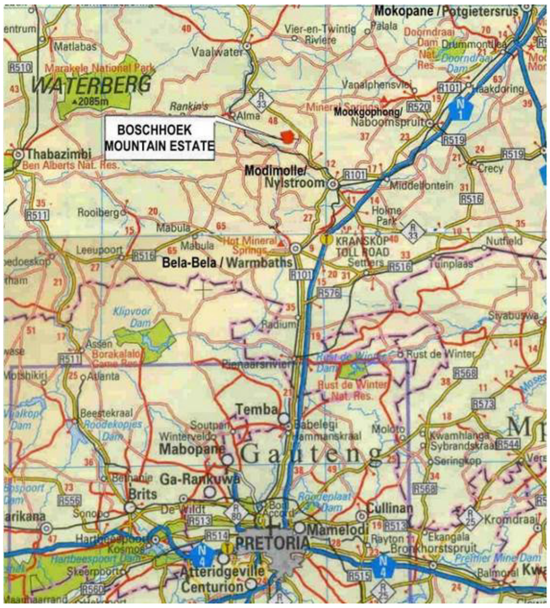
ABSTRACT

Rammed Earth (RE) is an ancient house construction technique which stood the test of time in various parts of the world. As the name indicates, it is literally built by compacting natural earth, soil and gravel between wooden plank shutter formwork forming the RE wall. The earth was traditionally compacted with hand tampers in succeeding layers of approximately 100 mm to 150 mm to refusal density in widths of 300 mm to 500 mm and even thicker walls. The parallel with road layer construction is obvious in the layer lifts of compaction and the compactive effort done at optimum moisture content (OMC). The only difference is this construction is done in successive layers compacted vertically between the boxed in shutter works. The vertical progression of such compacted layers forms the Rammed Earth (RE) wall when the formwork shutters are removed. This layered compacted earth wall forms a sturdy aesthetically pleasing ‘earthy’ wall structure. The wall is basically compacted to “refusal density”, thus being very solid and durable. The RE wall is a solid thick walled structure capable of significant load bearing and suitable for house wall construction. It has very good temperature and humidity control in the house due to the generally thicker walls than normally found in brick wall houses. In South Africa there is not a national guideline or SANS code for such house type construction. It is presented for acceptance as an engineered or engineered design per SANS definition. Australia upgraded their RE specifications and guidelines to include cement stabilisation of the rammed earth, thus resulting in an Engineered Rammed Earth (ERE) solution with obvious improvement in strength and durability. House building technology with a green footprint are promoted on Boschhoek Mountain Estate inclusive or mini wetland systems for sewerage, and mostly solar electricity, etc. Previously (2015), such an ERE house was designed and constructed to pleasing aesthetical standards and strength at half the cost of conventional brick-built houses. The latest roads stabilisation technology with Nano-silane in Nano Modified Emulsion (NME) and Nano Polymer Nano Silane (NPNS) offered an opportunity to replace the cement stabilisation. Various advantages with the Nano Silane were realised, inclusive of the desired water resistance, strength and encapsulation of clay particles or any deleterious minerals that would normally lead to the cracking of a road or such a cement-stabilised ERE wall panel. The technology transfer from roads to the house construction field is described and the end result or end use is clearly demonstrated meeting the end use specifications advocated in the new TRH 24 (2023) for gravel road upgrade to surfaced standards.

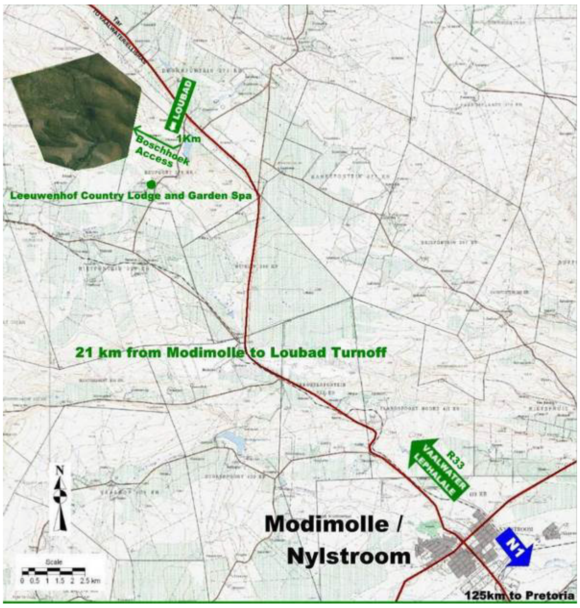
1. INTRODUCTION

1.1 Location

The Boschhoek Mountain Estate sanctuary is in a malaria free area approximately 22km northwest of Modemolle (formerly known as Nylstroom) in the Limpopo Province of South Africa. The location maps in Figure 1 indicate the position in a regional and local area context.



Provincial larger regional map



Local map Modemolle region

Figure 1: Regional maps identifying Boschhoek locality

Stands in this estate are typically 1 to 2 hectares in size and dwelling density was deliberately kept low by grouping a number of stands together with large undeveloped land in between. The estate development guidelines were designed to preserve, protect and maintain the unique environmental and physical attributes of the Waterberg biome on the estate. Green building designs and technology were promoted in these guidelines.

Owners were encouraged to make use of natural building materials and appropriate alternative building methods as far as possible as described in the developer guidelines and regulations. The intention of these guidelines is to blend all new structures into the natural environment. Architects interested and accredited in the design of structures in an ecologically sensitive environment are allowed to design the dwellings and strict enforcement of guidelines is practised to achieve these green footprint goals. In this paper, it will be shown how these green development "ideals" were met previously using Engineered Rammed Earth (ERE) construction (see definition later) of a village dwelling layout at Ox Wagon Trail. At that stage (2015) the technology transfers from the road building industry involved the use of cement stabilisation (6% to 10%) which provided a low cost and very "earthy" looking green footprint dwelling. This positive outcome subsequently inspired at least another dwelling to use this technology, but with concrete and steel frames, which largely negated the green footprint ideal. The Ox Wagon Trial ERE dwelling did inspire an American couple to request an ERE dwelling to be constructed at the Bataleur portion of Boschhoek. The new technology disruptor treatment involving nano-silane treatment was used to do the ERE walls on this dwelling at Bataleur, Boshhoek. This nano-silane treatment of the natural soil is a straight technology transfer from recent research and development in the roads industry. This paper describes this roads technology disruptor transfer also to the field of ERE home construction.

1.2 Physiograpic Background Information

The Boschhoek Mountain Estate has a predominantly mountain bushveld vegetation with grass Savanah in the open plains of the valleys and floodplains. The location of this stand is at the higher slope of a mountain and therefore considerable exposed rock out crops are visible. A number of large indigenous trees are on site with smaller bushveld type shrubs in between.

The local geology is indicated in Figure 2 as part of the larger Waterberg area geology. Corcoran et al. (2013) describe the area as quartz-rich with siliceous sedimentary material. The Alma and Swaershoek formations (see Figure 2) are underlying Boschhoek Mountain Estate. The Quartzite, Feldspar and Rock (QFR) fragments ratios are typically 80:7:13, therefore, as previously stated, very Silica(Si) rich. The geology of this local Boschhoek area varies between rock faces and outcrops of sandstone and diabase and considerable large strewn corner stone type in between the trees and on foothills. The local contours of the erf shows there is limited flat terrain as the general fall is 5% to 15% fall towards the northern direction. Large, exposed sandstone rock beds created the ideal place for placing foundations on rock in line with the “biblical advice” to rather build on rock than sand.

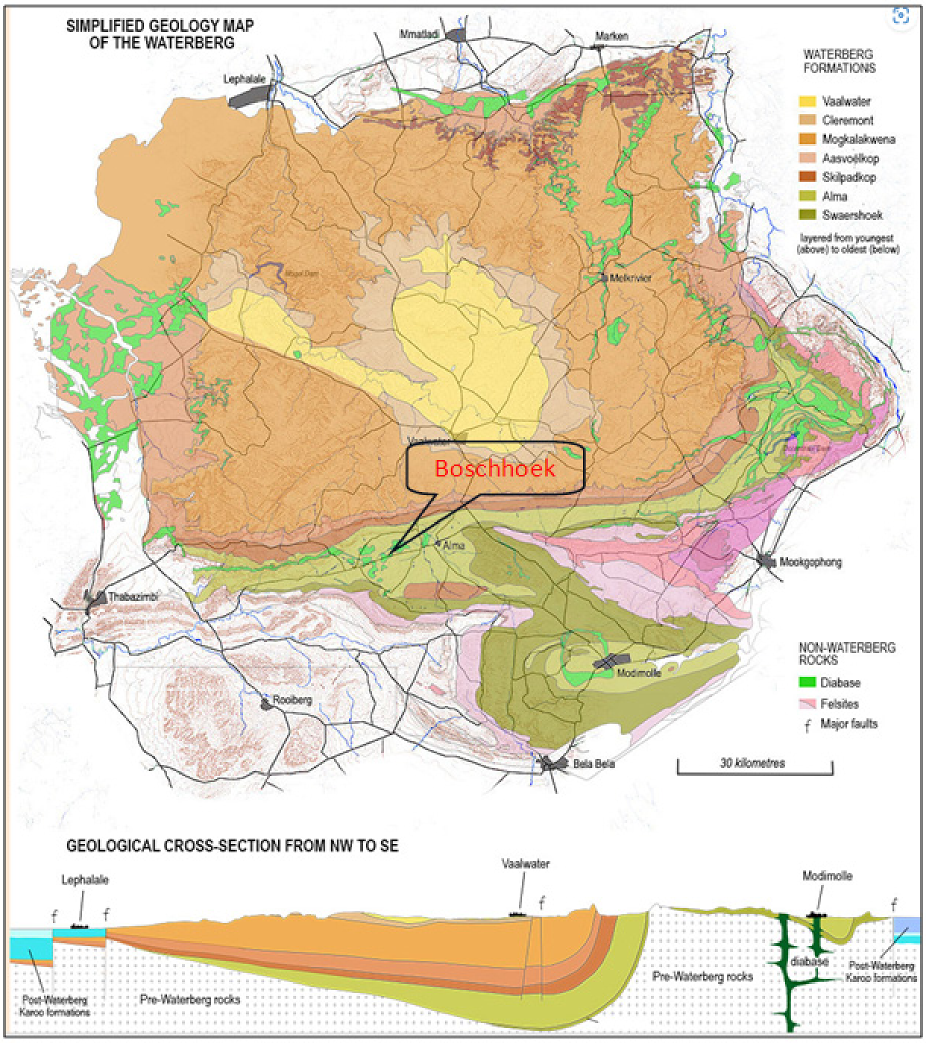


Figure 2: Waterberg geology with reference Modemolle-Alma

2. GREEN BUILDING DESIGN PRINCIPLES

The landscape and local environment directly influenced the design and layout. The slope and shape of the land at the Bataleur portion of Boschhoek were used as primary guidance in the layout of the buildings. Design in sympathy with local site conditions is one of the principles of 'green' building design (Maniatidis & Walker, 2003). The mountain slope on which the stand is, faces southwards. This is not optimum for the correct orientation of buildings in the southern hemisphere, but the building layout made maximum use of the eastern-facing side and the panoramic view the southern, western and eastern directions provide.

Maniatidis and Walker (2003) mention that a number of RE buildings follow the well-known original green-friendly design principles of Sthapatya Veda or Vedic architectural design. The purpose of Vedic architecture is to establish a harmonious relationship between an owner, a home, and the natural order of the universe. These design principles described above all form part of the basis of Sthapatya Veda design principles. East-facing entrances and exposure are strongly proposed in Sthapatya Veda designs with reference to the early morning sunrise. This was achieved with the main building to link with the outdoor living space of the deck, boma, and swimming pool. The northern main entrance and elevated roof area of the living area facing the southern side allows for maximum window exposure for light into the building and the panoramic view southwards down the valley below.

The development is, as already mentioned, off the grid which makes the use of solar energy with the use of solar panels a definite energy source. The large carport was deliberately oriented to have an inclined roof pitch sloping south to north and in length east-west. All Photo Voltaic (PV) sun panels for the off-grid energy supply were placed as roof cover on part of this north facing carport. All the west facing walls of all the buildings (including the carport battery room) are windowless to protect the buildings against the fierce western sunsets in the southern hemisphere. The extended deck areas enable seamless transfer between indoor and outdoor areas via large glass sliding doors and windows "hanging" from the Vierendeel steel girders spanning openings of up to 7 m. The main house portion has a large central living area with ensuite bedrooms on the western and eastern sides. A satellite village layout provides for the freestanding third and fourth bedrooms, placed separate and below the main building on the south-eastern side of the stand. These satellite buildings (bedrooms) also use the same orientation style and design principles described above. The result is all rooms or buildings have unobstructed south, west and eastern facing views towards the vista of the opposite valley and mountain.

3. RAMMED EARTH TECHNOLOGY

3.1 Background

Rammed Earth (RE) construction is part of the larger family of earth construction technologies (Stds Australia, 2002). RE walls are formed by compacting damp soil (in the roads industry this is defined as Optimum Moisture Content (OMC)) between temporary retaining forms (shutter boards and scaffolding formwork). Loose damp earth is poured into the shutter space in layers of 100 mm to 150 mm in successive layers and compacted. Compaction is done by hand with steel tampers or with compressed air type light weight mechanical tampers to basically refusal density. As soon as compaction is achieved on such a panel, it is dismantled and either extended up or linked to the side.

RE or Pisé construction has a long history in a number of countries, particularly where other traditional building material such as natural rock is not readily available. RE construction is practiced in North Africa, Australasia, regions of north and south America, China and Europe (particularly France, Germany and Spain and to a lesser extent the UK) (Maniatidis & Walker, 2003; Stds Australia, 2002). The original or older examples of RE were mostly constructed only with selected earth to provide a monolithic composition (Keable and Keable, 2010).

The advantages of RE are summed up by Bui et al. (2014): "*Firstly, using a local material (soil on site or near site), rammed earth construction have very low embodied energy. Secondly, rammed earth houses have an attractive appearance and present advantageous living comfort due to substantial thermal inertia and the 'natural regulator of moisture' of rammed earth walls*". These advantages are also confirmed in more detail by Minke (2006).

Lately, various stabilizer or modifier agents have been added to selected earth/natural gravels to provide more of an engineered material. Typical traditional stabilizing agents used are, cement, lime, bitumen and other proprietary chemical stabilizer agents. In Australia, cement is the stabilizing agent mostly added to improve the structural properties of RE (Stds. Australia, 2002) and should therefore be referred to as Engineered Rammed Earth (ERE) to make the distinction versus RE without stabilisation agents added. Earth as used in RE or ERE is a natural and universal building material and is offering a range of natural soil or earthy colours and textures of the completed sturdy looking walls.

RE/ERE dwellings provide pleasant interior living spaces. RE/ERE dwellings are characteristically cool in summer and warm in winter. Thermal resistance for a typical 300 mm thick RE wall is between 0.35 to 0.7 m^2 K/W (Maniatidis and Walker, 2003). RE /ERE construction is well suited for the owner builder as the basic material, earth, allows considerable scope for 'self-expression' in form (Stds Australia, 2002) and colour. The in situ casting and compaction avoid double handling of materials and within the earth construction family RE has a lower tendency for shrinkage cracks development due to material selection and high level of compaction (refusal density).

The standards and specifications of RE technology and construction are well-developed for developing or third world applications (Keable and Keable, 2010). In the first world (Walker et al, 2005 and Standards Australia, 2002) the ERE standards are also well developed. These references include detailed specifications on natural materials (RE) as well as modified or stabilized materials (ERE with engineered materials). No standards or specifications are yet available in South Africa, but the Australian Standards (2002) and the basis of the RE Zimbabwe standards, contained in Keable and Keable (2010), could be used as main guideline. The Oxwagen Trail dwelling (2015) was done as an ERE technology benefitting from the well-established South African road construction environment. The Home Building Manual (2014) of the National Home Builder Regulatory Council (NHBRC) as well as the National Building Regulations (NBR), as described in SANS 10400 Part A, allow for a competent person doing a rational design and evaluation as an accepted method of building regulation compliance.

3.2 Stabilised Rammed Earth

Lately, various stabiliser or modifier agents are added to the natural selected earth to provide more of an engineered material. Typical traditional stabilizing agents used are, cement, lime, bitumen and other proprietary chemical stabilizer agents. In Australia, cement is the stabilizing agent mostly added to improve the structural properties of RE (Stds Australia, 2002) and should therefore be referred to as Engineered Rammed Earth (ERE) to make the distinction versus RE without stabilization agents added. Earth as used in RE or ERE is a natural and universal building material and offers a range of natural soil or earthy colours and textures of the completed sturdy walls.

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3.3 Compaction of Rammed Earth

With ERE construction tampers or rammers (weighing 7 kg to 10 kg) operated manually, pneumatic or mechanically/electrically are used to dynamically compact the confined treated soil material. The vertical displacement or settlement of the compacted material transfers to shear and horizontal stress which is constrained by the sturdy shutter and scaffold system. The process and formwork system is diagrammatically illustrated in Figure 3 via a cross-section. Heavy compaction equipment such as for roads or trench reinstatement can not be used in ERE as it will bulge/destroy or deform the shutters and side forms. Great care must be exercised in the setup of the formwork to ensure no deformation or ‘kicking’ of the shutter boards happens during ERE compaction. Lower energy application, but higher repetitions of the dynamic compaction with the tampers or rammers on thinner layers of initial loose material also achieve high final density. Considerable road construction technology and knowledge could nevertheless be transferred to the adaption of ERE and some technological innovations could also be made to improve the end product.

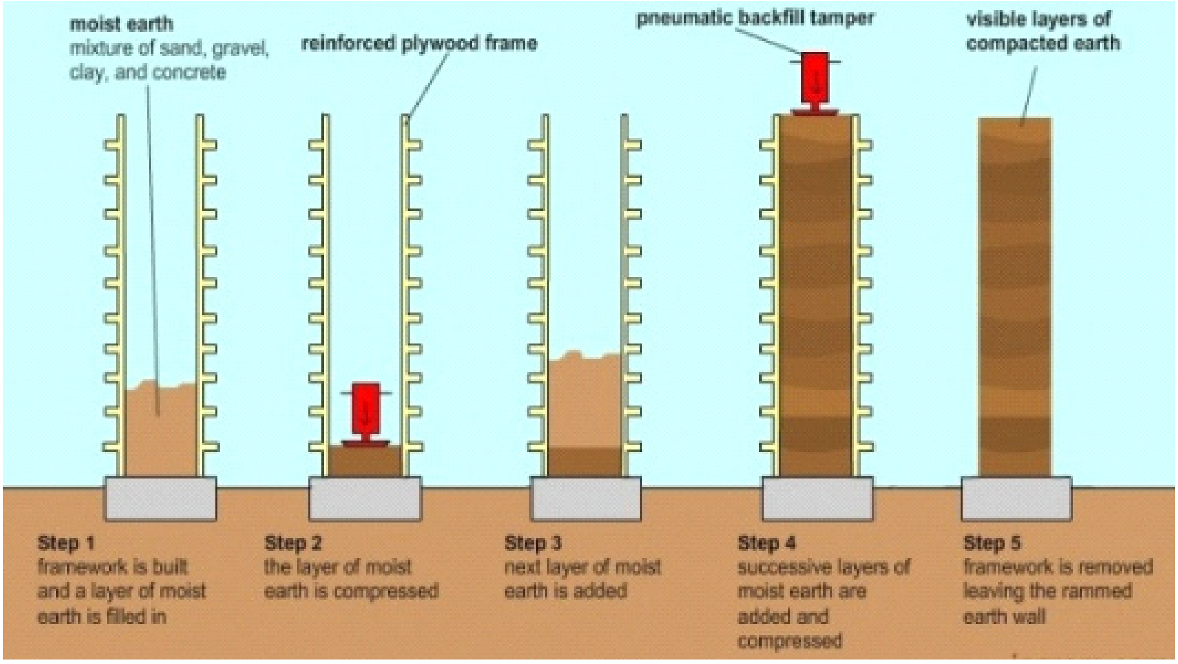

Figure 3: Illustration of RE construction with formwork and compaction of individual soil layers

4. LESSONS LEARNT FROM OXWAGON TRAIL DWELLING CONSTRUCTED WITH CEMENT STABILISED ERE

4.1 Impact of Variability of Material Used

Not all earth or soil can be used for ERE or RE. The soil or natural earth need to be selected and ensured that it is uniform in composition. Normal soil tests in the field and laboratory (Keable and Keable, 2010) are thus needed for such selection and preparation. The grading of soil suitable for RE/ERE is rather broad, but the ranges according to Stds Australia (2002) are as shown in Table 1. In Figure 4 various sand sourcing is illustrated by colour distinction of stock piles from various. In Figure 5, a close–up of the colour stratification is shown which can be achieved by using the various soil sources with different colour layers on the right-hand side of the image. This image also serves to show the scaffolding and shutter board system used on the left-hand side. The sandy soil found on site was analysed in Table 1 and did show low clay content and, therefore, low Plasticity Index (PI). However, other sand sources subsequently used did not have such low clay content and low PI.

The garage portion of the dwelling was constructed first as trial section. Wall lengths of more than 4 m (up to 7 m) were constructed as ERE walls. It included the corners linking another length of more than 4 m ERE constructed wall. This trial section showed that a wall length of 4 m should be the maximum as cracks tended to develop vertically in the ERE walls if longer than 4 m length. This was attributed to the variable sand sources clearly with higher fines content and with clay present. Cracks formed were filled with cement and sand slurry as it did not present any structural strength concerns. Adjustments to the length of wall panels were made for the construction of the main dwelling portion.

Brick pillars, as shown in Figure 6, were spaced at distances of 4 m maximum along longer wall sections. Such brick pillars were also placed at corners to overcome the apparent weak structural joint aspect at the corners. Not only did the brick pillars completely prevent cracking from re-occurring, but they also served to improve the linkage and bearing capacity of the roof structures. The shutter ply system used has also been fitted from a solid end anchor, making straight wall construction easier. A number of constructed dwellings in the Boschhoek Estate suffered from strong wind action lifting roofs. Therefore specific attention was given to anchorage via steel rods in depth of the brick pillars to prevent wind lift of the roof structure.

Figure 4: Different soil colours stockpiles with sieve to remove organic material

Figure 5: Colour stratification during construction.

Figure 6: Brick pillars with brick force shown as variation for end stops as well as door with sleeper planks around door frame before shutter work erection

The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were determined for local sand from the sand pit shown in Table 1 using the Modified Proctor density standard. The average MDD and OMC results for the Boschhoek site source are as follows:

MDD 1 870 kg/m^3 at OMC 10.3%

Even though Modified Proctor density tests are done for a reference value in RE material evaluation, in the roads industry Modified American Association of State Highway Officials (Mod AASHTO) density levels are specified. This provides for a higher MOD and a lower Optimum Moisture Content (OMC) as illustrated in Figure 7 due to the increased energy requirement. It was experienced on the Oxwagon Trail Dwelling that to compact ERE a higher density is in fact achievable as 'refusal density' was used as limit. Refusal density is achieved by using tampers with increased number of tamps (higher total energy) on thinner layers (100 mm) until the soil compacted in a confined space does not show any further downward settlement under continued tamping compactive effort. The principle of higher density hogging the Zero Voids line is illustrated in Figure 7 with increased density efforts. AASHTO Density has higher density than Standard Proctor as reference. A clear ringing noise can often also be heard when this density level is achieved (Keable and Keable, 2013).

4.2 Cement Treated ERE Strength Evaluation

4.2.1 Laboratory Designs

The Unconfined Compressive Strength (UCS) is a basic indicator of structural strength or bearing capacity of the RE. This test is used for natural soil and gravel samples as well as stabilised materials as it gives a basic indication of bearing capacity. Maniatidis and Walker (2003) refer to other sources for UCS characteristic values ranging between 0.4 to 0.7 MPa for a normal unstabilised RE material.

Cement stabilisation is used in Australia in proportions of 4% to 12% by mass. Material handling and mixing is very similar to that of stabilised pressed block manufacturers (Stds Australia, 2002) and as pointed out before road soil stabilisation. One representative Boschhoek sand sample cement stabilised at 5% by mass was tested. The cement used was Afrisam 32.5N and the single cement content was chosen to serve as reference value to gauge against the Australian experience and range of UCS values.

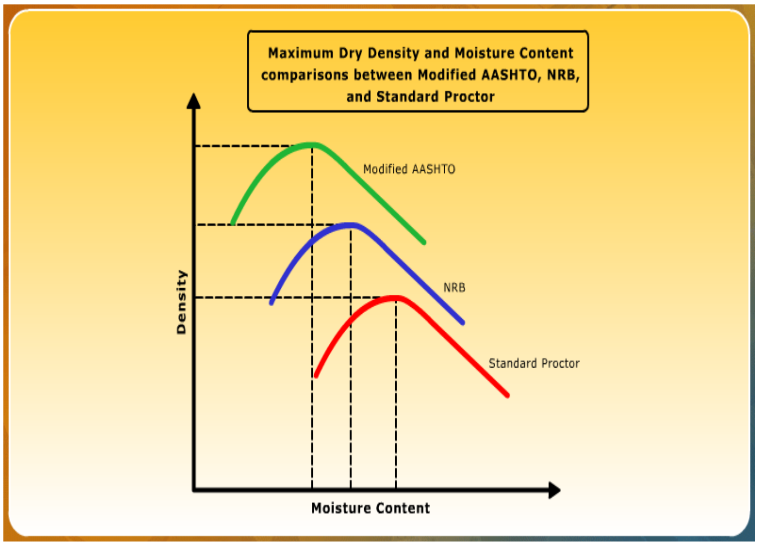

Figure 7: Density versus moisture curves for various compactive efforts

Table 1: Summary Soil Mortar Analysis

Fraction Description	***Size description (Keable and Keable, 2003)***	***Stds Australia specification Percentage passing***	***Sand pit close to spruit area on Boschhoek***
Gravel	75 mm to 2 mm	Not applicable	Not applicable
Sand	2 mm to 0.06 mm	45% to 75%	83
Silt	0.06 mm to 0.002 mm	10% to 30%	10
Clay	0.002 mm and smaller	Up to 20%	6

The average indicator UCS value thus determined was 951 kPa (rounded off to 1 MPa). The dry compressive strength UCS range prescribed by Stds Australia is between 1 and 15 MPa for cement stabilised RE construction. Thus 5% cement will only reach the lowest Australian value specified. It is therefore clear that more than 5% cement had to be used. It was thus decided to use closer to 10% cement addition for the Boschhoek material, which will clearly reach UCS values well within the specified range.

The initial UCS value of 1 MPa nevertheless means that at 5% normal cement the UCS value already provided for a typical C4 material classification as per the TRH14 (1987), normally associated with a road subbase type construction material class and quality description. As stated earlier cement stabilised RE is in effect successive C4 or preferably C3 layers constructed on top of each other in a confined space between the shutter formwork to form a solid wall. The difference is that road C4 is achieved by using a G6 (TRH14) material minimum. While the soil used in ERE may be as low as G7 or even a G8 soil/sand gravel material. It is clear, like concrete, the ERE is relying on the compressive strength of the ERE and not the tensile strength at all (Bui et al., 2014).

4.2.2 Field Strength Evaluations

Even though Keable and Keable (2013) describe a number of easy to do layman's type soil tests to determine the basic material properties, the material tests were done in an accredit SANAS soils laboratory to provide credible factual data for design decision making. As-built type tests used in ERE construction are mostly basic as coring and sampling will tend to destroy or disfigure the works. Such tests are therefore not conducive to actual quality control during construction. The indirect compressive strength test apparatus promoted by Keable and Keable (2013) has promise, but this apparatus is not readily available in South Africa and is only applied on a wall once completed and stripped of shuttering. The whole wall section is then often already completed if layers not meeting specification in between can pose a serious practical problem of rehabilitation or whole wall rejection.

The Rapid Compaction Control Device (RCCD) (de Beer et al., 1993) was originally developed for non-material experts to accommodate proper trench reinstatement practice in the road or road reserves (Horak, 1994; Horak et al., 2014). The operation and detail of the RCCD apparatus are illustrated in Figure 8 where the spring-loaded steel shaft with a conical point is pulled and released three times successively into the compacted RE. The resultant penetration can be read with a mounted side ruler. Penetrations after 3 blows typically vary between 10 mm to 100 mm. The penetration achieved is in fact an indication of in situ shear resistance which is correlated with bearing capacity also determined with the better known Dynamic Cone Penetrometer (DCP) and values of California Bearing Ratio (CBR) (de Beer et al., 1993).

The RCCD is used basically as a non-destructive test method directly on top of a compacted layer between the side formwork still in place. The RCCD can be used to do repeated and accurate measurements of penetration after the prescribed three successive "shots" of the pointed shaft. CBR values can be derived from the laboratory derived correlations. The application here is to determine the average penetration rate in terms of mm/blow to be able to determine material class. The typical TRH 4 summary type material classification derived from the TRH 14 is shown in Table 3 (de Beer et al., 1993).

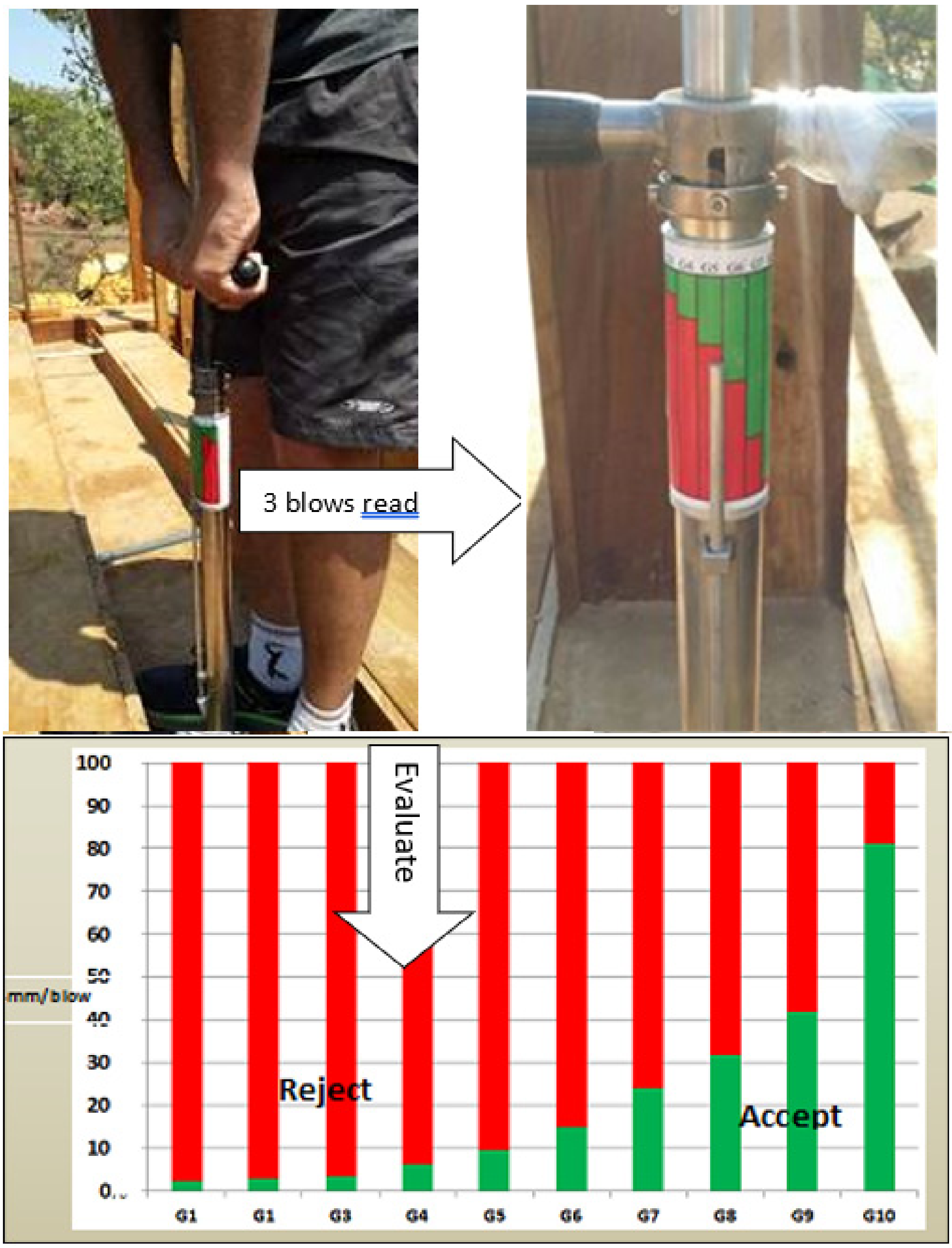

Figure 8: Demonstration of RCCD pull and shoot (3X) with a simplified colour evaluation chart on the outer cylinder shown below

As illustrated in Figure 8 the RCCD fits easily between the shutters and on top of the 300 mm wide compacted ERE layer for quick and easy evaluation. In order to use the RCCD effectively a reference value directly after compaction should be determined. It had been stated that the hydration process of cement in a cement-stabilised material will increase the CBR and UCS values over time. Therefore, directly after compaction, the bearing capacity must meet a minimum value associated with the material class based on its CBR value at MDD. The layer evaluated directly after compaction can be regarded as at its weakest. Typically the cement stabilized ERE is rated as an equivalent G6 or G7 layer directly after compaction. After a few days allowing for curing the RCCD testing rated as an equivalent G4 of C4 layer based on penetration rate (mm/blow). There was therefore sufficient strength gain after curing of the ERE walls.

Table 3: Material class rating by means of RCCD penetration rate (Source de Beer et al.,1993)

TRH14 code*	Brief Description	CBR range description as per TRH14 (%)	RCCD Penetration rate (mm/blow)
G4	Natural and crushed gravel with specified grading	More than 80	Less than 6.3
G5	Natural gravel with specified grading	More than 45	Less than 9.7
G6	Natural gravel	More than 25	Less than 15
G7	Natural gravel	More than 15	Less than 24
G8	Natural gravel or soil	More than 10	Less than 32
G9	Natural gravel or soil	More than 7	Less than 42
G10	Natural gravel with specified grading	More than 3	Less than 81
C3	Cement stabilised gravel	UCS of 1.5 to 3 MPa	3 to 1
C4	Cement stabilised gravel	UCS of 0.75 to 1.5 MPa	5.8 to 3

*Only natural gravel materials shown plus cement stabilised natural gravels.

5. NANO-MODIFIED EMULSION AS AN INNOVATIVE SOIL STABILIZER

5.1 Introduction

Recent research and associated use of new-age (nano) technology in road-building material applications have opened an alternative method of cost-effective stabilization or road-building materials. This subject area is recognized and supported by the latest SANRAL research project on Alternative Materials Technology or Soil Stabilisers' use of Nano sized particles in road design and construction. This new technology is classified as a technology disruptor in terms of novelty, type, and impact. It is currently in the process of technology implementation and technology transfer and has been included in the new Committee Draft TRH 24 (2022 and update 2023) dealing with the Upgrading of Gravel Roads to Paved Standards. The New-age Modified Emulsions (NME) are specified in TRH 24 as an end-use Committee of Transport Officials (COTO) format specification. NME use in road materials is in the early stages of implementation on a number of provincial and SANRAL road projects.

5.2 Nano-Modified Emulsion Background

Nano-silane products have been developed, tested and are used in the built environment to protect stone clad buildings in Europe since the 1860s. Initially lessons were learnt from protection of natural stone clad buildings and had now been successfully transferred to the road building environment. Jordaan and Steyn (2020) describe the implementation of these scientifically proven technologies to protect and improve naturally available granular materials for use in the design and construction of roads (Jordaan et al, 2023 and Horak et al, 2024).

The traditional approach to the use of materials in road building makes use of historically developed empirically derived international engineering standard laboratory tests. Materials are classified according to various strength and durability aspects in standards developed such as described in TRH 14 and in SAPEM. These material classification systems mainly aim to ensure that the presence of secondary minerals (which is the result of chemical decomposition of the primary minerals) that could be harmful to the performance of these materials in roads and pavement structures in the future, is kept to a minimum or restricted to prevent distress development.

Traditional stabilisation agents such as cement and lime are reactive in their bonding nature which typically leads to material behaviour challenges such as cracking and or crushing. This also often leads to premature failure in roads. These types of distress can often be associated with the mineralogy of the material and release of the potentially deleterious secondary minerals such as mica, montmorillonite, smectite, etc. which have negative effects on the strength and behaviour of such road building materials, particularly in the presence of water and with traffic loading combined.

Available and applicable nano-technologies can enable the utilisation of even lower quality natural gravel and soil materials (e.g. California Bearing Ratio (CBR) ranging between 10 to 45 (G8 to G6 in Table 3)) at a low risk in pavement structure performance. Nano-technology can substantially reduce the unit costs of road infrastructure if it can be modified/stabilised for use in the pavement layers and structure with improved bearing capacity and moisture resistance. Organo-functional nano-silane technologies have the ability to neutralise the presence of potentially harmful secondary minerals in materials. Through the application of a material compatible reactive nano-silane a chemical reaction can be activated with each material particle to change the surface characteristics to become hydrophobic (water repellent) and prevent the possible negative impact of secondary minerals on the performance of the road building material. See Figure 9 demonstrating the hydrophobic characteristic of briquettes when treated with NME.

Figure 9: Demonstration of water phobic characteristic achieved with nano-silane treatment (Jordaan & Steyn, 2020)

The traditional technologies used in road stabilisation (cement, lime and even bitumen) are often ineffective with lower quality granular material (e.g. G7 to G9 in Table 3). Such lower quality materials tend to have large percentages fine and very fine particles. The latter tend to have high percentages of clay fraction (less than 0.075 mm). In effect the stabilisation agent particles are often too large for the small particles of the clay fraction for good and permanent bonding. Ideally, the specific area of the particles to be bound together should be matched by the specific area that can be covered by the stabilising agent. With materials containing a grading with significant percentage of clay (< 0.002 mm in size) the stabilising agent should have a grading to match the increase in the area to be covered, creating a stable environment within the material. The nano scale size of nano-silane technologies enables the cost-effective linkage with such finer particles in soils and natural gravels. Thus such secondary mineral rich clay size particles can be "encapsulated" and covered by the nano-silane particles and thus prevented from exhibiting material weakening behaviour when such materials are exposed to water.

Nano-silane in itself is not effective, nor is it normally used as a stabilising agent alone. The nano-silane particles are literally too small to bridge the gaps between the granular particles of the road-building materials. Hence it is used as a modification to a material-compatible stabilising agent (bitumen or equivalent polymers) in an emulsion form to "permanently" attach the stabilizing agent (with larger particle size) to the road-building materials to form a highly flexible durable material in layers within the pavement structure. The relatively small size of the nano-silane particle (depending on the type of nano-silane and the quality of the product the size of nano-silanes) may vary from about 5 nm to less than 1 nm which results in a considerably high surface area per volume ratio. This implies a relatively small amount of the nano-silane is required to totally encapsulate all particles of the granular material (stone/gravel/soil) that is being treated/stabilized (for example, 1 l of nano-silane could easily have the same coverage area of 1 000 l of bitumen – with a normal bitumen emulsion produced particle being in the order of 1 000 to 5 000 nm in size).

The key to the use of nano-silane technologies in natural road/pavement building material is to do a more fundamental testing and evaluation of the proposed natural gravels or soils. The primary and secondary minerals are determined through X-Ray Diffraction (XRD) scans. The use of the XRD analysis also ensures the percentage Si in the gravel or soil is determined. Nano-silane forms a very strong permanent bond with the Si. These more fundamental minerology composition evaluation combined with basic engineering tests such as compressive strength, tensile strength and durability (assessing the hydrophobic effect achieved with the modified stabilising agent) are done to ensure the risk profile in terms of the road pavement category is managed over the known design period.

5.3 NME Specification

Recent Accelerated Pavement Testing (APT) and documented research and case studies have contributed to the development of NME specification as included in the new committee draft TRH 24 (2023). As will quickly be observed on investigating the NME specifications is that this NME specification is in effect "piggybacking" on the TG2 specifications developed for Bitumen Stabilised Materials (BSMs). The NME-treated material is evaluated with Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) tests, just like for cement, lime, or BSM designs.

In the normal road design practice for stabilised materials using cement or lime C3 and C4 materials are used. They are constructed using higher quality natural gravels (e.g. G5 and G6 for C3 and C4 respectively) to achieve strengths. The NME material range (NME 1, NME 2, NME3 and NME4) largely coincides with the C2 to C3/C4 quality on a comparative basis. The source materials for NME are including lower quality natural gravel materials

(G7 down to G9) which may otherwise be classified as marginal or substandard. They would not normally be allowed to be used for cement stabilised materials as excessive percentages of cement would be required (6% to 10%) with significant risk of cracking development or crushing. However, the same marginal natural gravels and soils can be treated with NME to achieve Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) values on par with C3 and C4 cemented materials, but without the risk of crack development.

In the new TRH 24 (2022/23) the concept of end use specifications are used. It specifies Retained Compressive Strength (RCS), which is UCS_{wet}/UCS_{dry} expressed as a percentage. It also specifies Retained Tensile Strength (RTS), which is expressed as ITS_{wet}/ITS_{dry}, expressed as percentage. RCS and RTS are thus durability parameters which improves the durability risk management. UCS wet and ITS wet values are used as the minimum criteria for a material to be reached before the design process or refinement is to proceed in the laboratory.

6. NME DESIGN FOR ERE WALL CONSTRUCTION

6.1 Introduction

The fact that NME provide strength gain similar to cement stabilisation on the same strength range as a C4 and a C3 in general (expressed as UCS and ITS values), but stays flexible and encapsulating deleterious minerals (e.g. clay particles), makes it an ideal stabilising agent to use in ERE design and construction. It is water phobic and therefore does not crack as the deleterious minerals are encapsulated. These clay mineral arresting aspect have significant durability improvements with NME treated ERE versus the previous cement stabilisation ERE described before as used on Ox Wagon Trail dwelling.

The mountainous area and associated topography of the bataleur dwelling site makes logistics to get building material on site a major issue. Various sand from sources outside Boschhoek therefore became a logistics nightmare. In this case a sand pit close to the Bataleur dwelling site could be utilised which helped with the transport and logistics issues. Rehabilitation of the sand pit formed a major part of the right to use this soil/sand source for the ERE construction on the Bataleur dwelling. The downside is that the colour stratification obtained for the Ox Wagon Trail dwelling could not be repeated at Bataleur dwelling due to the single soil/sand source.

6.2 NME Design for Bataleur ERE

The sandy soil source was evaluated as a G7 quality material. It is thus in the ideal range of material which will show significant benefit with NME stabilisation as demonstrated in Figure 4. As mentioned before the modern approach advocated with NME designs is to do a XRD of the material source. The XRD basically determine what the Si content is as this is the mineral with which the Nano-silane forms a permanent strong chemical bond. It also determines whether any secondary potentially deleterious minerals may be present. Based on the indications from the geology indicating very high Si content (80% and more) via the QFR ratio. Thus no XRD testing was done and soil/sand samples from site was tested at the GeoNano laboratories in Germiston. Confidence was also gained via the previous use of the similar sand source at the Ox Wagon Trail dwelling. In that case it was cement stabilised ERE.

The limited sample provided enabled the determination of the MDD and OMC. Their values were respectively 1 998 kg/m^3 and 8%. An NME application of 0.8% RNP type NME resulted in a wet UCS value of 2.9 MPa. The wet value rates potentially as good as a NME1. It was decided to also spray the completed ERE surface with an enrichment Nano-silane seal afterwards. The mix prepared was a ratio of 1 l NME with 10 l water. Assuming a 50% moisture content in the soil/sand a robust recipe mix for the site was developed. Typically 300 ml of the NME mixture was used on a 20 l plastic bucket of soil/sand. Additional water was added to ensure moisture content is at Optimum Moisture Content (OMC) or just below that. The sample squeeze in hand and dropping advocated by Keable and Keable (2013) was used to further evaluate on site. Subsequently the ratios were upscaled for a typical wheelbarrow of sand as basis for the mixing ratios.

Note in the case of the bateleur ERE construction Nano-Polymer- Nano-Silane (NPNS) was used with the emulsion being transparent polymer and not the bitumen Modified Emulsion. The NPNS was chosen specifically to ensure the natural earth colour will be seen and no blackening due to the bitumen in the bitumen emulsion. Therefore the generic reference to NME here implies NPNS.

7. BATALEUR ERE CONSTRUCTION WITH NPNS

The NPNS type NME treated ERE construction on both Ox Wagon Trail and Bateleur was done by unskilled labour. The site is also difficult to reach as explained by the logistic issues discussed before. In Figures 10 to 17 the ERE construction process is demonstrated in phases. Additional description is added to the Figures to read like a photo story. A few rigid methodology rules or recipe measures were implemented to ensure the actual NPNS-treated ERE walls on site can be constructed without any problems. These measures and processes are as follows:

1. The carport/garage functioning as the solar panel housing, inverter, and batteries was used as a trail project to perfect the other measures.
2. ERE panels less than 4 m in length were used throughout with brick and steel pillars framing the panels. The battery and inverter strong room was the only area where the height of up to 3 m panels was constructed. All the other panels at the front end of the carport were kept at a height of 1.2 m. This height is the shutter board marine plywood width making it easy to assemble and disassemble.
3. RCCD measurements could be taken during construction as well as after the shutter work was removed to confirm the strength gain after at least 48 hours curing period showed an equivalent strength of a G4/G3 or a C3/C2 equivalent material strength based on penetration rate of the RCCD.
4. The dwelling has a mixture of three brick-width pillars (400 mm x 400 mm). Thus wall panel lengths were largely determined by the pilar and brick wall sections. The spacing of the lengths of the latter brick wall and pillar sections was also largely determined by the spacing of the roof structure. Specially designed Vierendeel Steel girders were designed to give the roof structure a thin and sleek appearance by incorporating the timber or wooden planks within the Vierendeel girder and not on top as is normal with steel and wood beams. These Vierendeel steel girders were placed on these equally spaced brick wall sections. Wood planks or beams could thus also be extended to longer lengths with shorter spacings in between. Typically bathrooms were constructed using brick for obvious reasons related to services. In such cases the wood beams could be carried additionally with brick wall support as well as the Vierendeel girders.

5. The result of all this spacing is that most of the ERE panels were 4 m or less in length. They also ended up as 1.2 m in height on the outside walls. Lessons learnt from the Ox Wagon Trail showed the windows can hang from the steel girders or steel ring-beams at the top to increase the window areas significantly and overcome the issues with ERE construction over lintels or sleeper beams experienced at the Oxwagon Trail dwelling before.
6. There were at least two walls on the southern front which are in length just over 6 m, but 1.2 m in height. No cracking was observed on such longer walls confirming the crack resistance of NME treatment
7. Only the higher wall panels in the central living area had wall heights approaching 4.5 m, but widths approximately 4 m. None of these larger ERE wall panels showed any form of cracking.

	**Figure 10: Hand mixing of NME and water** Thorough hand mixing of soil/sand to ensure uniformity before placing if inlayers between the formwork.
	**Figure 11: Formwork setup using brick work as solid reference** Placing the marine plywood formwork in progress. The steel beam vertical kicker is already brought in place against which the horizontal evenly spaced planks will kick and outsides of plywood also get drawn tightly against brick wall and pillars.
	**Figure 12: Scaffolding and formwork from inside** Short ERE wall section between brick pillars at 1.2 m height to the left is a completed ERE wall. It is uniform in appearance and already cured and hard.

Figure 13: Higher panel construction

ERE wall construction of battery room at carport. Length below 2 m and height 3 m plus. Observe marine plywood formwork supported with thick horizontal planks evenly spaced from bottom to top. These planks in turn kick against steel beams used as pillars. Three brick width walls and pilar both sides add to solid formwork.

In foreground the soil mixed by hand with the correct volumetric proportion of NME is observed. The homogeneously mixed NME is handed upwards to be placed between the plywood formwork and compacted by hand

Figure 14: Removal of formwork

Two recently completed NME stabilised ERE walls. Below 4 m length and 1.2 m height. Removed marine plywood in foreground after 2 days. ERE walls appear smooth and hard.

Figure 15. Surface treatment application

Clearseal NPNS surface spray application done with hand spray to ensure surface hardness and water resistance are enhanced.

Figure 16. View from the south showing completed low height ERE panels

Vierendeel girders placed for low profile roof. Placement is in brick wall sections for adequate load transfer and linkage to steel reinforcement in brick pillars for wind uplift prevention. Open areas in between to be filled in with ERE walls with heights up to 4.5 m and width also approximately 4 m in length

	**Figure 17: View from south of carport with completed ERE wall panels.** Car port with short (less than 4 m) panels with 1.2 m height done as trial first. Part of carport roof is solar panels over the battery room on the left. Roof slants from back to front south to north for optimal sun exposure.

8. MAKING LOW VOLUME ROADS EROSION RESISTANT

It is well known that low volume traffic roads are prone to environmental distress more than vehicular distress causes. The Boschhoek Mountain Estate is true to its name located in the Waterberg Mountain range. It is hilly and basic gravel/earth roads often suffer from erosion and washaways. As mentioned before the Bataleur section is particularly mountainous causing major logistics problems. Long trucks could not be considered for deliveries of building materials, even when the roads were not washed away. Part of the problem are the measures used to prevent erosion on the roads. Typically earth humps are spaced over the steep gradients to dam up against and to be diverted via mitre drains on the side to daylight in the veld. On steep gradients these humps are placed at short distances and the result is this reduce speed even further of delivery trucks. Only short wheelbase trucks with large enough engines could be used. The nature of such humps is illustrated in Figure 18.

The Co-author experimented with Polymer treatment of natural soils on the access road to Oxwagon Trail before. This was done by hand with a water can applied polymer solution, levelling with a rake and tamping providing compaction. This road withstood erosion due to seasonal rains and functioned remarkably well. It was therefore logical to experiment with the NME on the Bataleur access road for the obvious reason of improving the logistics issue. For the Oxwagon Trail access road the humps were removed over a short trail section with steep gradient. The material was worked into the surfacing and treated with NME again via spraying can, spades, rake levelling and compaction via tampers. The completed trail section is shown in Figure 19, smoothed out without the hump. The obligatory test of water repellence was done as shown in Figure 20 as proof of effect. After seasonal rain the same section was visited during the rain and as shown in Figure 21 water flowed over this section without erosion evident.

	**Figure 18: Typical water erosion protection hump.** These earth humps are linked to side channels (mitre drains) diverting water from the earth/gravel surfaces. The steep gradients cause significant acceleration of the water sheet flow on the road resulting in erosion after seasonal rains.

	**Figure 19: Scene where hump was removed** The hump was removed and earth worked into levelled out road surface. The earth/gravel surfacing was treated with NME. All work was done by hand and tampers as per ERE construction used for density.
	**Figure 20: Water repellent demonstration** After construction proof of water repellent nature of the NME treated earth surfacing is demonstrated with water running down gradient without sinking into the earth
	**Figure 21: Proof of water erosion resistance** Image taken during seasonal rains show the clear water resistance allowing water to flow on the surface without erosion taking place

9. CONCLUDING REMARKS

The use of NME technology for use in and engineered wall construction with local earth/sand to form an ERE constructed wall panel was described. It is clear the same technology used for stabilised lower quality earth and soil in road construction can be used for ERE wall construction. It was shown that the same design approach and procedures can be sued. Strength determination in the field can be done by means of the RCCD. Prior experience with the successful cement stabilised ERE construction at Oxwagon Trail provided significant practical lessons learnt. Brick columns and interspaced walls provide good limitation to ERE wall section lengths as well as solid anchoring of the sturdy scaffolding and formwork needed for the ERE construction. The ERE provides for a very earthy and natural soil colour with good aesthetic appeal. ERE panels at the Bataleur dwelling could be constructed to longer lengths and heights due to the characteristic of NME treated soils not cracking.

Previous experimentation with a standard colourless polymer on the access road of Oxwagon Trail dwelling proved the gravel preservation and erosion resistance concept. It was thus logical to upscale such labour intensive road surface construction on the feeder road to Bataleur section of Boschhoek. The steep gradients of roads in the mountainous section leading up to Bataleur are protected against regular washaways and erosion using high earth humps and mitre drains. A short trail section was done by hand removing the speed reducing hump and treating the section with hand worked in NME. The result shows a water resistant erosion protected surface.

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