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Title: **"Sustainable Use of a Bauxite Residue (red sand) as Highway Embankment Materials"**

Sustainable use of a Bauxite Residue (red sand) as Highway Embankment Materials

ABSTRACT:

Disposal of bauxite residues by stockpiling is an economic burden for the alumina industry. In this study a by-product from bauxite residue Red Sand was stabilised by the addition of red lime (another by-product alumina refineries) and fly ash (a by-product from coal fired power generation). Investigations were then conducted to evaluate the potential use of the stabilised red sand mixture as a highway embankment material.

Our findings show that

1) the optimum stabilisation mixture was 75% Red Sand, 10% red lime and 15% fly ash (dry mass).
2) the improvement in strength was due to both mechanical and lime stabilisation.
3) for embankment heights less that 15m a slope of 2H:1V or flatter is acceptable for Red Sand alone, while a slope of 1H:4V or flatter meet the stability requirements for stabilised Red Sand..

This stabilisation of those industrial by-products for an embankment material can provide a sustainable reuse option in alternative to current stockpiling practices.

1.0 Introduction

The production of alumina by the Bayer process results in bauxite residue having a high pH and requiring long term impoundment at significant cost. Sustained research has resulted in the development of by-products produced to a standard. One potential product is coarse bauxite residue that is neutralised by carbonation and washed to low levels of salts. This product is here termed Red Sand.

While Red Sand may be suitable as construction fill, further stabilisation is required for use in highway embankments. Pozzolanic stabilisation, which is a result of the mixing Red Sand with fly ash (the finest fraction of coal ash produced in coal power stations) and red lime (Another by-product from the Bayer process),was the treatment used to improve Red Sand in this investigation.

With the production of up to 15 million tonnes per annum of Red Sand, use in construction represents a significant development towards greater sustainability for the minerals and construction industries. Replacement of virgin mined products negates the ecological impact of such mining, while rescue of by-products from impoundment reduces that ecological footprint also. With all construction projects, transport is the key, so establishment of new resource locations (alumina refineries) results in potentially lower transport costs and associated green house gas emissions for the construction industry.

2.0 Objectives

The aim of this study was to investigate the potential use of Red Sand as an embankment material. Sand stabilisation was to be achieved through a pozzolanic reaction between lime and fly ash acting as a cementitious mass. The study was divided into three objectives;

1) Evaluate the optimum percentage of Red Sand, red lime and fly ash

An optimisation program was developed following an extensive literature review that determined the governing ratios that influenced stabilised soil strength. An optimisation program allowed the total number of tests to be reduced and allowed a more focused effort on evaluating the engineering properties of a single optimum mixture.

2) Evaluate the engineering properties of the optimum stabilised red sand mixture

A literature review was conducted in order to determine the most important engineering characteristics embankment materials were required to possess. These were gradation, specific gravity, moisture-density characteristics, shear strength, compressibility, collapsibility and permeability. Laboratory testing was then carried out to determine these properties in order to establish whether stabilised red sand is a suitable embankment material.

3) Undertake a theoretical slope stability analysis

A simple slope stability analysis was performed to investigate the stability of Red Sand and stabilised Red Sand embankments to determine stable embankment geometries based on laboratory results.

3.0 Laboratory Results and Discussion

The laboratory testing was subdivided into two programs. The first program experimentally determined the optimum ratio of Red Sand, fly ash and red lime. The second program evaluated the engineering properties of the optimum stabilised red sand mixture.

3.1 Lime Stabilisation, Optimisation Program

The objective of this program was to determine the optimum proportion of Red Sand, fly ash and red lime that produce the best engineering properties necessary for embankment design. The governing ratios that determine strength are the ratio of fly ash to red lime and the ratio of Red Sand to fly ash & red lime. The research flow diagram is shown in figure 1. At the optimum ratio, the mixture has its highest maximum dry density which means the strength resulting from the transfer of force through individual particles is at the maximum. Optimisation requires a complete reaction between the fly ash and red lime while providing enough cementitious mass to fill the voids and cover the sand particles.

Figure 2 demonstrates that the optimum ratio of red lime to fly ash was 1:1.5 by dry weight; this provided the highest measured UCS value. Figure 3 demonstrates that the mixture of 75% Red Sand, 10% red lime and 15% fly ash produced the maximum dry density indicating that it was the optimum mixture.

3.2 Evaluation of Engineering Properties Program

The purpose of the evaluation of engineering properties program was to determine the engineering properties of the optimum stabilised Red Sand mixture. Numerous different tests were conducted to evaluate the engineering properties that govern embankment design and construction, included herein are brief summaries of the three most important tests conducted.

3.2.1 *Californian Bearing Ratio Test*

The Californian bearing ratio (CBR) was conducted to determine the bearing capacity of the stabilised red sand mixture. The CBR value would indicate whether the stabilised red sand would be capable of resisting loads applied to it from the overlying pavement layers and imposed traffic loads. Figure 4 demonstrates that the stabilised red sand showed higher CBR values than both Bassendean sand and Red Sand.

3.2.2 *Multistage Triaxial Test*

The main objective was to determine the shear strength of the stabilised red sand mixture in order to allow a slope stability analysis to be conducted. Figure 5 demonstrates the stress-strain characteristics of the stabilised red sand from the multistage triaxial test. Based the Mohr-Coulomb failure law and the testing results, the drained shear strength parameters of stabilised red sand were apparent cohesion, c_d=48 kPa and internal friction angle, $\phi_d=47.5^O$. These results were a marked improved from the shear strength parameters for washed & carbonated red sand alone, $\phi_d=45^O$ and can be accounted by the higher dry density and the stabilisation process.

3.2.3 *Resilient Modulus Test*

The resilient modulus (M_R) test measures a soils resistance to cyclic loading. Higher M_R values allow materials to have higher resistances to cyclic loading which prevents excessive deformations that can damage the overlying pavement layers. The test was conducted because the top portion of a highway embankment acts as the sub base of a pavement and therefore it is imperative that there is sufficient fatigue resistance to prevent excessive deformations over the life of the embankment. The resilient modulus was determined for the stabilised red sand mixture, Red Sand and for a typical sub base material, (crushed limestone).Results are shown in figure 6. The stabilised red sand mixture exhibited resilient modulus characteristics that exceeds that of Red Sand and is close to that of crushed limestone. The high results were due to the cementation of sand particles which helped to resist the deforming strain resulting from the cyclic loading.

4.0 Embankment Design

The limit equilibrium method employed in the slope stability analysis was the Bishop's Simplified Method of Slices. A two dimensional slope stability program was written in excel to calculate the factor of safety and a solver function applet was written to determine the lowest factor of safety. The assumptions made in writing the program are listed as: (Figure 7 demonstrates the assumptions by using the programs output to illustrate them)

1. The foundation soil is sufficiently strong to support the embankment
2. Failure does not occur through the foundation soil (it is assumed failure will occur at the foundation and embankment interface)
3. The shape of the failure surface is circular
4. Failure occurs through the toe of the embankment
5. Duncan (1996) suggested that for embankments a minimum factor of safety value of 1.3 should be used, this was increased to 1.5 because peak friction angles were used rather than critical friction angles

The results of the slope stability analysis are shown in figure 8 and figure 9. As seen in figure 8, with a minimum acceptable safety factor of 1.5 the steepest acceptable slope for the red sand is 2H:1V. From figure 9, for any embankment height less that 15m with an acceptable factor of safety of 1.5, the steepest acceptable slope for the stabilised red sand is 1H:4V. The results clearly indicate that the stabilised red sand can have steeper embankment slopes than the Red Sand embankments due to the higher friction angle (from 45^O to 47.5^O) and higher cohesion (from 0 to 48kPa). This increased slope results in numerous economical benefits, foremost being the reduction in construction materials, which produces a cheaper design and secondly the reduction in embankment width which results in the reduction of land required to be purchased.

5.0 Conclusion

The following conclusions are made based on the literature review, laboratory testing and analysis:

1. The experimental program successfully found the optimum stabilisation mixture, which then allowed for focused and in depth engineering tests to be conducted.

2. There was a large improvement in strength with the addition of fly ash and red lime to the Red Sand. This was due to both mechanical and lime stabilisation. Mechanical stabilisation occurred due to the addition of silt sized fly ash and lime stabilisation occurred due to the pozzolanic reaction between the fly ash and red lime.
3. Limit equilibrium slope stability analysis of embankments with different geometries was performed to determine suitable slopes that satisfied the strength requirement. The results indicated that for embankment heights less that 15m a slope of 2H:1V or flatter for washed and carbonated red sand while a slope of 1H:4V or flatter for stabilised red sand meet the stability requirements.

Based on the results of this study, it appears that both Red Sand and the stabilised red sand mixtures are suitable for use in highway embankments, if proper design and construction procedures are followed.

6.0 Recommendations

It is recommended that research be conducted into the following areas:

1. Further tests should be conducted to determine what affect other parameters such as temperature, moisture content (wet and dry side of optimum) and compaction (90% and 95% of MDD) have on the optimum stabilised red sand mixture.
2. Further research needs to focus on correlating the laboratory test results to the field performance of the stabilised red sand mixture. An instrumented prototype test section should serve this purpose.
3. A detailed cost analysis should be undertaken to determine the feasibility of utilising the stabilised red sand as an embankment material. The cost analysis should include the material, construction and transportation costs of the soil.
4. Results from this study should be used to assist with a detailed sustainability assessment upon on the use of Red Sand in construction. Evaluations should look at the potential reduction in transport and mining energy consumption, the reduced ecological impact through reduction in residue storage and the reduced ecological footprint through replacement of virgin sand “fill*”. At time*

of press, such a review is being proposed at the Centre for Sustainable Resource Processing (CSRP) in West Australia.

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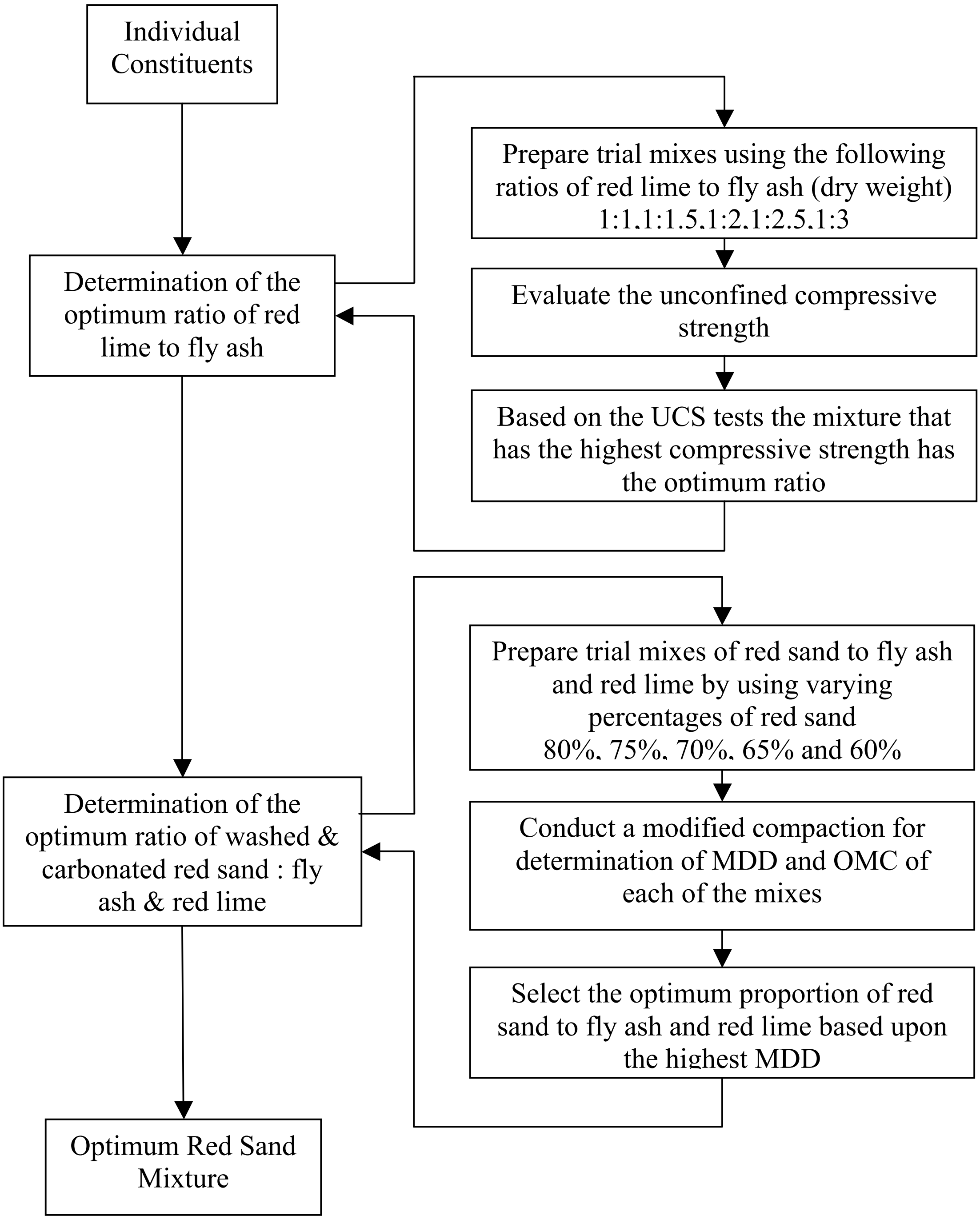

Figure 1 Flow Chart of the Developed Optimisation Program

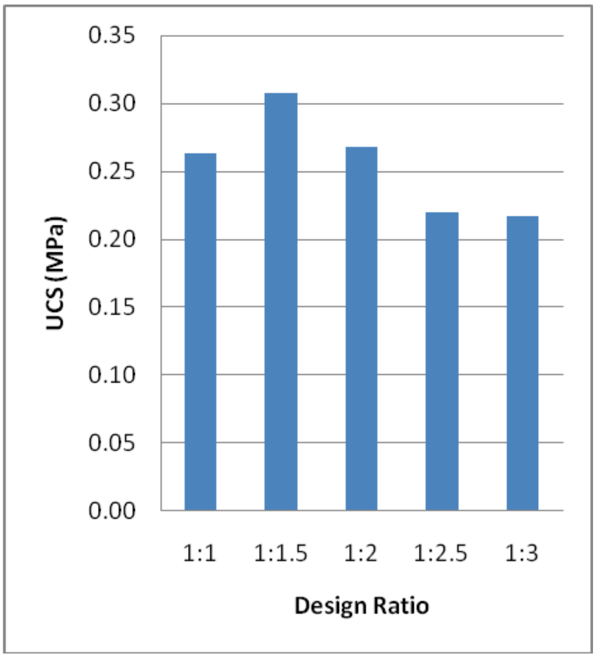

Figure 2 UCS Results for the Optimisation Program

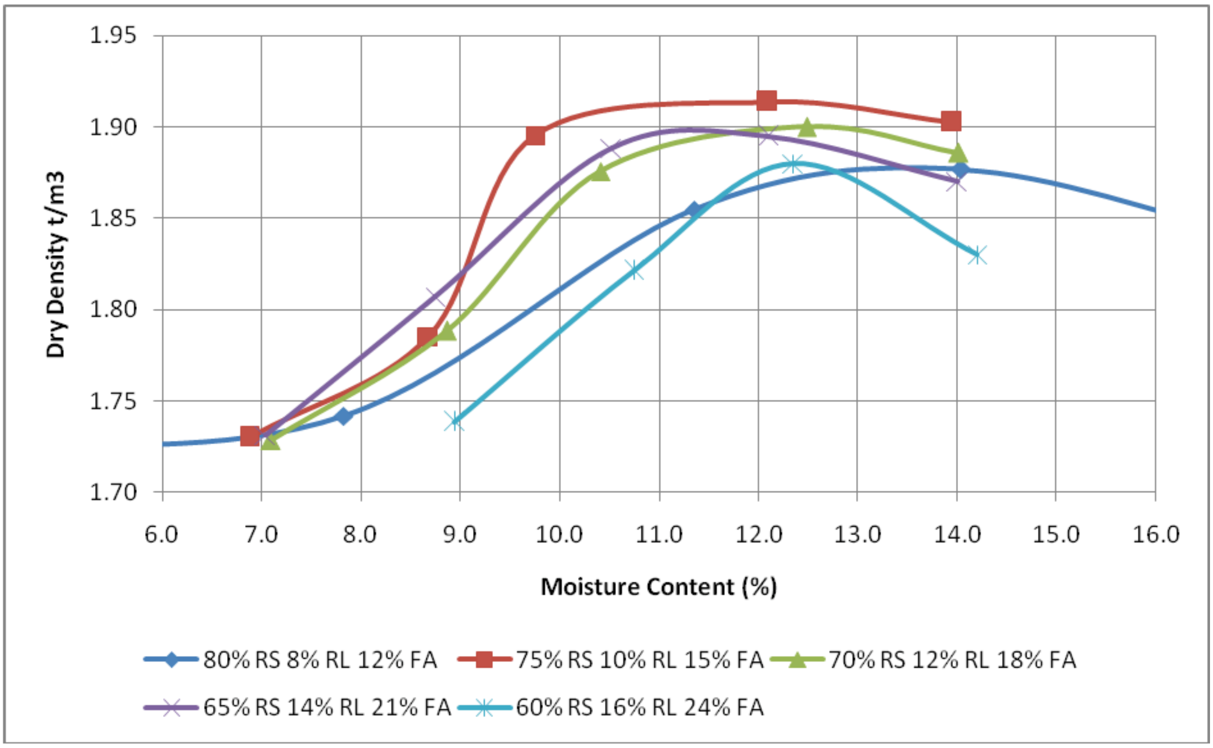

Figure 3 Dry Density versus Moisture Content Curves for the Optimisation Program

Legend
RS = Red Sand
RL = Red Lime
FA = Fly Ash

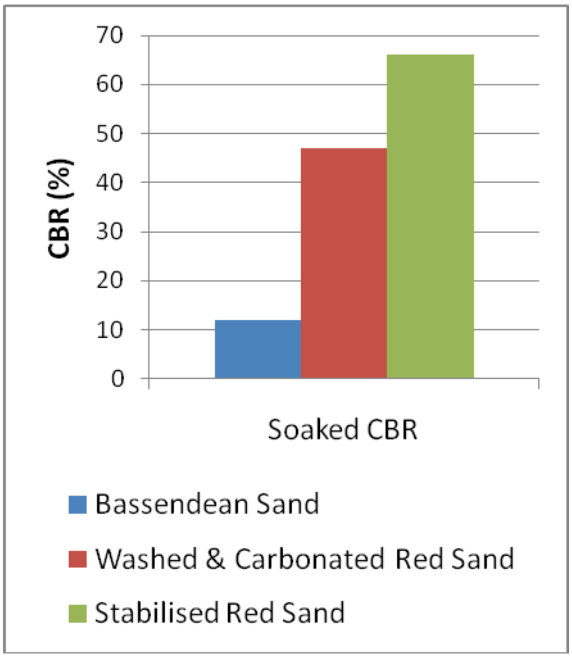

Figure 4 Californian Bearing Ratio Test Results

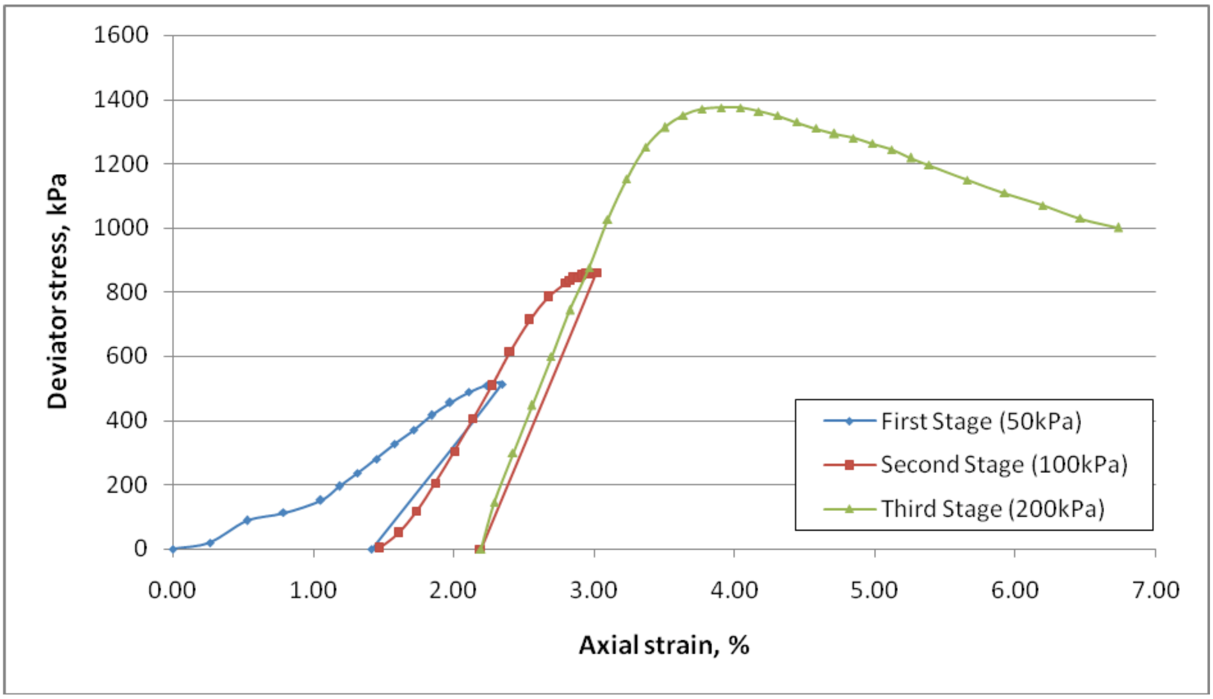

Figure 5 Multistage Triaxial Test Results

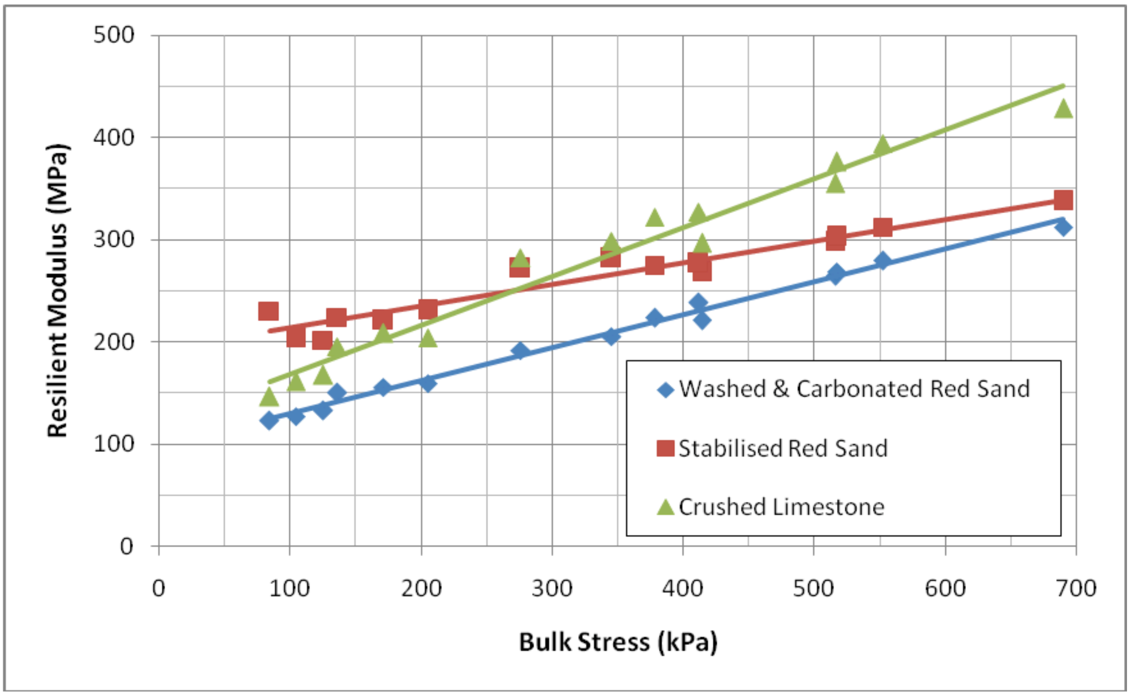

Figure 6 Resilient Modulus Test Results

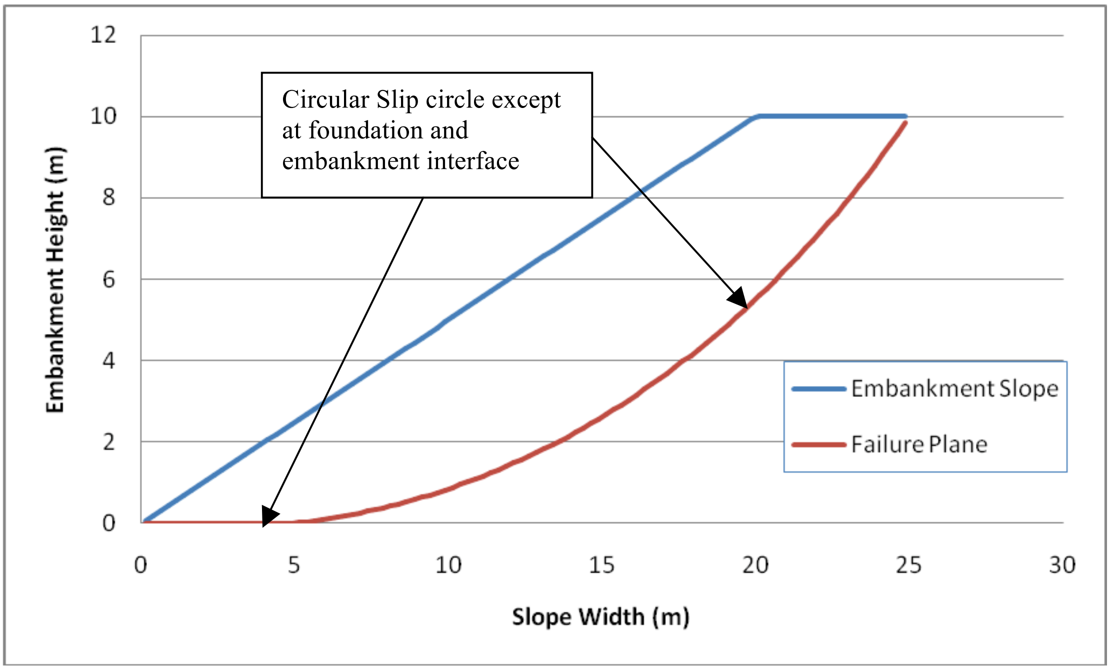

Figure 7 Graphical representation of slope stability assumptions

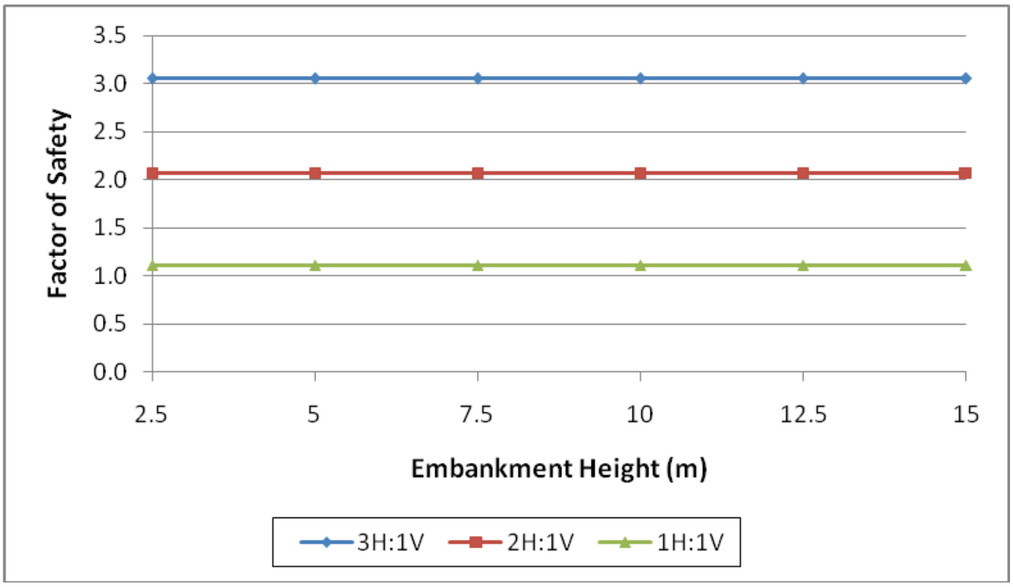

Figure 8 Red Sand Slope Stability Results

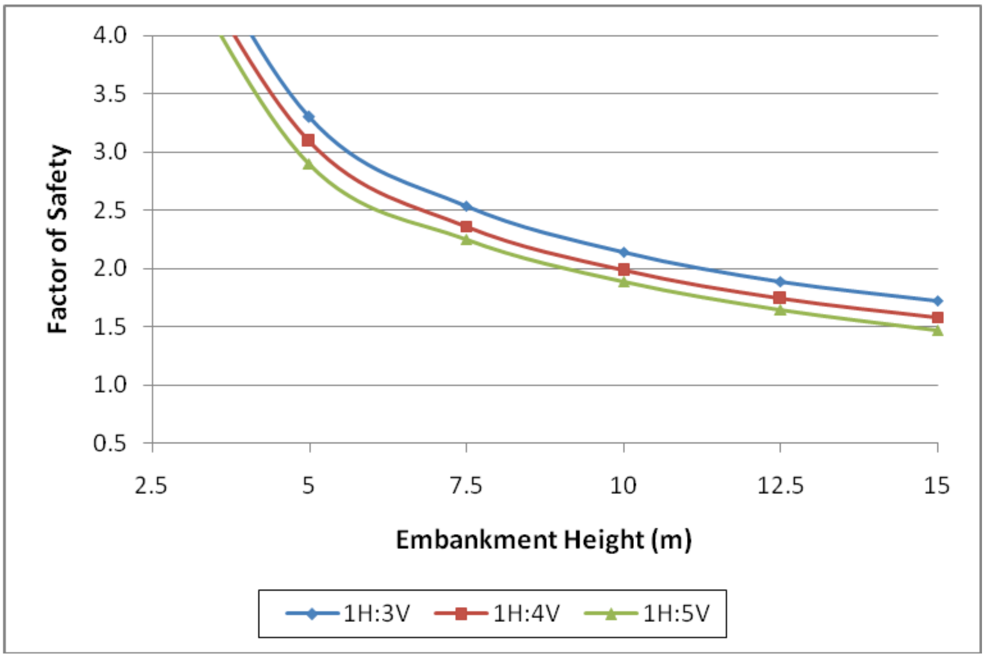

Figure 9 Stabilised Red Sand Slope Stability Results