

Title:

Coarse Bauxite Residue for Roadway Construction Materials

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ABSTRACT:

About 25 million tonnes of bauxite residue from alumina refining are generated in Australia each year. Managing this residue is costly, and the reuse of coarse bauxite residues is becoming an increasingly attractive and sustainable solution to the problem. Using coarse bauxite residue in road construction has the potential for large volume reuse. This study investigated whether coarse bauxite residue is a viable road base material in Western Australia. A pozzolanic-stabilised mixture was created to improve the properties of the residue, to satisfy the minimum requirements for road base. Laboratory tests for resilient modulus and permanent deformation were then performed.

Comparisons were made between the stabilised residue and conventional road base material used in Western Australia. The performance of the stabilised residue was superior to that of the conventional material, and can provide improved performance when used as road base material in Western Australia.

Keywords: bauxite residue; pozzolanic-stabilised mixture; fly ash; road base; resilient modulus; permanent deformation

1. Background

The aluminium and bauxite industry in Australia consists of five bauxite mines, six alumina refineries, six primary aluminium smelters, twelve extrusion mills, and four rolled product mills. From these, Australia produces about one-quarter of the world's alumina. Australia's alumina production is expected to be about 21.1 million tonnes in 2010–11, and the bulk of production is exported. These exports (approximately 17.3 million tonnes in 2010–11), are expected to generate revenue of \$6.68 billion in that year. Imports of alumina are negligible by comparison. The size of the local market for alumina, estimated at \$1.40 billion in 2010–11, is dwarfed by exports (IBISWorld, 2011).

Australia is also the largest producer of bauxite worldwide, accounting for about one-third of global output. Its bauxite production is expected to be about 68.0 million tonnes in 2010–11. Most bauxite mined in Australia is processed into alumina locally, but 7.5 million tonnes, valued at about \$171.9 million, is expected to be exported in 2010–11 (IBISWorld, 2011). In Western Australia, numerous bauxite deposits located

in the Darling Ranges south of Perth have underpinned the long-term development of the local alumina industry. Western Australia has four alumina refineries, located at Kwinana, Pinjarra, Wagerup, and at Worsley near Collie. In 2009, their combined alumina production was approximately 12.4 Mt.

Bauxite deposits in the Darling Ranges contain high levels of quartz, which creates a coarse residue fraction. This is unlike other bauxite deposits, which generally result in fine residues, called “red mud”. This unique coarse fraction has been called “*coarse bauxite residue*” in this study, and has a typical particle size in excess of 100 microns.

In contrast, the general form of bauxite residues from most alumina refineries is a fine residue called “*red mud*”. As a result, previous research into bauxite residues has usually only investigated the use of red mud. The physical, chemical, and mineral properties of bauxite residues from an alumina factory in China were studied (Zang et al., 2001). Its undesirable engineering properties were identified, and methods for storing, reinforcing, and using the red mud particular to that area were recommended. The study concluded that red mud could be used as roadbed material, as a silicate cement product, and as a silicate fertiliser (Zang et al., 2001). Another review of red mud (Paramguru et al., 2005) reported that the standard disposal practice was to discharge it into the sea or impound it. A number of alternative strategies have been developed to deal with the waste, including landfill, land reclamation, and specific uses such as building materials and inorganic chemicals. Economic evaluation of specific process strategies to recover valuable metals has depended on the specific composition of the red mud (Paramguru et al., 2005). An investigation of the mechanical and physicochemical properties of bauxite residue in the United Kingdom found that a red

mud storage facility could be considered for future rehabilitation and construction activity (Newson et al., 2006). Red mud has compression behaviour similar to clayey soils, but frictional behaviour closer to sandy soils, and appears to be structured with features consistent with sensitive, cemented clay soils (Newson et al., 2006).

In Western Australia, the most promising large-volume products from bauxite residue have been grouped into three types: Red Sand, ALKALOAM® (carbonated red mud), and REDLIME™ (solid lime residue) (Cooling and Jamieson, 2004). Alcoa has isolated the red sand (here the raw red sand is referred to as *coarse bauxite residue*), neutralised the residual caustic through carbonation, and washed it free of salt. Their initial report suggests this sand would be suitable as fill and for construction (Cooling and Jamieson, 2004). A preliminary study of the potential use of coarse bauxite residue in the construction industry as road base, embankment, and seawall fill materials was recently demonstrated (Jitsangiam and Nikraz, 2010). Curtin University has also reported the superior properties of concrete produced using coarse bauxite residue as the fine aggregate in concrete mixtures (Davoodi and Nikraz, 2009).

Using bauxite residue as a fill material is an attractive option, because a large volume of it is required in new development projects. Investigating this opportunity consequently became a collaborative research program with the Australian aluminium industry, led by Alcoa, The Centre for Sustainable Resource Processing (CSRP), various universities and institutes throughout Australia.

In this study, a soil stabilisation technique using pozzolanic-stabilised mixtures (PSM) was employed to improve the properties of raw coarse bauxite residue to meet roadway material specifications. The intent of this stabilisation technique was to use other by-products from industry in Western Australia as stabilising materials. A

pozzolanic-stabilised mixture consisting of fly ash (a by-product from coal power stations), and lime kiln dust as an activator (a by-product from quicklime manufacturing), was subsequently developed.

The significance of this study is that the research outcomes may reduce bauxite residues from the alumina industry by reusing a major waste product (the coarse bauxite residue). This would also create a new, large-volume source of construction materials as traditional sources decline. This could both reduce construction costs and provide an alternative choice for construction materials. Using these by-products of existing industrial processes would significantly contribute towards sustainability and residue reuse.

2. Materials

2.1 Coarse bauxite residue

The coarse bauxite residue used in this study was sourced from one alumina refinery in Western Australia. The basic geotechnical properties of the residue were characterised to evaluate the possibility of using it for engineering works. Specific gravity, particle size distribution, Atterberg limits, compaction characteristics, California Bearing Ratio (CBR) values, water conductivity, and shear strength were investigated and are shown in Table 1 and Figure 1.

The particle size distribution for the coarse bauxite residue is shown in Figure 1. The majority of the fractions lie within the defined sand particle size distribution (PSD), with a small fraction being defined as silt. The residue can be grouped in the soil group SP-SM poorly-graded sands mixture with silty soils, based on the Unified Soil

Classification System (USCS). A comparison between the bauxite residue and Perth yellow sand is also illustrated in Figure 1. The coarse bauxite residue particle size characteristics are very similar to that of Perth sand. Most fractions of both are situated within a sand range of 0.06–2.00 mm.

The particles shown in Figure 2 illustrate the different particle appearances of the coarse bauxite residue and natural Perth sand. The natural Perth sand is well rounded and frosted in appearance, whereas the particles of the coarse bauxite residue (formed by crushing larger mineral chunks) have sharp edges and corners. The surfaces are not striated, frosted, or etched.

Based on the geotechnical properties alone, coarse bauxite residue would appear to be a good fill material. The angularity of the residue particles provides the high shear resistance necessary for geotechnical engineering. However, road construction materials also have to resist the cyclic loads of vehicles moving in traffic. Coarse bauxite residue may have the potential to be used in road construction, if its fundamental properties can be improved to meet roadway specifications or be comparable with commonly-used roadway materials.

2.2 Fly ash and lime kiln dust

Class F fly ash (ASTM, 2000) was obtained from the Collie Coal Power Station. Its specific gravity was 2.03. Particle size classification indicated 17% clay, 68% silt, and 15% fine sand. The fly ash exhibited non-plastic behaviour and was grey in colour. The chemical analysis was 48% SiO₂, 29% Al₂O₃, 12.7% Fe₂O₃, 1.78% CaO, 1.67% TiO₂, and 1.69% P₂O₅. The fly ash pH was 5.5 and the loss on ignition at 1000°C was 1.61%.

Lime kiln dust was sourced from Cockburn Cement located at Kwinana. The composition was 59.46% CaO, 4.49% MgO, and 1.86% SO₃.

2.3 Cement modified-crushed rock base

Crushed rock meeting the Main Roads base course standard specifications (MAIN ROADS Western Australia, 2003), was obtained from a local Gosnells Quarry. 2% General Purpose (GP) cement (COCKBURN CEMENT, 2006) was added to the crushed rock to form a cement modified-crushed rock base, which is a commonly-used road base material in Western Australian roads. This was the reference standard for roadway material used for comparison in this study.

3. Pozzolanic-Stabilised Mixture (PSM)

Pozzolanic-Stabilised Mixture (PSM) (IBISWorld, 2011) is a soil stabilisation technique which is applied to stabilise the base or sub-base layer of pavements. A stabilised base or sub-base layer provides sufficient load-bearing strata to transfer the traffic load between the asphalt surface, which directly receives the wheel loadings of vehicular traffic, and the underlying subgrade soil. Stabilised base or sub-base materials may be used to provide support for either flexible or rigid pavements, but are more frequently used with flexible pavements. Coal fly ash, produced during the combustion of bituminous coal, is frequently used in stabilised base mixtures. Since this type of fly ash is a pozzolan, the mixtures in which it is used are often referred to as pozzolanic-stabilised base mixtures. Pozzolans are materials composed of amorphous siliceous or

siliceous and aluminous material in a finely divided (powdery) form (similar in size to Portland cement particles) that will, in the presence of water, react with an activator to form compounds possessing cementitious properties. Pozzolan activators are alkaline materials that contain calcium and magnesium compounds in sufficient amounts to chemically react in the presence of water with the silicates and aluminates in the pozzolan. In PSM compositions, fly ash is usually used in combination with either lime, Portland cement or kiln dust, with water, to form the matrix that cements the aggregate particles together.

4. Research methodology

The aim of this study was to use the pozzolanic-stabilisation technique (IBISWorld, 2011) to improve the properties of coarse bauxite residue for use as a roadway material. The research methodology in this study was divided into two parts.

The first part was to stabilise the coarse bauxite residue, using pozzolanic stabilised mixtures (PSM). The intent of this stabilisation technique is to use by-products from industry in Western Australia as stabilising materials. In this case, the PSM was a mixture of coarse bauxite residue combined with Class F fly ash (a by-product from coal power stations), lime kiln dust (a by-product from quicklime manufacturing), and water. The pozzolanic reaction creates bonds between material particles, leading to an improvement of the coarse bauxite residue properties. The optimum proportion of coarse bauxite residue, fly ash and lime kiln dust was determined by compaction and unconfined compressive strength testing of different mixtures. The objective was to establish the mixture that achieved an unconfined

compressive strength of between 0.6 MPa and 1.0 MPa (MAIN ROADS Western Australia, 2003), which is the optimum range for road base material in Western Australia. This optimum strength range avoids a rigid base layer which would result in fatigue distress on the asphalt surfacing. Details of the stabilisation process for coarse bauxite residue are shown in Figure 3.

The second part of the study was verification of the chosen mix. Commonly-used base course material which satisfies Western Australia Main Roads' specifications is crushed rock with 2% GP cement. This was used as the reference or control material. Samples were tested in a Repeated Load Triaxial Apparatus to determine their resilient modulus and permanent deformation characteristics, which represent the response of the material under cyclic loads. The method used was in accordance with the standard method of Ausroads APRG 00/33-2000 (Voung and Brimble, 2000).

5. Experimental work

5.1 Stabilisation of Coarse bauxite residues

5.1.1 Compaction tests

Modified compaction tests were performed on the coarse bauxite residue and fly ash mixture, with proportions of the coarse bauxite residue to fly ash of 90:10, 80:20, 70:30, 60:40, and 50:50, following the Western Australian Main Roads standard (MAIN ROADS Western Australia, 1997a). Pre-measured amounts of the coarse bauxite residue and fly ash were initially mixed slowly by mixing machine, and then water was sprayed on gradually. Once mixed thoroughly, the specimens were compacted (MAIN

ROADS Western Australia, 1997b) in a 105 mm diameter standard cylindrical mould, to determine the most dense mixture.

5.1.2 Unconfined compressive strength tests

The unconfined compressive strength is typically used to determine the quality of a mixture design in pavement engineering. The unconfined compressive strength test specified in the Western Australian Main Roads standard, WA 143.1, was followed using a strain rate of 1.0 mm min^{-1} . Tests were carried out on specimens consisting of varying mixtures of coarse bauxite residue, fly ash, and lime kiln dust (in various fly ash and lime kiln dust ratios, or lime:fly ash (LF) ratios, of 1:1, 1:2, 1:3, 1:4, and 1:5) that had been cured for seven days. Following ASTM C 593-95, the mixtures were compacted in a cylindrical mould 105 mm in diameter, 115.5 mm in height, and in five layers of an equal height, using a modified rammer to achieve a specific unit weight for specimen preparation. After compaction, the specimens were extruded with a hydraulic jack, sealed with plastic wrap, and placed in an oven at 38 degrees Celsius for a curing time of seven days. This procedure identified the maximum dry density and gave an optimum water content for the optimum ratio of coarse bauxite residue and fly ash. Figure 4 shows the sample preparation for the unconfined compressive strength tests.

5.2 Verification of stabilised coarse bauxite residues

The stabilised coarse bauxite residue was tested in a repeated load triaxial apparatus to determine its resilient modulus and permanent deformation, for comparison with the characteristics of conventional road base materials used in Western Australia.

5.2.1 Specimen preparation

All specimens were prepared based upon the optimum proportions of coarse bauxite residue, fly ash, and lime kiln dust, which had been established in the compaction and stabilisation stages. Mixtures were oven dried for 24 hours to accurately determine their dry mass, and allowed to cool before being mixed with the appropriate water content. The mixing procedure consisted of adding the optimum water content (based upon the dry mass of coarse bauxite residue including fly ash), into the coarse bauxite residue and curing for four hours. Fly ash and lime was then added in optimum proportions and the mix was mixed in the mixing machine for five minutes or until the mixture became uniform in colour and texture. It was then compacted, using a modified compaction method, in a standard mould 100 mm in diameter and 200 mm in height. Compaction was achieved with 25 blows of a 4.9 kg rammer at a 450 mm drop height in eight layers. To assure a good bond between the layers, each layer was scarified to a depth of 6 mm before the next layer was compacted. After compacting, the weight of each specimen and mould was determined, and the specimen was carefully removed from the mould. The specimen was reweighed immediately after removal from the mould, wrapped in plastic to prevent loss of moisture, and placed in a forced-air circulation oven maintained at 38 degrees Celsius for a seven day curing period.

5.2.2 Repeated Load Triaxial (RLT) tests

The standard method of Austroads APRG 00/33-2000 (Voung and Brimble, 2000) was followed for the resilient modulus and the permanent deformation tests. A UTM-14P digital servo control testing machine was used in the Geomechanics

Laboratory, Department of Civil Engineering, Curtin University as illustrated in Figure 5.

Permanent deformation testing was performed first. Specimens were cycled 10,000 times through three stress stages, each involving specific dynamic deviator stresses of 350 kPa, 450 kPa, and 550 kPa. All stages were conducted at a constant static confining pressure of 50 kPa.

Directly after the permanent deformation test, each specimen was then tested for resilient modulus, to check its elastic condition through multiple loading stress stages. This involved the application of another 65 stress stages of cyclic loading. This process simulates the complicated traffic loading acting on a pavement. Two hundred loading cycles of each stress stage were applied to the specimens.

6. Results and Discussion

6.1 Stabilisation of coarse bauxite residue

The first stage of coarse bauxite residue stabilisation was to determine the optimum proportion of fly ash.

Figure 6 shows the compacted dry density versus the water content curves for various mixtures. The results show that coarse bauxite residue (BR) and fly ash (FA) mixes achieve higher maximum dry density than their corresponding individual components. The highest dry densities were achieved with a fly ash content in the range of 20–40 %. Increasing the fly ash content to 50% caused a relative reduction in the maximum dry density. Studies of silty sands similar to these mixtures reveal that for a

low content of non-plastic silt (0–25%), the dry density increases with increasing fines content because the fines occupy the voids between sand particles. However, if the fines content exceeds 25%, there is a decrease in dry density (Kuerbis et al., 1988). For coarse bauxite residue, the addition of fly ash increases the dry density to a maximum at about 30% fly ash. We suspect that higher proportions of fly ash cause the coarse bauxite residue particles to separate, and fine particle interactions begin to dominate. For fly ash contents of 40% and 50%, the coarse bauxite residue particles are likely to be separated, floating in a fly ash matrix, hence the density decreases. From Figure 6, the highest dry packing density was achieved with 70% coarse bauxite residue and 30% fly ash (dry weight), with an optimum water content of 9.2%.

This optimum mixture was then used as a basis to determine the appropriate amount of activator (lime kiln dust) required. Mixtures with different levels of lime kiln dust were then tested for unconfined compressive strength (UCS).

All the specimens increased in unconfined compressive strength with curing time, as shown in Figure 7. The results clearly show that increasing the ratio of lime kiln dust from 1:5 to 1:1 diminished the unconfined compressive strength. Western Australia Main Roads have a specification for UCS of between 600 kPa and 1000 kPa at a curing time of seven days. LF ratios of 1:5 and 1:4 achieved this specification, with the lower content of lime kiln dust favoured, for practicability of handling.

Based on the results of the compaction and unconfined compressive strength tests, the selected mix for further investigation was 70% coarse bauxite residue, 25% fly ash and 5% lime kiln dust (dry weight).

6.2 Verification of stabilised coarse bauxite residue

Resilient modulus and permanent deformation were used as indicators in the verification stage, because both characteristics are significant to road performance. Successful pavement layers must exhibit high resilient modulus in order to spread load adequately and to reduce the resilient deformation of upper bituminous layers. The pavement must resist internal permanent deformation which might contribute to surface rutting (Dawson A.R. , 1993). The resilient modulus or stiffness of pavement structures is also a critical factor in determining the thickness and composition of pavement layers. It simulates the pavement behaviour under repeated loading, replicating traffic loading conditions. The permanent deformation of pavement materials is manifested as rutting and shoving, the visible damage on the road coming from excess deformation of the pavement. This is caused by the pavement material having insufficient stability to cope with the prevailing loading and environmental conditions. Consequently, both resilient modulus and permanent deformation characteristics are suitable parameters to examine the suitability of stabilised coarse bauxite residue for road construction.

In Western Australia, crushed rock mixed with 2 % GP cement achieves the required standards, and hence is used as a control or reference material. It is proposed that if the stabilised coarse bauxite residue performs equally to or better than the control sample in terms of resilient modulus and permanent deformation characteristics, then it can be used for road base material in Western Australia.

The results of resilient modulus testing can be seen in Figure 8. Clearly, the performance of the stabilised coarse bauxite residue exceeds that of the reference material. The stabilised coarse bauxite residue exhibits a higher resilient modulus than

that of the commonly-used road base material in Western Australia for all different stress states.

Figure 9 shows the permanent deformation characteristics of the stabilised coarse bauxite residue and crushed rock with 2% GP cement added. It can be clearly seen that the permanent deformation of the stabilised coarse bauxite residue is smaller than that of the conventional material at every stress stage applied to the specimens. Hence it can be concluded that stabilised coarse bauxite residue could be used for the base course construction of roads.

7. Conclusions

In Western Australia, the Darling Range bauxite deposits contain high levels of quartz, which results in a coarse residue fraction being produced during alumina production. This residue has a typical particle size in excess of 100 microns. This study focused on the use of coarse bauxite residue for road construction in Western Australia. A pozzolanic-stabilised soil technique was investigated to satisfy the minimum requirements for road base construction. Pozzolanic-stabilised mixtures consisted of coarse bauxite residue, Class F fly ash (a by-product from coal power stations) and lime kiln dust (a by-product from quicklime manufacturing). Mixtures were assessed based on their compaction, unconfined compressive strength, resilient modulus and permanent deformation. Based on the results of compaction and unconfined compressive strength tests, the optimum mix selected for further investigation was 70% coarse bauxite residue, 25% fly ash and 5% lime kiln dust (dry weight). Comparisons were made between the stabilised coarse bauxite residue and conventional road base used in

Western Australia (crushed rock with 2% Portland cement). The results of resilient modulus and permanent deformation tests show the stabilised coarse bauxite residue exhibits resilient modulus and permanent deformation characteristics that exceed those of the commonly used material for road base.

Overall results indicate that stabilised coarse bauxite residue could provide improved performance when used as a road base material in Western Australia.

8. Acknowledgements

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Figures

Figure 1. Particle size distribution of a coarse bauxite residue and Perth yellow sand

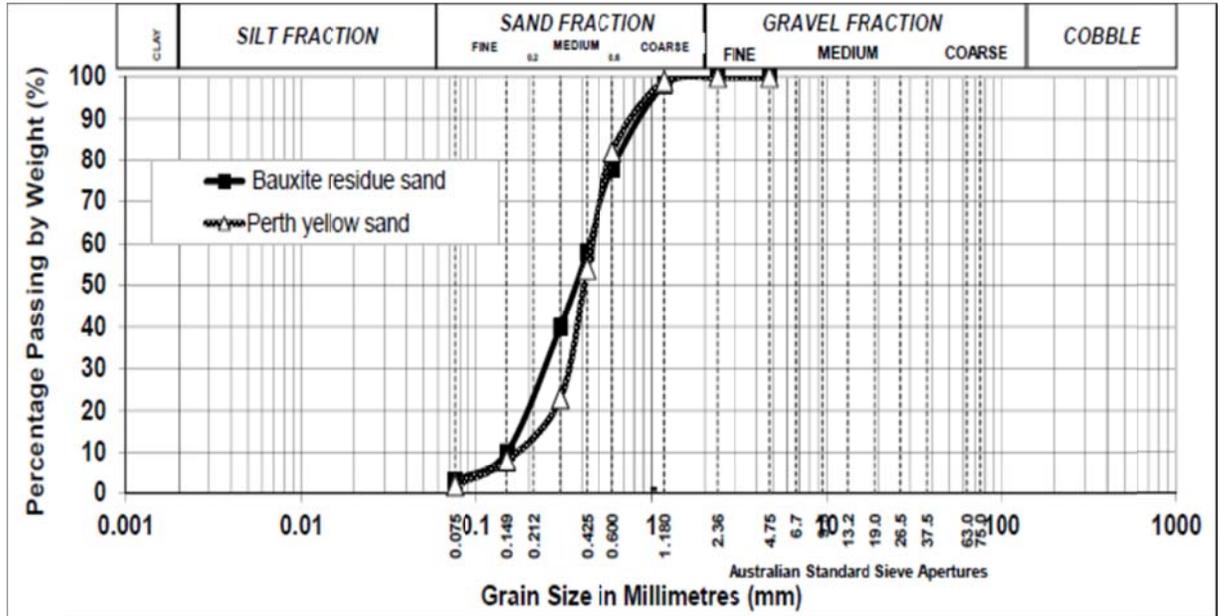


Figure 2. Optical microscopy comparison of red and natural sand

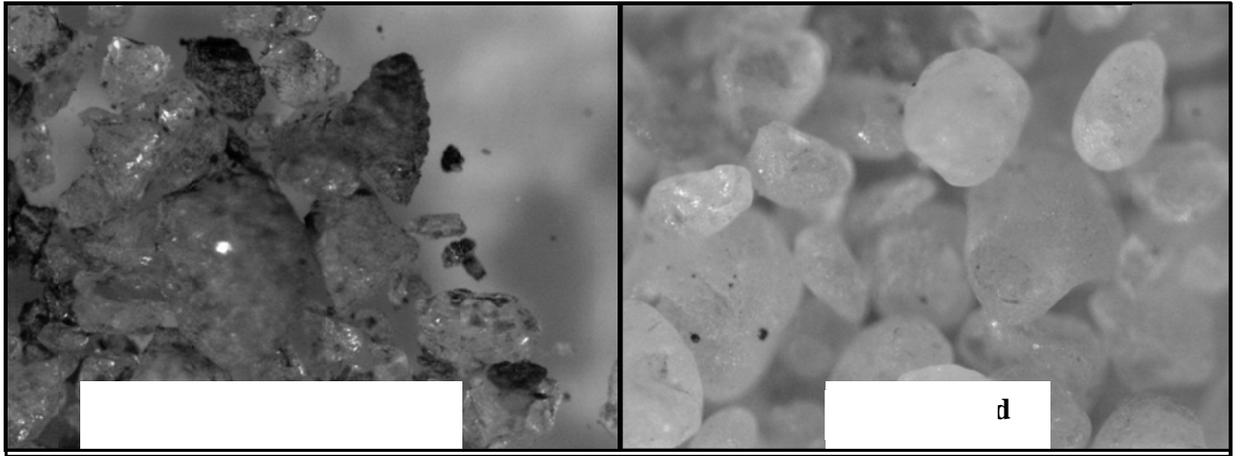


Figure 3. Coarse bauxite residue stabilisation details

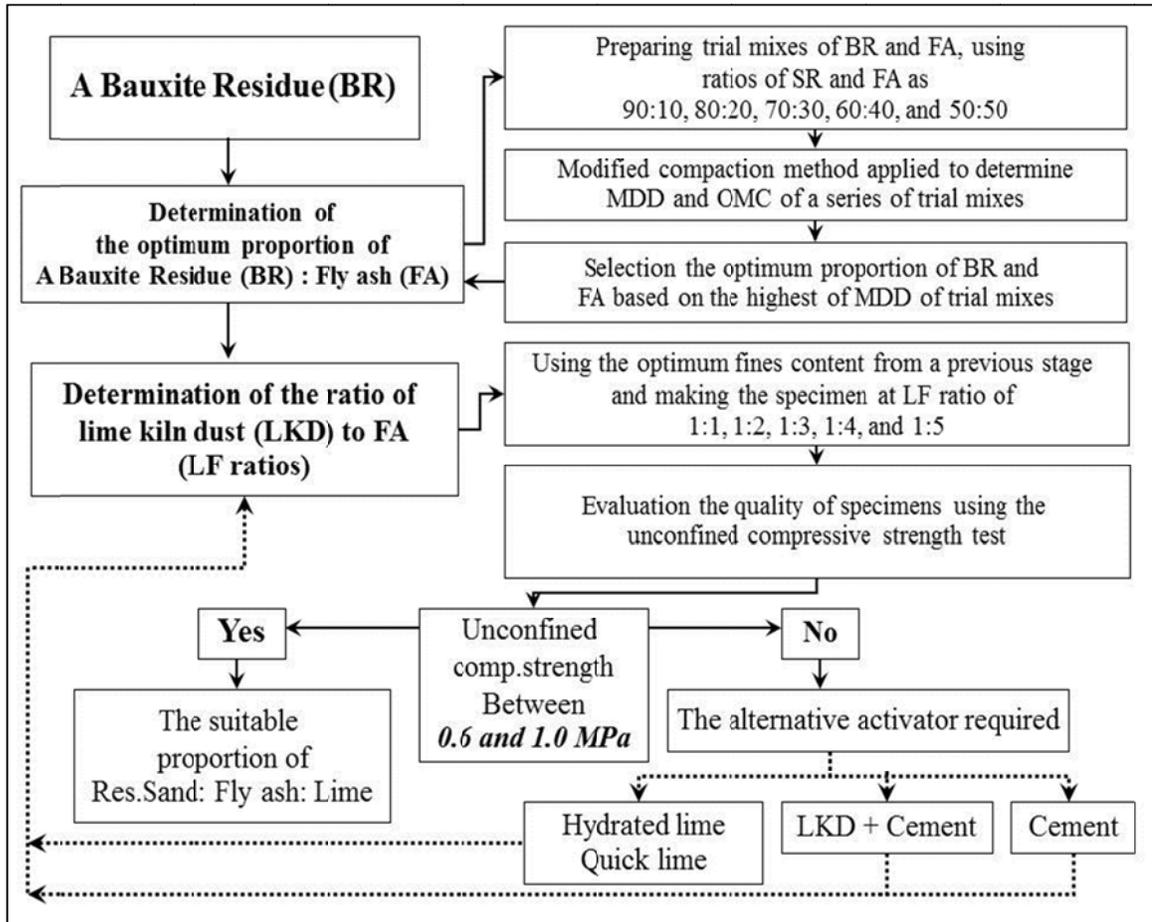


Figure 4. Sample preparation for unconfined compressive strength tests



Figure 5. Repeated load triaxial (RLT) apparatus

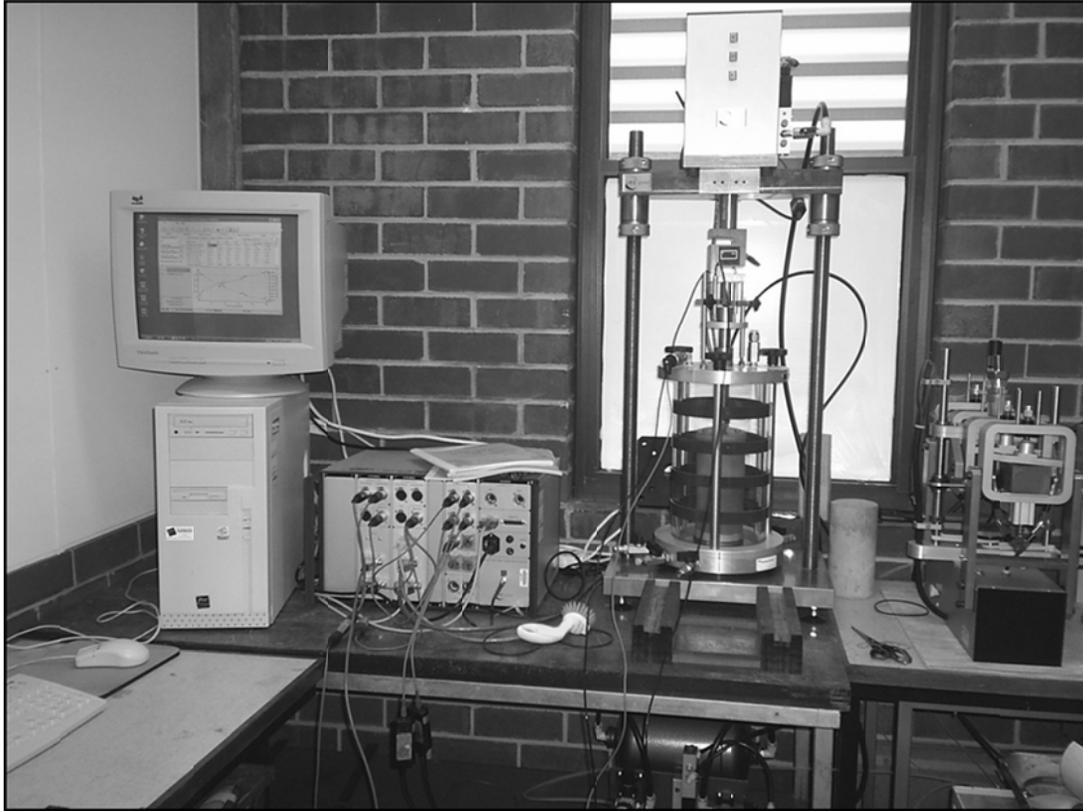
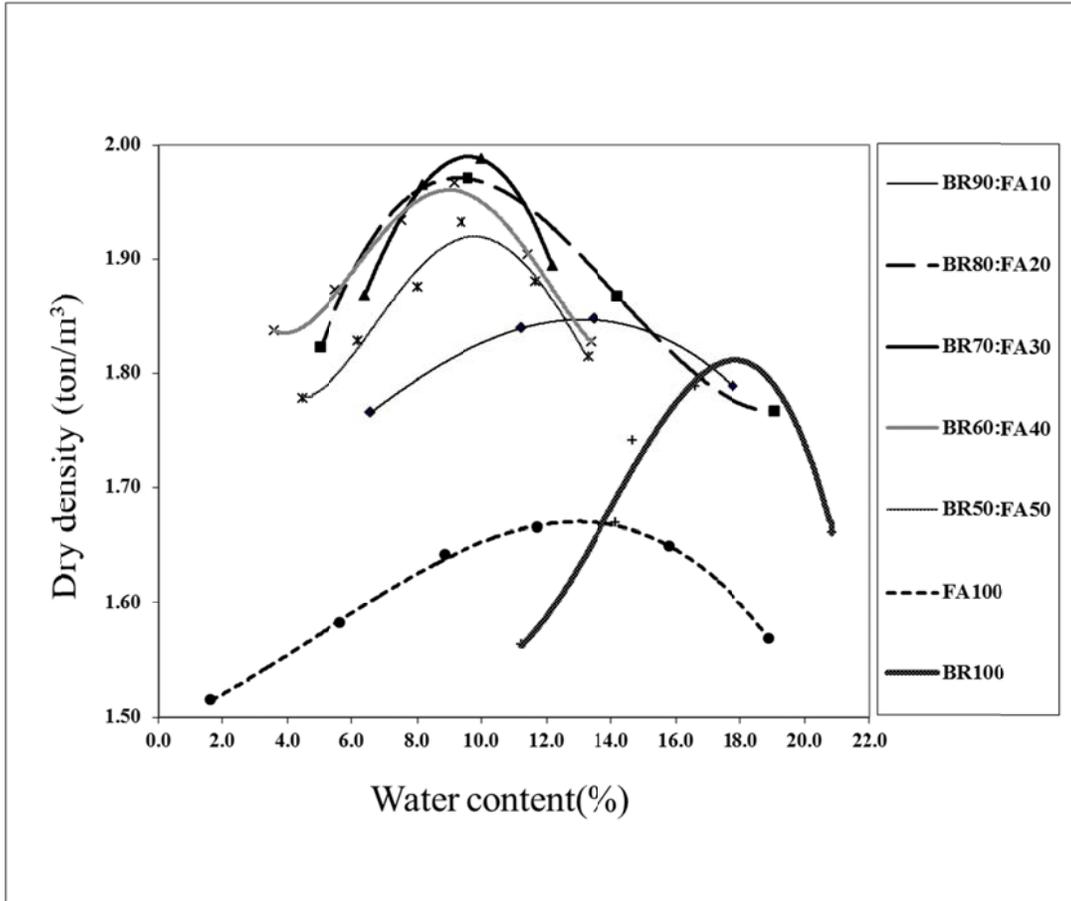
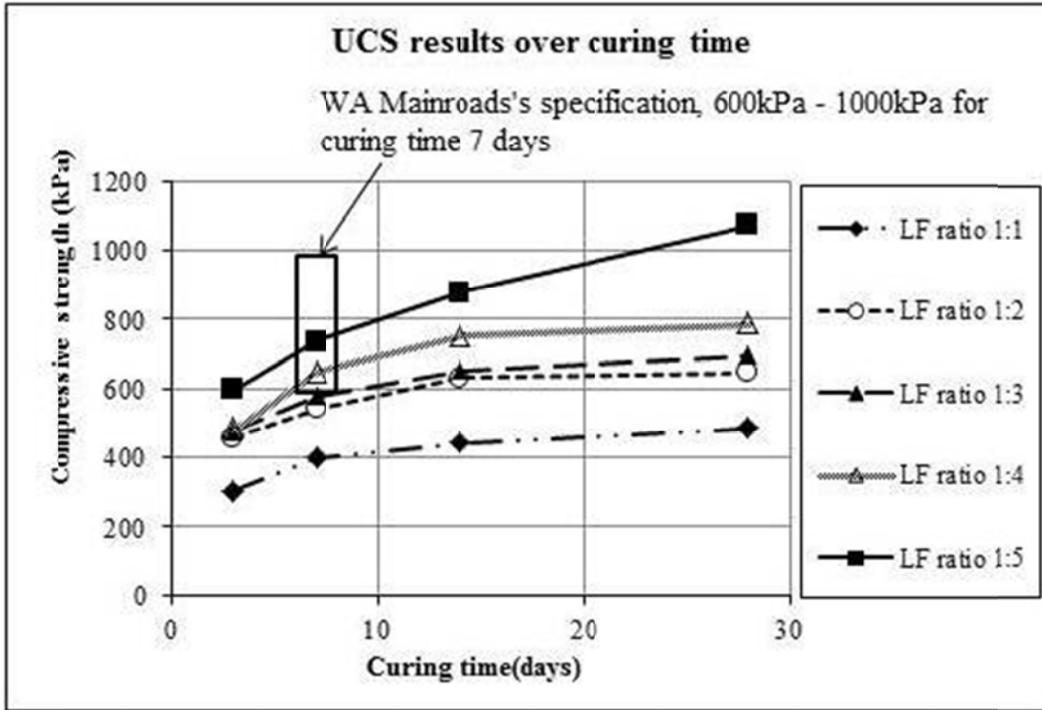


Figure 6. Compaction curves for coarse bauxite residue and fly ash mixtures



BR90:FA10 = Bauxite residue 90% + Fly ash 10%, for example

Figure 7. Unconfined compressive strength of coarse bauxite residue mixes



LF ratio = ratio of lime kiln dust to fly ash

Figure 8. Resilient modulus against numbers of stress stages for stabilised coarse bauxite residue and crushed rock with 2% GP cement

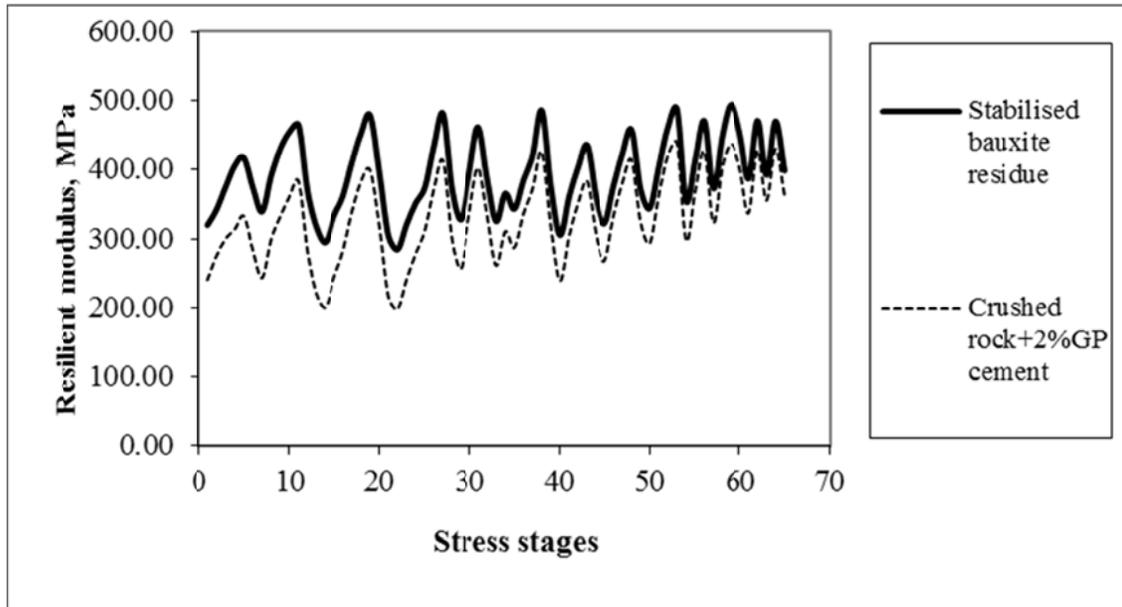
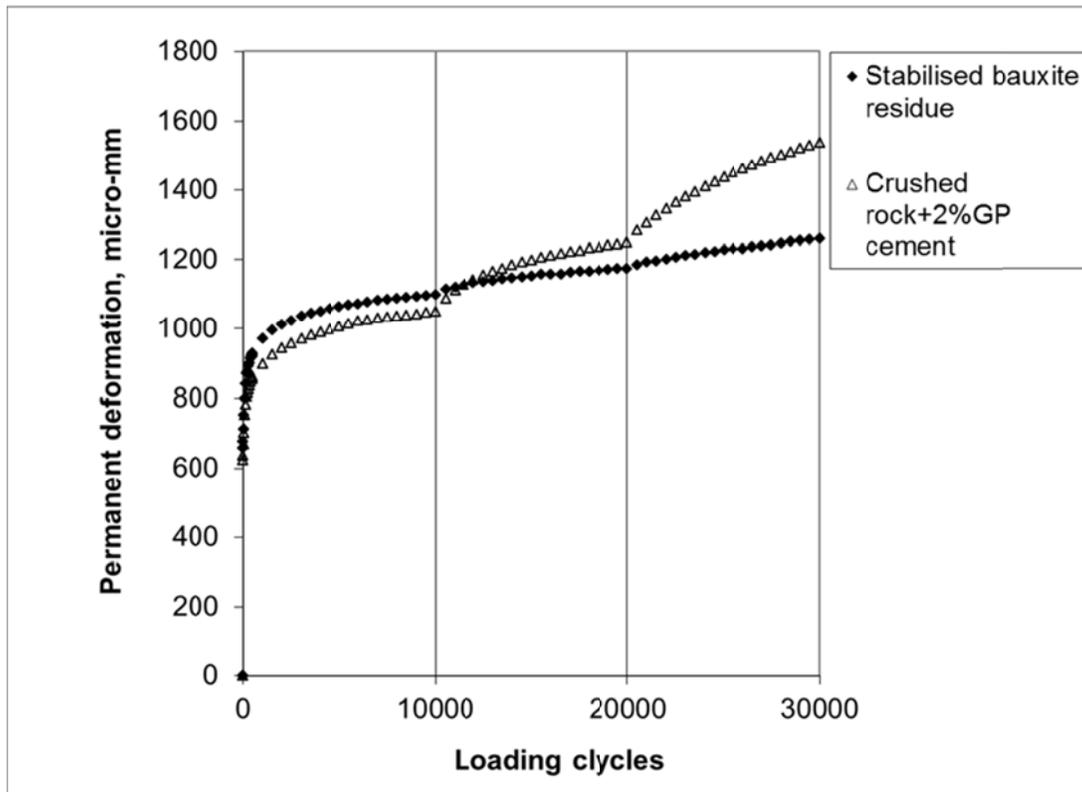


Figure 9. Permanent deformation against load cycles for stabilised coarse bauxite residue and crushed rock with 2% GP cement added



Tables

Table 1. Geotechnical properties of a coarse bauxite residue

Properties	Values			
Specific gravity	3.03			
Atterberg limit	None Plasticity			
Compaction	Modified		Standard	
	MDD (t/m ³)	OMC (%)	MDD (t/m ³)	OMC (%)
	1.83	17.6	1.60	20.2
CBR	Modified		Standard	
	Soaked (%)	Unsoaked (%)	N/T***	
	55	48		
Water Conductivity	Coefficient of Permeability (cm/sec)			
	Void Ratio, e = 0.65*		Void Ratio, e = 0.89*	
	1.54×10^{-4}		6.93×10^{-4}	
Shear Strength**	Friction Angles, ϕ (°)			
	Void Ratio, e = 0.65*		Void Ratio, e = 0.89*	
	At Ultimate Strength	At Peak Strength	At Ultimate Strength	At Peak Strength
	40.03	45.00	37.48	40.56

*The compacted coarse bauxite residue at the condition of the standard compaction test has a void ratio of 0.89 and at the condition of the modified compaction test has a void ratio of 0.65.

** Shear strength properties were conducted by the standard direct shear test.

*** N/T = Not tested