Western Australian School of Mines

Research and Application of Non-traditional Chemical Stabilizers on Bauxite Residue (Red Sand) Dust Control

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledge has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The research do not include any human and animal ethics issue.

Signature: *Xuhan Ding*

Date: 28/06/2018

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Abstract

Due to the dramatic demand of aluminium in the modern economy, bauxite mining associated with aluminium manufacturing causes more serious environmental impact. One of the primary pollution sources during these activities is from the bauxite residue (red sand). Its major detrimental consequences include health diseases and environmental contamination, such as upper respiratory tract and eye irritation, wheezing and rhinitis, soil salinization, caustic liquor leaching, water pH alteration, genotoxic effects on plants, and aquatic animals. Therefore, the management of bauxite residue is of great concern and requires solutions which are environmental friendly, cost, and time effectively.

Although the treatment of red sand dust pollution is challenging, one of the potential approaches to mitigate such issues is the application of non-traditional chemical stabilizers. Via spread on red sand surface, non-traditional chemical stabilizers are effective in adhering surface sand particles to construct a crust with a certain strength and thickness. It is confirmed that the reactions between stabilizers and red sand particles during the formation of crusts include both physical bonding and chemical reactions such as neutralization and polyvalent coupling. However, a number of barriers still exist among previous studies which need comprehensive and systematic improvement. Firstly, the application of non-traditional stabilizers to sand-type materials is common, but few studies could be found on their application to red sand. Meanwhile, most of the previous studies investigated the behaviour of stabilizer on the mechanical properties of sand and the dust control performance separately, and the results were not correlated. Thus, detailed investigation among the modification of the mechanical properties of treated crust and the resulted dust control behaviour is necessary for a cost and timely effective manner.

This thesis aims at providing a comprehensive investigation on improved dust control practice of red sand by applying different type of non-traditional stabilizers. Firstly, a comprehensive literature

review is presented to review the application of non-traditional stabilizers to stabilize materials which have similar sorts of characteristics/properties as red sand, explore their function mechanisms, investigate the performance of various stabilizers evaluated by different criteria, and finally, discuss their applicability to red sand dust control. After that, a series of studies employing polymer and lignosulfonate stabilizers are presented to deeply investigate the relationships and potential mechanisms between all physical and mechanical properties of formed crust and the final dust erosion resistance. Both the application of single stabilizer or two stabilizers' mixtures are studied. Factors include the type of stabilizers, the concentration of stabilizer solutions, the mix ratio of stabilizers' mixtures, and the length of curing time. The investigated physical and mechanical properties of treated samples and their crusts include water retention property, optimum moisture content and maximum dry density, unconfined compressive strength, crust thickness, density, and penetration resistance. Numbers of experimental design methods were employed to manage the process of studies and make the data more reliable, which are single comparative design, 2^k factorial design, fractional factorial design, and response surface design.

According to the studies, the mechanisms of dust emission and chemical stabilization of red sand are proposed. The performance of different non-traditional stabilizers on dust control is studied and compared, and dust control performance and the change of mechanical properties are correlated for a sound red sand dust control strategy.

Abbreviations List

ALCOA	Aluminium Company of America
ANOVA	Analysis of variance
AS	Australian Standard
ASTM	Americould Society for Testing and Materials
BBD	Box-Behnken Design
CFD	Computational fluid dynamics
CTD	Crust thickness and density
GG	Guar gum
LS	Lignosulfonate stabilizer
LS-C	Lignosulfonate calcium
LS-S	Lignosulfonate sodium
MDD	Maximum dry density
MS	Mean square
NPS	Natural polymer stabilizer
OMC	Optimum moisture content
PAM	Polyacrylamide
PMMA	Poly methyl Mehta acryl
PS	Polymer stabilizer
RDA	Residue drying area
RS	Resin stabilizer
SGN	Number of soil grains
SNQ-T	Student-Newman-Keuls-Q
SP	Poorly graded sand
SPS	Synthetic polymer stabilizer
SS	Sum of squares
TFV	Threshold friction velocity
UCS	Unconfined compressive strength
UV	Ultraviolet
XG	Xanthan gum

List of Publications Included in the Thesis

This thesis incorporates four journal papers that were published, include three SCI journal papers and one conference paper. The copyright of these papers were checked and they are appropriate to be re-used in the thesis and in an institutional repository.

Journal Papers

1. Xu, G., Ding, X., Kuruppu, M., Zhou, W., & Biswas, W. (2018). Research and application of non-traditional chemical stabilizers on bauxite residue (red sand) dust control, a review. *Science of The Total Environment, 616-617*, 1552-1565. http://dx.doi.org/https://doi.org/10.1016/j.scitotenv.2017.10.158

2. Ding, X., Xu, G., Kizil, M., Zhou, W., & Guo, X. (2018). Lignosulfonate Treating Bauxite Residue Dust Pollution: Enhancement of Mechanical Properties and Wind Erosion Behavior. *Water, Air, & Soil Pollution, 229*(7), 214. http://dx.doi.org/10.1007/s11270-018-3876-0

3. Ding, X., Xu, G., Zhou, W., & Kuruppu, M. (2018). Effect of Synthetic and Natural Polymers on Reducing Bauxite Residue Dust Pollution. *Environmental Technology,* http://dx.doi.org/https://doi.org/10.1080/09593330.2018.1505963

4. Ding, X., Xu, G., Zhou, W., Biswas, W., Guo, X. (2018) Treatment of bauxite residue dust pollution by improving the structural stability by employing synthetic and natural polymers. Submitted to Journal of Environmental Science and Health, Part A. Under Review

Conference Paper

1. Xuhan Ding, Guang Xu, Boris Albijanic, Mahinda Kuruppu (2015). A laboratory experiment design for the study of bauxite residue dust control. *The 15th North Americould Mine Ventilation Symposium*

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1. Chapter 1

Outline

1. Background

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1.1 Background

The production of aluminium is mainly through the use of the Bayer process as shown in Figure 1, which has a product to by-product (bauxite residue) ratio of 0.7 to 2. 5 [1]. According to the data from World Bank as shown in Table 1 [2], the annual production of bauxite increased from 176.8 Mt to 296.1 Mt in the year 2005 to 2017. Due to the large aluminium commercial production, vast quantities of bauxite residue were generated. Bauxite residue could be separated into two fractions, which are

a. Coarse fraction with particle size larger than 150 μm (Red sand)

b. Fine fraction with particle size finer than 150 μm (Red mud)

Red sand fraction account for 60 % of the total residue and the rest of residue belongs to red mud [3-5]. In actual practise, "dry stacking" method was mostly preferred for the storage of bauxite residue by constructing a residue drying area (RDA) [6-9]. Red sand is used to build the dyke walls for the deposition and drying of the red mud. In this situation, the surface of the dyke wall is susceptible to wind erosion due to the deformation of the internal bonding of sand particles due to surface efflorescence and sodium molar volume decreasing (Klauber, et al., 2016). The confirmed detriments include:

a. Upper respiratory tract and eye irritation, wheezing, and rhinitis

b. Soil salinization, caustic liquor leaching, water pH alteration

c. Genotoxic effects on plants and aquatic animals

Thus, systematic treatment of red sand dust pollution by applying non-traditional chemical stabilizers is raised and is the focus of this thesis. In general, the chemical stabilizer is classified into traditional stabilizers and non-traditional stabilizer. Traditional stabilizers refers to materials from traditional civil engineering and construction site, such as fly ash, lime, bitumen, and cement. Most of these products have negative environmental or occupational health and safety issues. Some of them are even toxic and may affect the pH value of groundwater and soil. In some cases, the increased pH value may even affect the structural strength, durability and longevity of

infrastructure. Non-traditional stabilizer normally consists of polymers, lignosulfonates, resin etc. They create less harm to the natural eco-system with comparable dust control efficiency. Therefore, advantages such as good dust control performance, low resources and energy consumption, and environmental friendliness bring non-traditional stabilizers greater potential and wider applicability.

Table 1 Bauxite production and consumption data

Category	Annual (million metric tons)							
	1990	2000	2005	2010	2014	2015	2016	2017
Bauxite Production	114.8	138.9	176.8	228.8	259.5	287.5	280.3	296.1
Refined Production	19.4	24.3	31.8	41.5	53.9	57.6	57.9	58.7
Refined Consumption	19.2	25	31.6	40.6	54.3	57.5	58.1	59.3
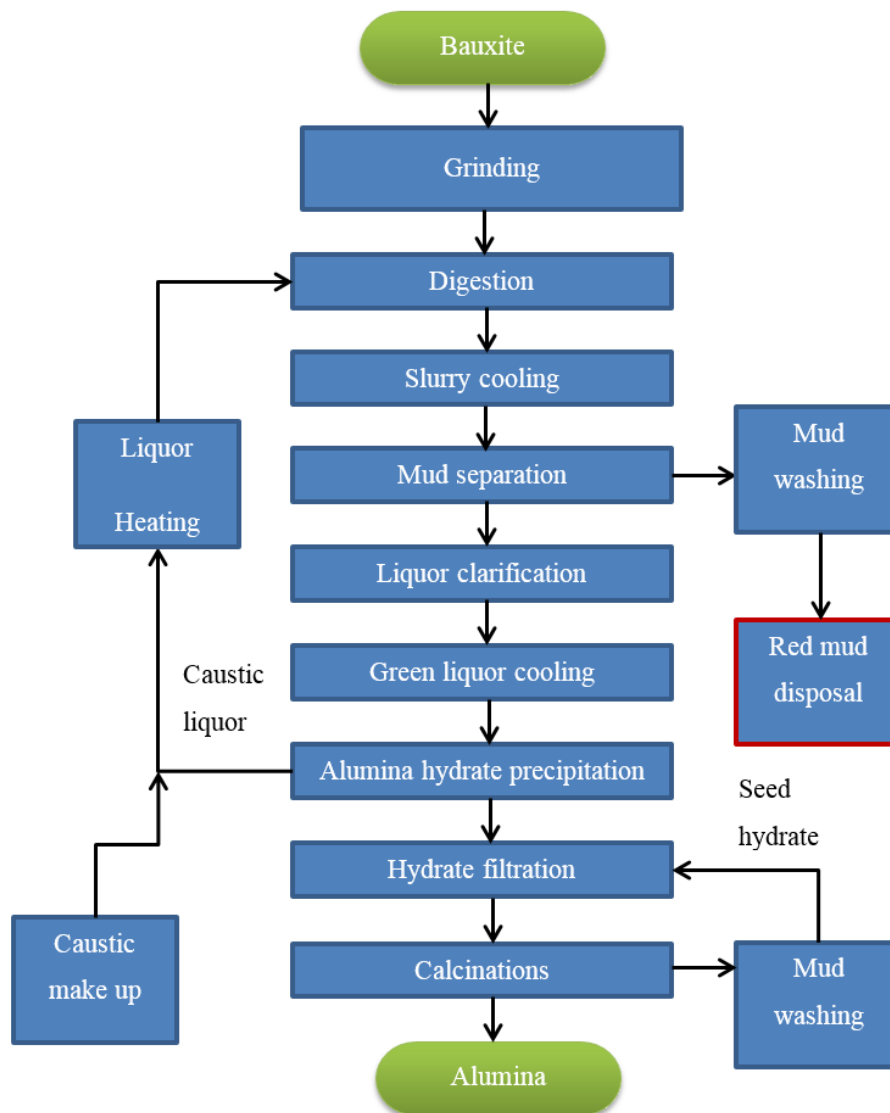
Figure 1. Brief description of the Bayer Process

1.2 Research Problems and Objectives

1.2.1 Research Problems

Although the research and application of chemical stabilizers on dust control is common, numbers of gaps and shortages still exist when studying red sand dust control. Thus, this thesis attempts to address the following major problems.

a. The studies on application of non-traditional stabilizers to red sand for dust control purpose are limited.

b. No systematic investigation on the behaviour of mechanical properties and dust control performance of non-traditional stabilizer treated sand has been carried out.

c. The mechanism of different non-traditional stabilizer treats red sand is unclear.

d. The findings of the improvement of mechanical properties and the modification of dust control resistance are not correlated.

e. No cost effective and timely method to determine the dust control performance of one non-traditional stabilizer are known.

1.2.2 Research Objectives

In order to overcome the problems listed in section 1.2.1, some major objectives need to be fulfilled.

The first main objective is the review and the analysis of previous studies. This work could help to classify and correlate their data and findings of the application of chemical stabilizers on other sand-type materials. This objective could be achieved by the steps as shown below:

a. Review of application of non-traditional stabilizers to stabilize materials which have similar characteristics/properties as red sand.

b. Exploration of their function mechanisms.

c. Investigation of the performance of various stabilizers evaluated by different criteria

d. Discussion of their applicability to red sand dust control.

The second objective is to develop a cost and timely effective approach for red sand dust control by applying non-traditional stabilizers. It could be achieved via the following steps.

a. Study of the improvement of dust control practice of red sand by applying LS via analysing the relationship between the modification of mechanical properties and wind erosion resistance. Properties such as moisture retention, OMC and MDD, crust thickness and density, UCS and penetration resistance are tested.

b. Employment of wind tunnel test to perform and evaluate the actual dust erosion resistance of red sand after treated by non-traditional stabilizers

The third and the most important objective is to develop predictors for the determination of the performance of non-traditional stabilizer in an accurate and timely effective manner. This objective could be achieve via the following steps.

a. Correlation of the results from mechanical test and wind tunnel test together to assess the significance of each mechanical properties to dust erosion resistance.

b. Development of mathematic models to determine the mechanical property most correlated to the dust erosion resistance, and which could be the appropriate predictor.

1.3 Thesis Structure Arrangement

As illustrated in Figure 2, the ultimate goal of this thesis is to develop cost and timely effective stabilizers for the purpose of the dust control of bauxite residue (red sand). To realize this goal, the main body of this thesis started with a comprehensive literature review presented in "Chapter 2" which systematically explored and evaluated three non-traditional chemical stabilizers that could be potentially used for controlling red sand dust and served as theoretical basis for the studies presented in the following chapters. In chapter 2. Commonly used evaluation methods in various studies are compared and summarized; the stabilization mechanisms are examined; and the performance of three types of stabilizers are compared and evaluated. This review identified the challenges existed in previous studies and the objectives such as develop suitable quantitative

methods for evaluating the dust suppression efficiency of soil stabilizers, and determine the appropriate additive quantities that achieve both economic and performance effectiveness.

Chapter 3 is a preliminary study is with no lab work which introduced the procedures that could be potentially used to determine the effectiveness of non-traditional stabilizer on red sand dust control. Different experimental design methods and image processing procedures are introduced.

Followed by that, four chapters (Chapter 4 to Chapter 7) refers to four independent studies that demonstrated four tasks which aim at overcome three objectives such as identify performance index, develop novel stabilizers and establish cost and timely effective strategies for red sand dust control. A series of experimental methods were utilized such as the quantification of physical and mechanical properties, and wind tunnel simulations. A variety of statistical experimental design methods were also employed to ensure the reliability and the accuracy of the experimental data and findings.

Chapter 8 refers to an integral conclusion which summarized the main findings and highlighted the core achievements of each independent studies. Current limitations were also stated to guide the directions of the future work.
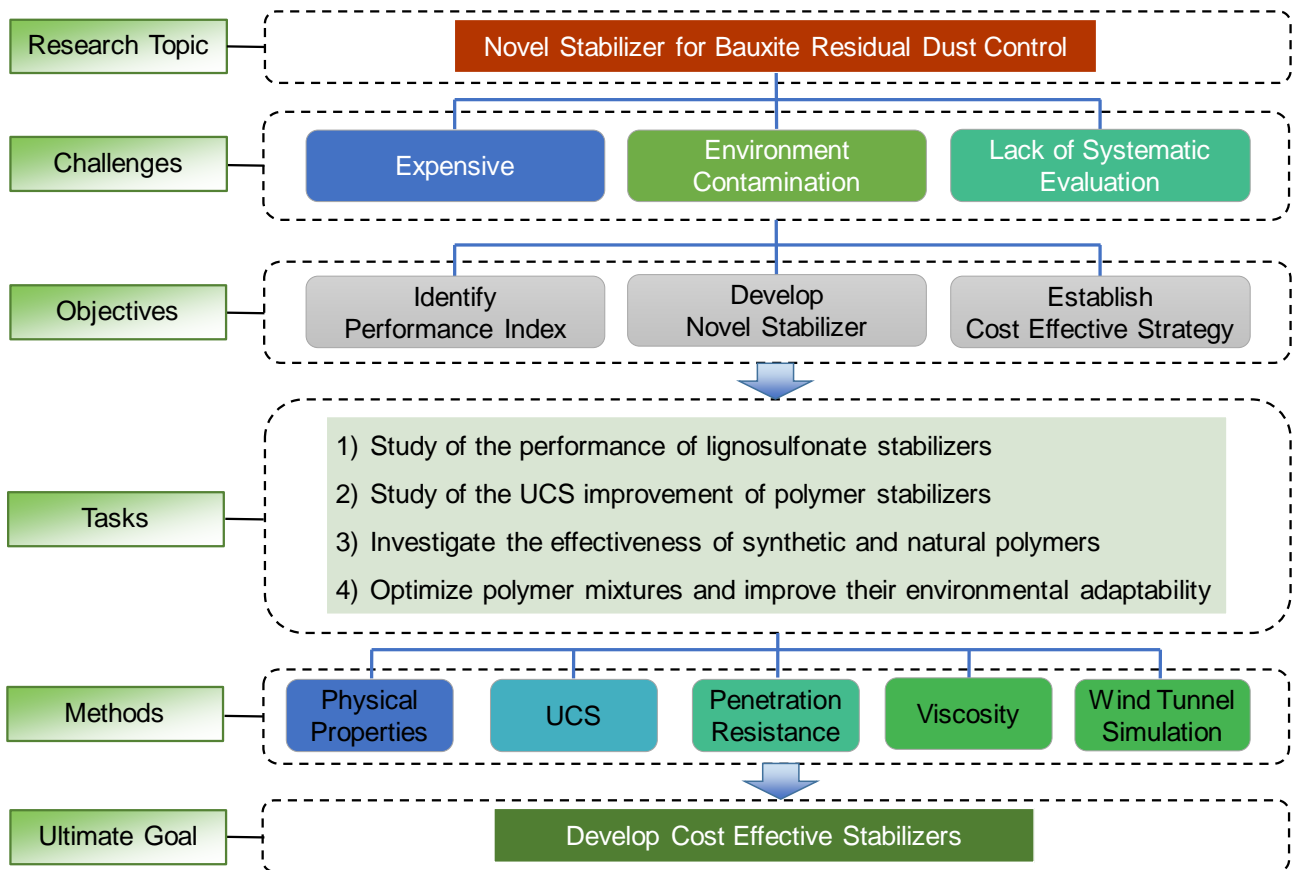
Figure 2 The scheme of the thesis structure

Chapter 2, Chapter 3 and Chapter 4

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5. Chapter 5

Treatment of bauxite residue dust pollution by improving the structural stability by employing synthetic and natural polymers

After the study of lignosulfonate stabilizers, this chapter compiled a new study of another kind of non-traditional stabilizer (polymers). Previous research focused more on investigating the effect of single polymers on the mechanical properties of treated materials. However, no research has been done on the combined effect of different types of PS on red sand. As illustrated in Chapter 2, UCS could be regarded as a key index for predicting the dust control performance of polymer treated sand. Thus, this chapter devoted to the investigation of the effect of two polymers combination on the UCS of treated red sand.

5.1 Abstract

The residue drying area is the major source of fugitive red sand dust emissions in the bauxite mining industry and may cause serious environmental and safety issues to surrounding communities and ecosystems. Synthetic polymer stabilizers and natural polymer stabilizer are one of the promising non-traditional stabilizers to mitigate such issues. This research investigated the unconfined compressive strengths of RS using synthetic and natural polymer stabilizers and to determine an optimum application concentration and mixing ratio of the polyacrylamide and guar gum mixture for a better dust control strategy. Results illustrated that both polyacrylamide and guar gum could improve the unconfined compressive strength of red sand with higher concentration, and polyacrylamide apparently outperform guar gum in stabilizing sand particles. The mixture of polyacrylamide and guar gum is more effective than individual uses. The optimum combination of polymer concentration and the mixing ratio are 0.94 wt. % and 0.6 (polyacrylamide : total (polyacrylamide + guar gum)), respectively. A rigorous regression model was also developed to predict the unconfined compressive strength value based on application concentration and mixing ratio for the purpose of cost and time efficiency.

5.2 Introduction

The production and disposal of bauxite residue (red sand) poses acute environmental impacts to both mine sites and the surrounding regions. It does not only cause health issues,

including upper respiratory tract, lung and eye irritation, wheezing and rhinitis, due to the emitted RS dust [1], but also has adverse impacts on the ecosystem, such as salinity problem, and water pH alteration [37-39]. Therefore, fugitive RS dust management is a major concern which requires long-lasting, fast-acting and effective solutions.

Bauxite residue is one of the primary by-products of the aluminium refinery process referred to as the Bayer process. It is mainly constituted by the insoluble bauxite ore after the extraction of alumina, and heaps of metallic oxide [31, 32]. Bauxite residue is separated into coarse fraction named RS with a particle size larger than 150 µm (i.e. 60 % of the residue), and fine fraction named red mud with the particle size finer than 150 µm (i.e. 40%) [3-5]. The mass fraction of the metallic oxide and the phase of the residue vary with refinery sites and plants due to different levels of process technics and geological characteristics. The major treatment of bauxite residue is the "dry stacking" disposal method [10], where RS is used to construct the dike walls for the storage and drying of red mud. However, this method in fact causes the generation and emission of RS dust from the dike wall due to the breakdown of the internal bonding between surface particles after capillary salt transportation, surface efflorescence, and the reduction of sodium molar volume when exposed to dry conditions [36].

One effective way to mitigate dust emission is the chemical stabilization of RS via the application of polymer stabilizer (PS). Studies revealed that a positive improvement on unconfined compressive strength (UCS) correlate to increases in other mechanical properties, such as the shear strength and crust surface hardness, and the final dust erosion resistance [54, 60]. Thus, UCS could be used as an index to predict its effectiveness of dust control [139]. The UCS improving mechanism depends on various PS types. Cationic PS tends to react with the negatively charged particle surface of clay fraction of sand through the neutralization process [55]. However, anionic PS attracts particles with multivalent cations such as Na^+, K^+, Ca^{2+} and Mg^{2+}, while non-ionic PS mainly adsorb particles via the Van der Waals (VDW) force [55]. Normally, ionic or covalent

bonds provide the highest bonding energy with short lasting time, while bonds caused by VDW force offer weak bond energy over a long period [150].

PS is generally classified into synthetic polymer stabilizer (SPS) and natural polymer stabilizer (NPS). Synthetic polymers are manually extracted from petroleum oil while natural polymers only occur in nature environment and the majority of them are water-based. Previous studies emphasized on the utilization of SPS only to enhance the structural strengthen and dust control of treated materials, but no research has been done on NPS and the combined effect of different types of stabilizers on RS. For example, for SPS studies, one research [57] analysed the effectiveness on improving compressive strength of poly (methyl methacrylate) (PMMA) and polyvinyl acetate when applied to soil. When the concentrations of stabilizers are within the range of 0.4 to 3.7 wt. %, an approximately linear improvement of UCS of RS with the increase of stabilizer concentration was observed. This finding was confirmed by another study on the investigation of sandy soil structure strength improvement by acrylic emulsion PS for a concentration range between 0.5 and 2 wt. % [82]. However, different conclusions were made when considering a wider concentration range of stabilizers. For example, one PS named "STW Stabilizer", when used in a concentration range of 0 to 10 wt. %, showed a fast improvement on UCS at the initial stage, but it leveled off when further increasing the concentration [54, 66]. Other studies also confirmed this finding [54, 65, 112]. However, not many studies have been carried out on NPS for the dust control performance improvement, and very few of them showed the correlation between this performance and the UCS. Only Chen, Ramey, Weiland, Lee and Zhang [151] and Chang and Cho [152] assessed the UCS of materials treated by each single PS. Chen et al. found that the UCS increases linearly when the stabilizer concentration increases from 0 to 0.5 wt. %., Chang et al. employed a wider stabilizer concentration range and further illustrated that the UCS increases with higher NPS concentration and this improvement is much more obvious when continuously increasing the NPS amount [152, 153]. However, as no research has been done on the

combined effect of different types of PS on red sand, studies in this paper is necessary for a better strategy of applying stabilizer for RS dust control.

This paper aims at the investigation on the combined effect of SPS and NPS on the UCS of RS, and determine the optimum mixing ratio of these two stabilizers to achieve the best result for a cost effective manner. Whether the stabilizer concentration has significant effect on the UCS was investigated. After that, the combined effect of the two stabilizers are investigated via the 2^k experimental design. Finally, an optimum application scheme including combined application mixing ratio and total application concentration was determined by using the response surface experimental design method.

5.3 Materials and Methods

5.3.1 Sands

The red loam sand was purchased and used as the substitute for test samples due to restricted availability of RS materials. It has a particle size distribution mainly ranging from 0.04 mm to 0.7 mm which is similar with the RS. Particles size distribution test was performed by following the standard AS 1289.3.6.1. The sand is classified as poorly graded sand (SP) (based on the Unified Soil Classification System raised by American Society for Testing and Materials in 1985). The sand constituents were identified to be similar with red sand. Sand was oven-dried at 75 ˚C, and sieved to the diameter <1.18 mm. The processed sand has an optimum moisture content (OMC) of 5 % and maximum dry density (MDD) of 2.16 g/cm^3 by following the standard AS 1289.5.2.1 [154].

5.3.2 Stabilizers

One synthetic polymer named "polyacrylamide (PAM)" and one natural polymer named "guar gum" were applied in this study. They were purchased from Sigma Aldrich (Australia) as powders. PAM is a water-soluble linear polymer formed by the free radical polymerization of the acrylamide monomer. It is formed by acrylate-based transparent particles with a molecular weight

of 3 ~ 25 million daltons [155]. PAM could be used in agricultural field to control soil erosion during irrigation [19, 62, 64, 156], to reduce dust emission in arid and semi-arid areas [63, 114], and for the rapid building of helicopter landing pad [155, 157]. Guar gum is isolated from the endosperm of the lobus seed of the *Cyamopsis tetragonoloba* [158]. It is a natural cationic polymer with the most effective water solubility. It has a molecular weight of 220,000 daltons. Guar gum is normally produced in white powder state and could form transparent solution with high viscosity which exhibits non-Newtonian rheological properties.

5.4 UCS Test

The UCS mainly represents the change of structural strength of the treated sand. In this study, sand was adequately mixed with deionized water first to achieve its optimum moisture content which is identified in section 5.3.1, and then thoroughly mixed with the polymer powder. This method could greatly simplify the preparation procedure with lower requirements of the preparation apparatus. High-speed blender ensures uniform mixing of stabilizer power and wet sand. The mixture was sealed for two hours to allow adequate interaction between the stabilizer power and the moisture. After that, the mixture was then compacted into a 4×8 cm ($Diameter$ ×Height) cylindrical mould reported by Ding and Xu [149]. During the compaction, a 2.5 kg top load was lightly applied onto the surface of the specimen and a vibration table was employed for uniform compaction. All samples were air dried under ambient temperature and humidity until the weight change per day is below 0.2 g. The STX-100 soil test equipment is used at a loading rate of 1 mm/min by following the standard ASTM D2166/D2166M [159]. The prepared sample and the cylindrical mould are described in Figure 3.

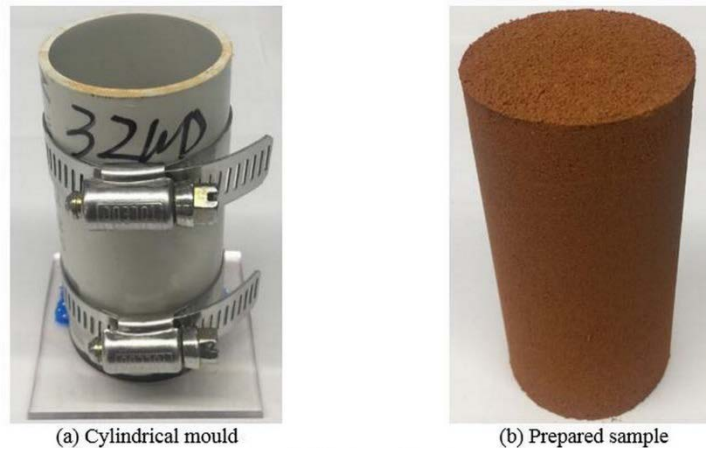(a) Cylindrical mould   (b) Prepared sample

Figure 3. Cylindrical mould and sample

Firstly, one test based on the simple comparative design, was conducted firstly to determine whether the stabilizer concentration has significant effect on the UCS of the treated sand. Two stabilizer concentrations (0.2 and 1 wt. %) were selected according to Chen, Ramey, Weiland, Lee and Zhang [151]. Five replicates were prepared for this test to achieve more reliable data. Secondly, two stabilizers were applied simultaneously in different mixing ratio for their concentrations between 0.2 and 1 wt. % in the specimens, to assess their structural performance in terms of UCS via a 2^k design. 2^k design is one of the experimental design methods which is extremely useful by providing the smallest number of runs when studying k factors at two levels [160]. Five different PAM : total mixing ratios were selected (0, 0.25, 0.5, 0.75 and 1) and 3 replicates were prepared for each combination as shown in Table 2. Lastly, the response surface design was used to determine the optimum application concentration and mixing ratio. As the maximum stabilizer concentration is 1wt. % due to the limited water solubility of these polymers, the experimental region is confined. Thus, the optimal designs for response surface experimental method is used, and the details are shown in Table 3.

Table 2 Sample preparation for 2^k design

PAM : Total	Guar gum : Total	Replicates
0 : 1	1 : 1	3
0.25 : 1	0.75 : 1	3
0. 5 : 1	0.5 : 1	3
0.75 : 1	0.25 : 1	3
1 : 1	0 : 1	3

Table 3 The UCS test experimental design

Run	Factor 1 Concentration (wt. %) of PS	Factor 2 PAM:Total
1	0.20	1.00
2	0.47	0.00
3	1.00	0.50
4	0.60	0.25
5	0.20	0.00
6	0.60	1.00
7	1.00	0.50
8	0.80	0.75
9	1.00	1.00
10	1.00	0.00
11	0.60	0.25
12	0.40	0.75
13	0.60	0.25
14	0.60	1.00
15	0.20	0.50
16	0.20	0.50

5.5 Results and Discussion

The performance of non-traditional stabilizers to improve the UCS of red send dust has been investigated. As confirmed by Figure 4, PAM performed better than guar gum in strengthening the UCS of RS. As the concentration of the stabilizer increased from 0.2 wt. % to 1 wt. %, the UCS of PAM treated sample increased from 0.708 MPa to 1.102 MPa, and guar gum treated sample increased from 0.605 MPa to 0.915 MPa. T-test was performed to evaluate the significance of the mean difference of the UCS data. The assessment of t-test is achieved by comparing the calculated t-value with the p-value in t-table which corresponds to the significance level. If the calculated t-value is less than the t-table value, there are significant difference between means. In this study, the t_0 of both PAM and Guar Gum treated sand is much lower than $t_{0.025,8}$. Thus, the mean difference of the UCS is significant which is due to the change of concentrations rather than test errors. Results is consistent with the study by Iyengar, Masad, Rodriguez, Bazzi, Little and Hanley [55] and Khatami and O'Kelly [150] who illustrated a similar improvement in UCS after the individual application of acrylate-based SPS and NPS.
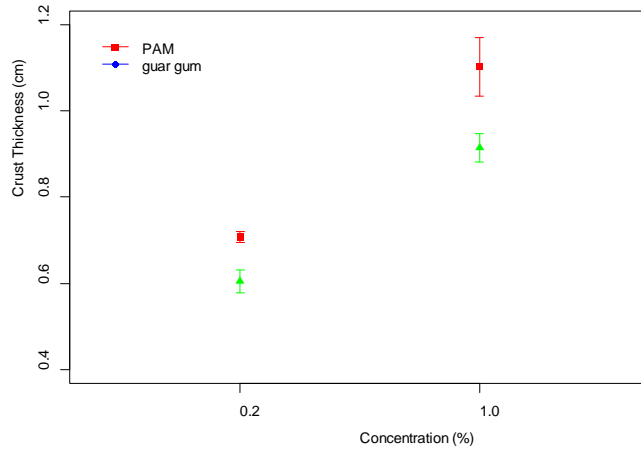
Figure 4. UCS simple comparative test results

To evaluate the performance of PAM and guar gum mixture on the UCS of tested sand, tests based on the 2^k design have been performed (Figure 5). As 1wt. % stabilizer could achieve better UCS, the total stabilizer concentration was fixed at 1 wt. % in this test, but different combination ratios of the two stabilizers were used to strengthen structural stability of samples. The combination ratio denotes the fraction of PAM in the amount of total applied stabilizers. The combined use of two stabilizers resulted higher UCS of RS than they were used individually. The UCS with 0.75 wt. % PAM and 0.25 wt. % guar gum achieved the maximum UCS of 1.385 MPa, which is 1.5 times of that treated by only guar gum and 1.23 times of that treated by only PAM.

Figure 5. UCS of samples treated by polymers in different mixing ratio

Based on the above 2^k design experiments, it is confirmed that an optimum combination ratio exist when the overall application concentration is 1 wt. %. Test based on the response surface design has been conducted to further investigate as to how UCS changes with combination ratios and the concentrations of PS in treated sand. 16 runs were performed based on the optimal design for response surface, as shown in Table 3.
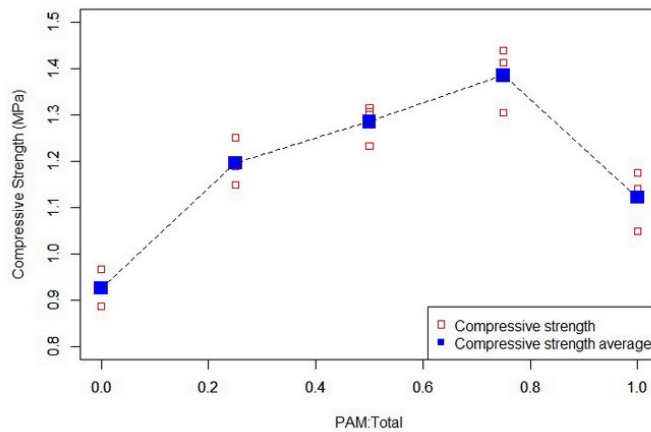
The ANOVA results presented in Table 5 suggested that both stabilizer concentration and mixing ratio have significant effects on the UCS. It appears from Figure 6 and Figure 7 that generally UCS increases with stabilizer concentration, and a plateau is reached at concentrations around 1 wt. %. The PAM : total ratio of 0.6 at the concentration of 0.94 wt. % achieved the optimum UCS. A quadratic empirical equation 6, has been generated based on these results to determine an optimum UCS for different levels of concentration and mixing ratio of PSs in this test. In equation 6, x is the stabilizer concentration and y is the ratio of PAM : Total. Figure 8 is the scatter plot of actual vs predicted value indicating the differences between the predicted value and observed records with the R^2 equalling to 0.9775. It shows all the predicted values well agree with the actual. To further validate the model accuracy, the independent data sets from the 2^k design experiments are used to calculate the prediction error. As could be seen in Table 4, the predicted errors are all below 6% indicating an acceptable model reliability.
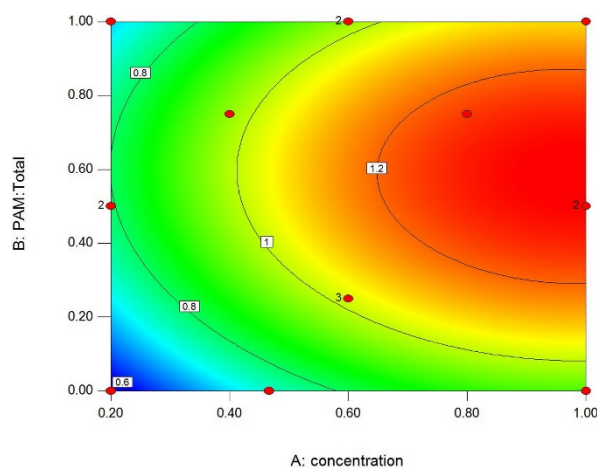
Figure 6. Contour plot of UCS test (MPa)
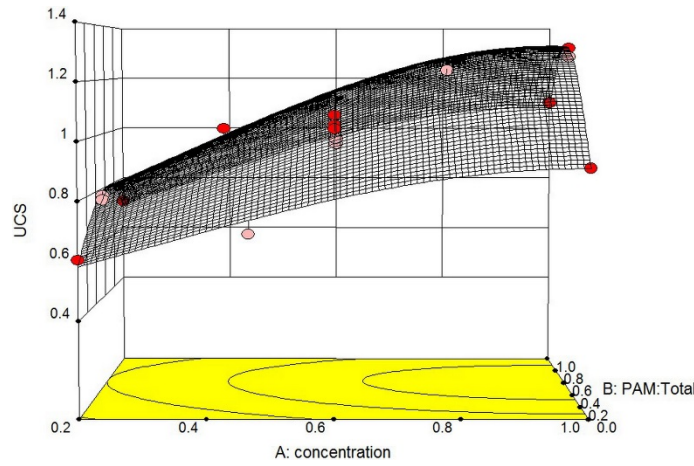
Figure 7. Perspective 3D plot of the UCS test (MPa)
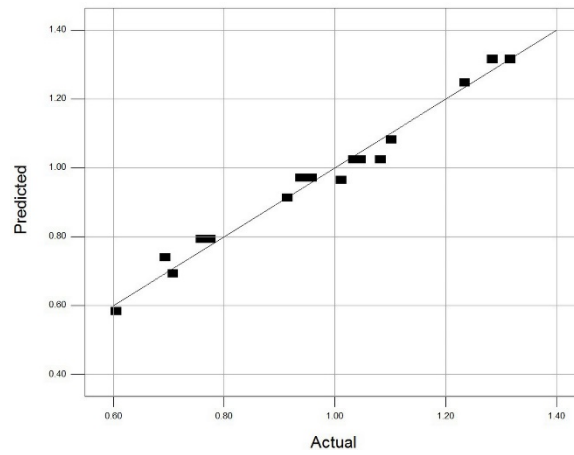
Figure 8. Predicted vs. actual UCS value plot of the constructed model (MPa)

It is noted that the values of UCS obtained in this study are lower than other studies. The maximum UCS in this study is 1.317 MPa, but in other studies it is improved up to 3.2 MPa when the NPS concentration is about 0.5 wt. %. [152] This is mainly because of the difference in the mixing method used in sample preparation. Although the preparation method used in the current study required the mixtures of the sand and stabilizers to be sealed for two hours for improved interaction of the stabilizer-sand-water, however, compared to the wet mix mentioned in section 2.3, the current preparation method may not offer complete mixing and interaction, which may result in a reduction on the UCS of treated samples.

$$\frac{1}{\sqrt{UCS}} = 0.414x^2 + 0.528y^2 - 0.825x - 0.642y + 1.457 \qquad \text{(Equation 1)}$$

Table 4 Assessment of model accuracy

Concentration (wt. %)	Mixing Ratio (PAM:Total)	Actual Observed Average Value (MPa)	Model Predicted Value (MPa)	Error (MPa)	Error (%)
1	0	0.926	0.914	0.012	1.3%
1	0.25	1.196	1.185	0.011	0.9%
1	0.5	1.285	1.362	0.077	6%
1	0.75	1.385	1.347	0.038	2.7%
1	1	1.121	1.151	0.030	2.7%

Table 5 ANOVA of UCS test based on response surface design

Source	Sum of Squares	Df	Mean square	f value	p(F)
Model	0.22	5	0.044	89.34	<0.0001
Concentration	0.13	1	0.13	273.77	<0.0001
PAM:Total	0.019	1	0.019	37.95	<0.0001
(Concentration)²	0.015	1	0.015	31.01	0.0002
(PAM:Total)²	0.052	1	0.052	105.74	<0.0001

5.6 Conclusion

It is noted that both polyacrylamide and guar gum provide improved unconfined compressive strength with higher concentration, and polyacrylamide apparently outperform guar gum. The mixture of polyacrylamide and guar gum could improve the unconfined compressive strength performance than if they are used individually in red sand. Response surface test further illustrates that the optimum combination of polymer concentration and mixing ratio are 0.94 wt. % and 0.6 (PAM : Total), respectively. A regression model was developed to determine unconfined compressive strength for different concentration and mixing ratio of the two investigated stabilizers in red sand.

This study is one of the tasks aiming at developing more effective dust control solutions by using chemical stabilizers. Most notably, this is one of the few studies to our knowledge to investigate the use of both synthetic and natural polymers for enhancing the structure strength of red sand for reducing dust pollution potentials. It is noted that the combination of polyacrylamide and guar gum improved the unconfined compressive strength of treated sand up to 1.5 times higher than each single stabilizer treatment. Results of this paper provide significant evidence that even though the single application of polymer could improve the unconfined compressive strength of treated

sand, the combination usage of non-ionic and cationic polymer may result in an advanced enhancement. With the identification of the optimal mix ratio, more economical dust control strategy could be achieved.

5.7 Acknowledgements

Chapter 6

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7. Chapter 7

The viscosity of polymer mixtures and environmental adaptability study in treating bauxite residue dust pollution

A good polymer stabilizer is environmental friendly, show good performance on conserving water, adhering sand particles and providing long term, adequate and stable dust control. This chapter focuses on a systematic environmental adaptability study of polymer stabilizers to evaluate their performance when facing wet condition, high temperature and long-term strong ultraviolent exposure. As the relationship between the viscosity of stabilizer solution and the penetration resistance is not clear, this chapter will also investigate the effect of stabilizer viscosities on the penetration resistance and final dust control performance of treated sand.

7.1 Abstract

The utilization of polymer stabilizers is a promising method in mitigating bauxite residue (red sand) dust pollution. Its thickening property could effectively bind sand particles by constructing crusts to withstand wind erosion. Previous studies recommended the mixture of polymer solutions for a better dust control performance. However, there are limited studies which discussed the effects their viscosity on the structure strength of formed crusts and the final erosion resistance. The environmental adaptability of polymer mixtures was also rarely investigated. Thus, this paper investigates the relationship between polymer viscosity, environmental adaptability and the final dust control performance. Results illustrated that the applied polymers have excellent ability in withstanding wetting, high temperature, and long-term ultraviolent exposure, which indicates a broad applicability in wet conditions and desert regions. For single cationic polymers or polymer mixtures containing cationic polymers, higher viscosity resulted in better crust strength and dust erosion resistance. Thus, the viscosity of polymer mixtures could be used to predict the structure strength of formed crust and the final erosion resistance of treated sand.

7.2 Introduction

Due to large scale bauxite mining and aluminium extraction via the Bayer Process, large amounts of bauxite residue are generated annually [35, 139]. At the end of 2014, the global bauxite residue inventory reached 3.5 billion tons [6, 35]. Bauxite residue is generally separated into a

coarse fraction named "red sand" with particle sizes >150μm and a fine fraction named "red mud" which is finer than 150μm [4]. As the bauxite residue is highly alkaline and contains large amounts of fine, heavy metal particles and some radioactive components, such as Uranium-238 and Thorium-232, direct discharge of bauxite residue is prohibited for its adverse impacts on humans and the ecosystem [37-39]. Some adverse impacts include human upper respiratory system damage, eye irritation due to red sand dust, soil salinity and water pH alteration [12].

Dry stacking is the most commonly used method for the disposal and storage of bauxite residue due to its advantages of having minimal soil and ground water contamination. In this method, red sand is used to build the dike wall for the disposal and drying of red mud. If left untreated, the surface of dike walls and the red mud is subjected to severe fugitive dust emission and thus requires effective management [176]. However, due to differences in chemical and physical properties, the method used for red mud dust control is different from that of the red sand. This paper only focuses on the dust control of red sand.

One potential approach to mitigating red sand dust pollution is the application of polymer stabilizers [167, 177, 178]. Polymer stabilizers are generally synthetic or naturalized, and both of these revealed effective strengthening effects on treated materials. For example, Liu et al. [54] and Ayeldeen et al. (Ayeldeen et al., 2017) reported an improvement of cohesion forces between sand particles after being treated by polymer stabilizers. Meanwhile, the compressive strength of treated sand was enhanced at higher stabilizer concentrations and was demonstrated by Zandieh et al. [57] and Chen et al. [151]. The improvement of structure strength is attributed to micro-mechanisms such as enhanced particle interactions and adhesion and the thicker polymer film, which is attributed to the viscosity of polymer stabilizers [112]. The relationship between stabilizers dynamic viscosity and dust control performance is not clear; however, the dynamic viscosity of the stabilizer solution was indicated to effectively and accurately predict the dust control performance [179]. Meanwhile, the improvement of the environmental adaptability of polymer stabilizers and its impact on dust control efficiency lacks investigation.

Thus, this paper aims to investigate the relationship between polymer stabilizers viscosity, environmental adaptability and the corresponding dust control performance. Their environmental adaptabilities are represented by the penetration resistance of the formed crust. We discussed and correlated the results of each test to determine the environmental adaptability of polymer mixtures and whether the solutions' dynamic viscosity might affect the penetration resistance and wind erosion resistance of treated sand. As shown in Figure 9, both individual polymer application and the application of two polymers combined were employed. The dynamic viscosities of polymer stabilizers at different concentrations were evaluated firstly. Wet-dry cycle tests, temperature bearing tests and UV aging tests were then conducted to investigate the actual performance of polymer stabilizers after exposure to rainfall and direct sunshine. Finally, wind tunnel tests were employed to analyse their enhancements on wind erosion resistance. Findings were useful in fulfilling the ultimate objectives of developing a more accurate and effective approach to evaluate and predict the dust control performance of polymer stabilizers, and to determine the optimum polymer combination.
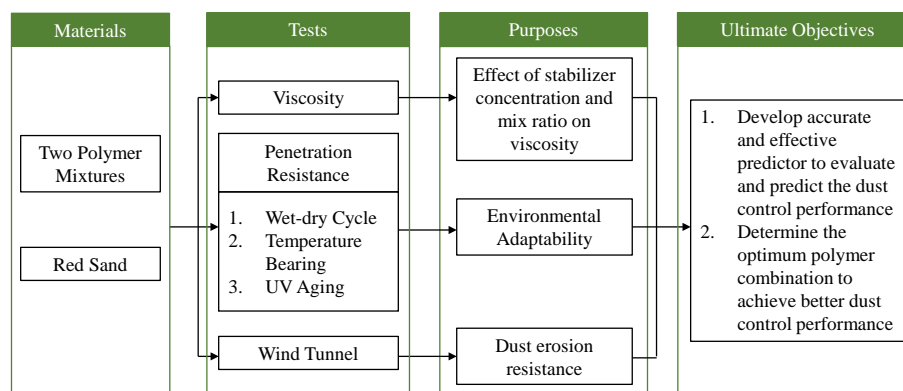
Figure 9. Experimental flowchart

7.3 Experiments

7.3.1 Materials

Three polymer stabilizers: non-cationic polyacrylamide (PAM), cationic guar gum and anionic xanthan gum, were used in this study. PAM is a synthetic polymer and the other two are natural polymers.

PAM is a linear polymer manufactured from acrylamide monomer with a molecular mass of 3-25 million g [155]. It is utilized in the removal of metal ions and organic matters [180-182], erosion control in agriculture irrigation and arid regions [18, 63, 64, 156], and helicopter landing pad enhancements [155]. The raw, non-cationic 1.6 wt. % PAM was purchased from *All Chemical Manufacturing & Consultancy* as a solution.

Xanthan gum belongs to the natural polysaccharide and was found in the 1950s. It is a kind of anionic linear linked $\beta - D$ glucose constituted by glucose, mannose and glucuronic with a molar ratio of 1.4:1:1 [183, 184]. The xanthan gum powder forms stable gel-type solutions when mixed with water owing to its excellent hydrophilic property [166, 185]. The pseudo-plasticity, thickening characters, and the high bearing capacity to temperature and pH allows xanthan gum to be used as thickener in industrial, mining, civil and food manufacturing fields [167, 186]. The raw xanthan gum was purchased from *Sigma Aldrich*.

Guar gum is a natural galactomannan processed from endosperm of cluster bean [158, 164, 177]. Similar to xanthan gum, cationic guar gum powder also forms a stable, transparent gel solution when properly mixed with water. It is commonly applied in the field of food manufacturing, medicine, and civil engineering as a thickener and precipitant [177, 178, 187-193]. The original guar gum powder was purchased from *Sigma Aldrich*.

Due to the lack of red sand availability, the red loam sand was purchased as a substitute for test samples. It has similar particle size distributions with red sand, and it is classified as poorly

graded sand (SP) based on the Unified Soil Classification System. The optimum moisture content and maximum dry density of the sand is 5.5 % and 2.16 g/cm^3, respectively.

Sand was dried and then sieved to finer than 1.18 mm to ensure consistency of particle conditions. Stabilizer solutions and powders were diluted and dissolved with deionised water to pre-determined concentrations (0.4, 0.8 and 1.2 wt. %). Moulds for the penetration resistance measurements were cylindrical with a dimension of 10 cm (D) × 5 cm (H), and the dimension of cuboid moulds for wind tunnel test was 21.7 (L) × 14.2 cm (W) × 3.5 cm (H). Slight compaction was ensured when pouring sand into the moulds. After compaction, adequate deionized water was uniformly sprayed onto the levelled sand surface until the optimum moisture content was reached. Sand was then wrapped and sealed for one day to reproduce the moisture conditions of on-site red sand. After that, the electric sprayer was employed to uniformly spray the stabilizer solution onto the sand surface with an application rate of 2 L/m^2. Samples were then dried under ambient temperature and humidity before tests.

7.3.2 Dynamic Viscosity Test

Dynamic viscosity tests on stabilizer solutions were performed to investigate whether the polymer mixture solutions achieved higher dynamic viscosity than single polymer solutions, and also attempted to establish a relationship between the dynamic viscosity of stabilizers and the mechanical properties (penetration resistance) of its formed crust. The dynamic viscosity of polymer stabilizer solutions mainly reflected the internal friction between solute and solvent molecules. In this study, the effects of polymer concentrations were investigated at three levels: 0.4, 0.8 and 1.2 wt. %. For each concentration level, three different stabilizer mix ratios were selected: 1:3, 2:2 and 3:1. As temperature significantly affects the dynamic viscosity, all samples were tested under the ambient temperature of 20 ˚C. The detailed arrangements of these tests are shown in Table 6. Each combination was replicated three times.

Table 6 Arrangement of dynamic viscosity tests

Concentration	Stabilizer	Mix ratio
	PAM	4:0
	GG	4:0
	XG	4:0
	PAM:GG	1:3
	PAM:GG	2:2
	PAM:GG	3:1
0.4 wt. %	PAM:XG	1:3
	PAM:XG	2:2
	PAM:XG	3:1
	GG:XG	1:3
	GG:XG	2:2
	GG:XG	3:1
	PAM	4:0
	GG	4:0
	XG	4:0
	PAM:GG	1:3
	PAM:GG	2:2
	PAM:GG	3:1
0.8 wt. %	PAM:XG	1:3
	PAM:XG	2:2
	PAM:XG	3:1
	GG:XG	1:3
	GG:XG	2:2
	GG:XG	3:1
	PAM	4:0
	GG	4:0
	XG	4:0
	PAM:GG	1:3
	PAM:GG	2:2
	PAM:GG	3:1
1.2 wt. %	PAM:XG	1:3
	PAM:XG	2:2
	PAM:XG	3:1
	GG:XG	1:3
	GG:XG	2:2
	GG:XG	3:1

7.3.3 Penetration Resistance Tests

7.3.3.1 Wet-dry cycling tests and temperature bearing tests

Wet-dry cycle tests were utilized to investigate the water resisting capacity of each stabilizer by testing the penetration resistance of formed crusts after numbers of wetting-drying cycles. In this study, four factors were considered: polymer mixtures (PAM&GG, GG&XG, and PAM&XG), mixture concentrations (0.4, 0.8 and 1.2 wt. %), mix ratios (1:3, 2:2 and 3:1), and the number of cycles (0, 1 and 2). L9 (3^4) orthogonal design was employed to reduce the number of runs. Detailed arrangement of the wet-dry cycle tests is described in Table 7. Each combination was replicated

three times. Samples for these tests were prepared as described in section 7.3.2. For each wetting cycle, 2 L/m^2 of deionized water was sprayed uniformly onto the surface of dried crust. As shown in Figure 10, the penetration resistance test was conducted after the crust was dried entirely. The STX-100 soil tri-axial test system was employed with a self-designed extension connector and needle to measure the penetration resistance. The penetration rate was fixed at 5mm/min. The needle used for this test was 2mm in diameter and 30° in cone angle.
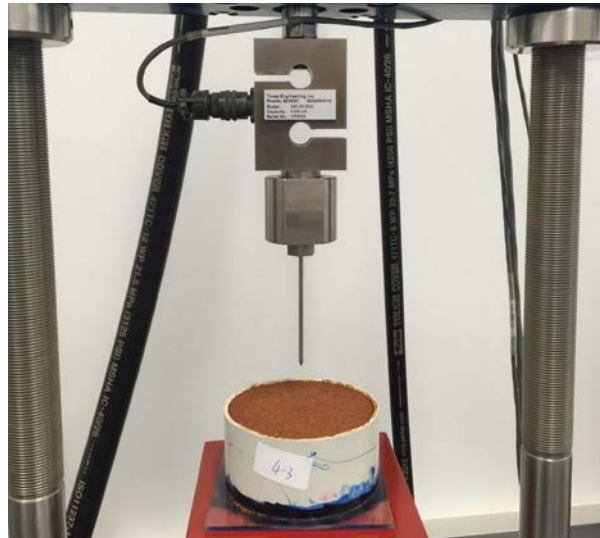
Figure 10. Penetration resistance test apparatus

Table 7 Orthogonal experimental design for the environmental adaptability test

Run	Stabilizer	Concentration (Wt. %)	Mix ratio	Number of Cycles	Exposure Duration (day)
1	PAM:GG	0.8	2:2	1	6
2	PAM:XG	0.8	1:3	2	9
3	PAM:XG	1.2	2:2	0	3
4	PAM:XG	0.4	3:1	1	6
5	PAM:GG	1.2	3:1	2	9
6	PAM:GG	0.4	1:3	0	3
7	GG:XG	0.8	3:1	0	3
8	GG:XG	1.2	1:3	1	6
9	GG:XG	0.4	2:2	2	9

Temperature bearing tests investigated the adaptability of polymers in high temperature areas. Penetration tests were conducted on samples cured for one week under ambient conditions and a 50 °C environment. Three factors were considered: the stabilizer mixture types, stabilizer concentrations, and mix ratios. Levels of each factor are the same with those described in section 7.3.3.1.

7.3.3.2 UV Aging Test

UV aging tests simulated the anti-aging properties of polymer treated samples when exposed to direct sunlight for long periods of time. The aging resistance of the consolidated layer (formed crust) is one of the basic predictors for evaluating the service life of the stabilizers. As the storage of bauxite residue is generally located in desert climates with long-term direct sunshine and high UV intensity, this experiment was performed in a UV aging oven which had two UVA-340 UV tubes. A few days or weeks of direct ultraviolet radiation in the oven was equivalent to months or years of exposure to sunlight onsite. In this study, the UV exposure duration is setup as a factor. Three, six and nine days of exposure was performed on 27 samples by following the L9 (3^4) orthogonal experimental design as described in Table 7. Each run was replicated three times.

7.3.4 Wind Tunnel Test

Wind tunnel simulations offer a more effective and accurate environment to investigate the dust control performance of stabilizers. In this study, wind speed was fixed at 20 m/s, which was consistent with the maximum wind velocity observed onsite. Dried samples prepared in cuboid moulds were placed onto the tray holder in the wind tunnel with a 30˚ angle (as shown in Figure 11) to reflect the slope of the dike wall of the actual residue drying area. The weight change of each sample was recorded every two minutes. Crust protective periods were also monitored. Each run was replicated thrice and the failure time was determined with the averaged data.
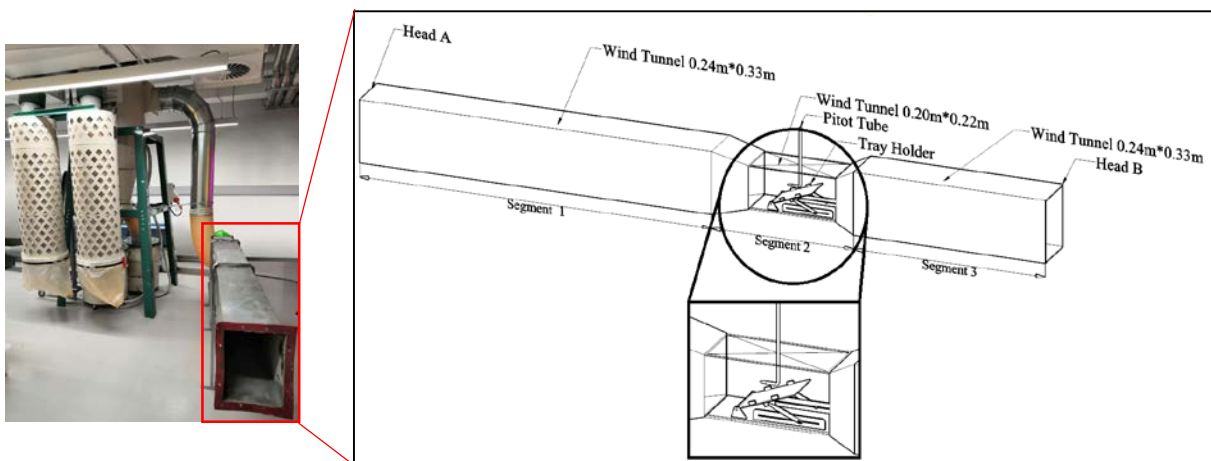

Figure 11. Diagram of wind tunnel simulation system

7.5 Results and Discussion

For non-Newtonian fluids, the dynamic viscosities decrease at higher shear rates. Figure 12 shows the dynamic viscosity comparison of each single polymer solution. It is noted that the dynamic viscosities of each polymer solution increased with higher concentrations, but these improvements are less obvious at higher concentrations. The increased viscosity may be caused by the increased amount of hydration water around polymer molecules which reduces the flexibility of the polymer chain [194]. The dynamic viscosity of xanthan gum solution is higher than PAM and guar gum. This superiority is inconspicuous at lower concentrations but tends to be more evident at higher concentrations.

Figure 13 shows the test results for the polymer mixtures, and they demonstrated that higher concentration resulted in higher viscosity (red lines are generally higher). It revealed that when two polymers are mixed, the increase of viscosity is dominated by the concentration of one polymer. For example, for the PAM-GG mixture, the viscosity increased with higher PAM content (in Figure 13 (a), for concentrations with same coloured lines, round dotted line is higher than the other two). However, for GG-XG and PAM-XG mixtures, the xanthan gum content is the major factor that influenced viscosity (in Figure 13 (b) and (c), triangle dotted line is higher than the other two lines with the same colour). Overall, the PAM-XG mixture generated the highest viscosity.

To compare the viscosities of single polymer and polymer mixture solutions, the test results are represented in Figure 14 using 0.8% as the representative concentration. It was shown that the viscosity of polymer mixtures was not necessarily higher than each single polymer solution. PAM-GG mixture revealed higher dynamic viscosities compared with each single polymer solution (Figure 14 (a)). However, PAM-XG and GG-XG mixtures resulted in significant reductions in dynamic viscosity (Figure 14 (b) and (c)).
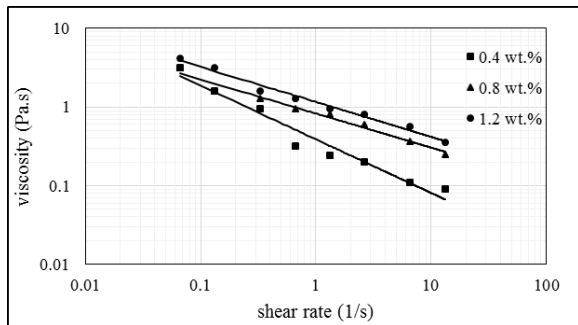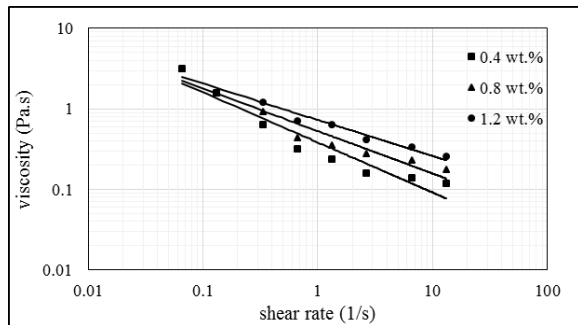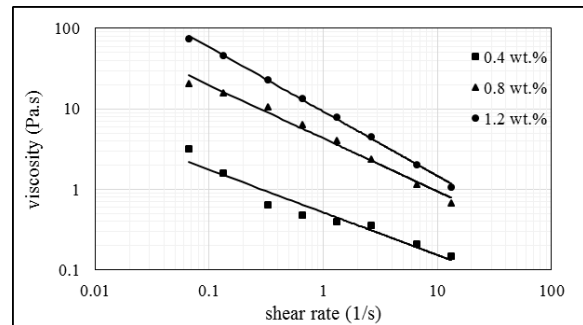
(a) PAM   (b) guar gum   (c) xanthan gum
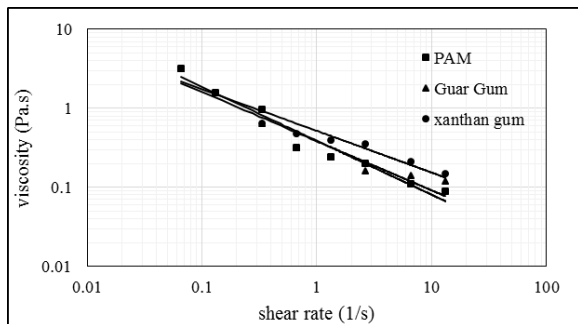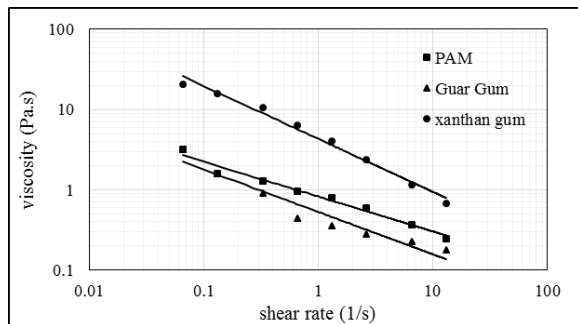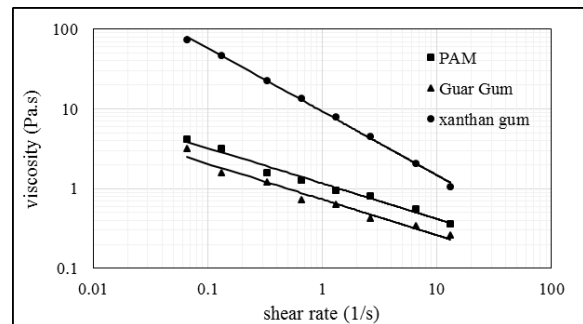
(d) 0.4 wt. %   (e) 0.8 wt. %   (f) 1.2 wt. %

Figure 12. Dynamic viscosity comparison of single polymer solutions

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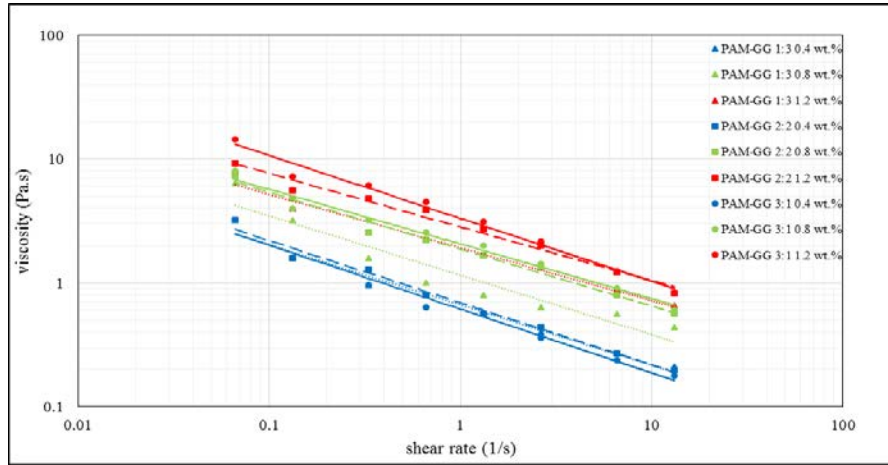
(a) PAM-GG
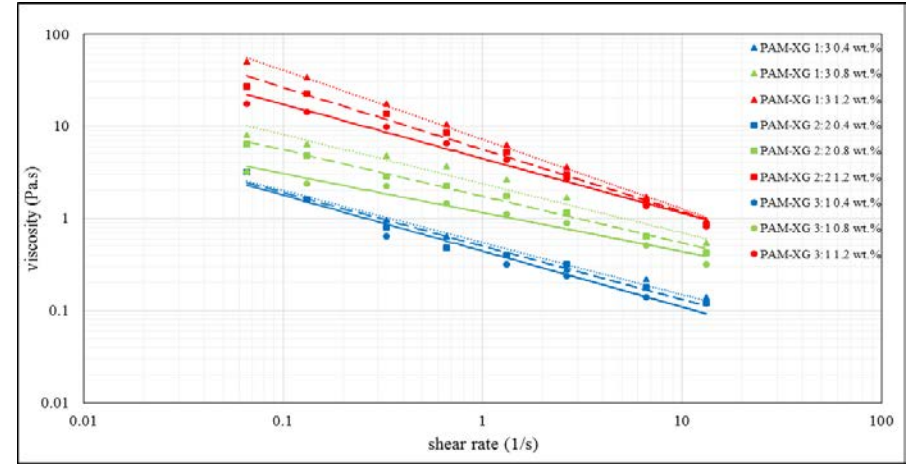
(b) PAM-XG
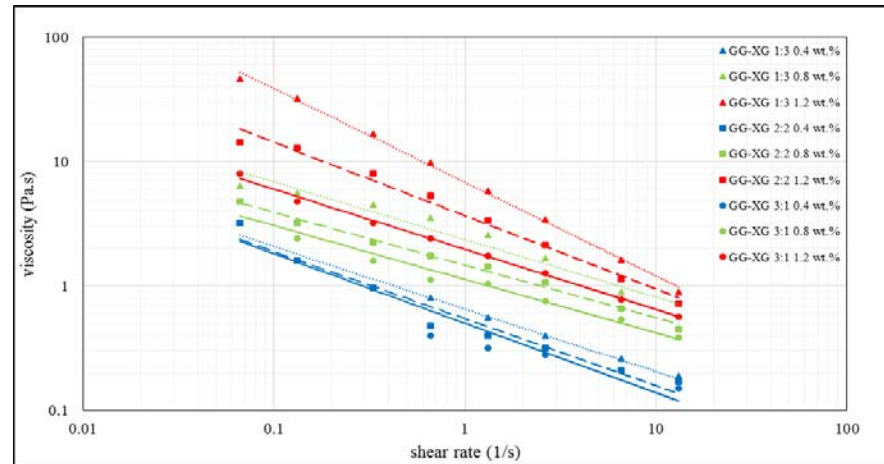
(c) GG-XG

Figure 13. Dynamic viscosity comparison of two polymer mixtures

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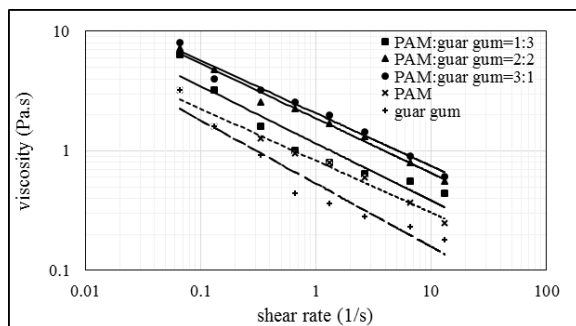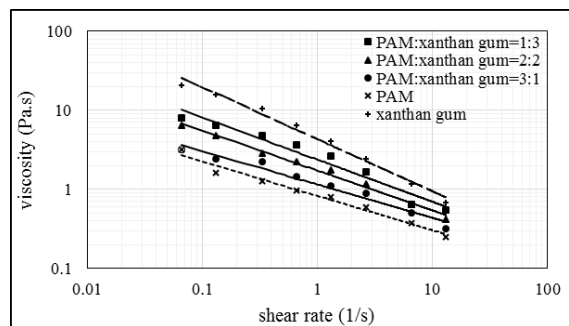
(a) PAM and guar gum   (b) PAM and xanthan gum   (c) guar gum and xanthan gum
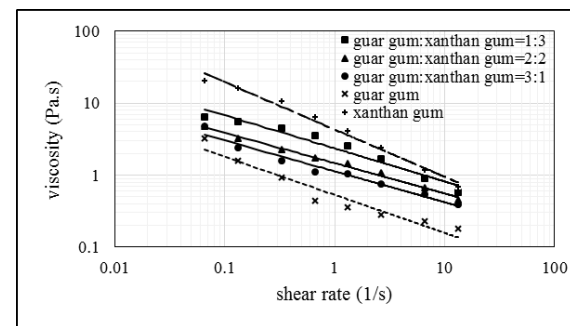
Figure 14. Dynamic viscosity comparison of polymers mixture at different mix ratio (0.8 wt. %)

Table 8 shows the data analysis of the orthogonal experimental design for the wet-dry cycling tests. It demonstrated that the number of the wet-dry cycles do not influence the penetration resistance. The absolute range refers to the absolute value of the difference between the maximum and minimum "k_n", which reflects the significance of each factor. The value for factor 4 (number of wettings) is much lower than factor 2 (mixture concentration) and factor 3 (mix ratio). One possible explanation is, with the loss of water during exposure to the atmosphere, the polymer chain tends to aggregate to form a film structure or a single, linear, longer polymer chain. During this process, the hydroxyl and carboxyl groups tend to complex with the SiO_2 and metal cations of sand particles. As a result, the polymer and sand particles are able to form surface crusts which are insoluble, elastic, and strong. As these processes are irreversible in water, the formed crust is able to withstand water disintegration. By using Table 8, the optimum combination of each factor, for the highest penetration resistance, was found to be with 1.2 wt. % GG-XG mixture at 1:3 mix ratio and two wetting cycles. This was determined by the corresponding levels for each factor with the highest "k_n" value (the average of each level).

Table 8 Data analysis of wet-dry cycling tests

| Runs	Factor 1 Polymer mixture	Factor 2 Mixture concentration (wt. %)	Factor 3 Mix ratio	Factor 4 Number of wettings	Penetration resistance (N) averaged
1	PAM:GG	0.4	1:3	0	17.08
2	PAM:GG	0.8	2:2	1	21.74
3	PAM:GG	1.2	3:1	2	25.7
4	GG:XG	0.4	2:2	2	15.32
5	GG:XG	0.8	3:1	0	19.22
6	GG:XG	1.2	1:3	1	32.4
7	PAM:XG	0.4	3:1	1	13.72
8	PAM:XG	0.8	1:3	2	22.08
9	PAM:XG	1.2	2:2	0	28.75
K_1	64.52	46.12	71.56	65.05	
K_2	66.94	63.04	65.81	67.86	
K_3	64.55	86.85	58.64	63.1	
k_1	21.51	15.37	23.85	21.68	
k_2	22.31	21.01	21.94	22.62	
k_3	21.52	28.95	19.55	21.03	
Absolute Range	0.8	13.58	4.3	1.62	

The data analysis of the orthogonal experimental design for the temperature bearing test is presented in Table 9. The absolute range value for each factor shows that the penetration resistance

is only affected by the polymer concentration and the mix ratio. The absolute range of polymer concentrations and mix ratios are 13.72 and 4.6, respectively, which is significantly higher than that of the polymer mixtures types. This result is consistent with the findings from Table 8 where specimens were treated at 20 ˚C. The highest penetration resistance was observed at the concentration of 1.2 wt. % and the mix ratio of 1:3.

The penetration resistance comparisons between 20 ˚C and 50 ˚C are displayed in

Figure 15, which demonstrated that the penetration resistance increased at higher temperatures. The penetration resistance of specimens treated at 50 ˚C is 1.1 to 1.25 times of those which were cured at ambient temperature.

Observations also revealed that the temperature could also change the brittleness of the crust formed by polymer mixtures. The brittleness of the crusts treated at 50 ˚C was obviously higher than those that were treated at ambient temperature. During the test, penetration resistance of crust treated at 50 ˚C decreased dramatically after reaching the peak value instead of a period of vibration near the peak value which was observed for crust treated at 20 ˚C.

Table 9 Data analysis of temperature bearing tests at 50 ℃

Runs	Factor 1 Polymer mixture	Factor 2 Mixture concentration (wt. %)	Factor 3 Mix ratio	Penetration resistance (N) Averaged
1	PAM:GG	0.4	1:3	20.55
2	PAM:XG	0.8	1:3	26.92
3	PAM:GG	1.2	3:1	29.73
4	GG:XG	0.8	3:1	23.38
5	PAM:XG	0.4	3:1	17.13
6	GG:XG	1.2	1:3	36.56
7	PAM:XG	1.2	2:2	31.31
8	PAM:GG	0.8	2:2	24.53
9	GG:XG	0.4	2:2	18.74
K_1	74.81	56.42	84.03	
K_2	78.68	74.83	74.58	
K_3	75.36	97.6	70.24	
k_1	24.94	18.81	28.01	
k_2	26.23	24.95	24.86	
k_3	25.12	32.53	23.41	
Absolute Range	1.29	13.72	4.6	
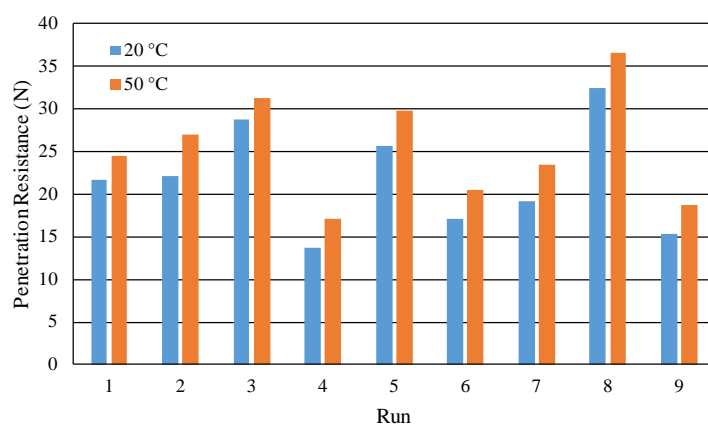
Figure 15. Penetration resistance of crust treated at 50 ˚C and 20 ˚C

Figure 16 provides a comparison of the crust penetration resistances before and after UV exposure. It was apparent that penetration resistances were increased after UV exposure. Regardless of the type of polymer mixture, concentration and mix ratio, UV treated crusts showed an improvement of 1.16 to 1.25 times on penetration resistance. During the tests, the crusts and samples remained intact and no colour changes were observed with the prolonged exposure period.

The data analysis of the orthogonal experimental design for the penetration test results under different UV exposure durations (3-9 days) are presented in Table 10. Similar to other test results, the mixture concentration and mix ratio significantly affected the resulting crust penetration resistance. The absolute range of mixture concentrations and mix ratios are 18.39 and 4.89, respectively, which are obviously higher than the other two factors. Compared to Figure 16, it suggests UV treatment of samples was a significant factor that improved the formed crust strength. SNK-Q test of the UV aging data performed in Table 11 identified whether the means of penetration resistance are significantly different from each other. Results indicated that although slight improvement on penetration resistance was observed due to longer UV aging period, this improvement was identified as insignificant, which means the length of UV aging is insignificant to the corresponding penetration resistance. The highest penetration resistance was observed in guar gum-xanthan gum mixture at 1.2 wt. % and 1:3 mix ratio.

Table 10 Data analysis of UV-aging tests

Runs	Factor 1 Polymer mixture	Factor 2 Mixture concentration (wt. %)	Factor 3 Mix ratio	Factor 4 UV duration (day)	Penetration resistance (N) Averaged
1	PAM:XG	1.2	2:2	3	39.53
2	PAM:GG	0.8	2:2	6	29.63
3	PAM:XG	0.4	3:1	6	20.92
4	GG:XG	1.2	1:3	6	43.52
5	GG:XG	0.4	2:2	9	22.75
6	PAM:GG	0.4	1:3	3	23.15
7	PAM:XG	0.8	1:3	9	33.34
8	GG:XG	0.8	3:1	3	25.51
9	PAM:GG	1.2	3:1	9	38.93
K_1	91.71	66.82	100.01	88.19	
K_2	91.78	88.48	91.91	94.07	
K_3	93.79	121.98	85.36	95.02	
k_1	30.57	22.27	33.34	29.40	
k_2	30.59	29.49	30.64	31.36	
k_3	31.26	40.66	28.45	31.67	
Absolute Range	0.69	18.39	4.89	2.27	
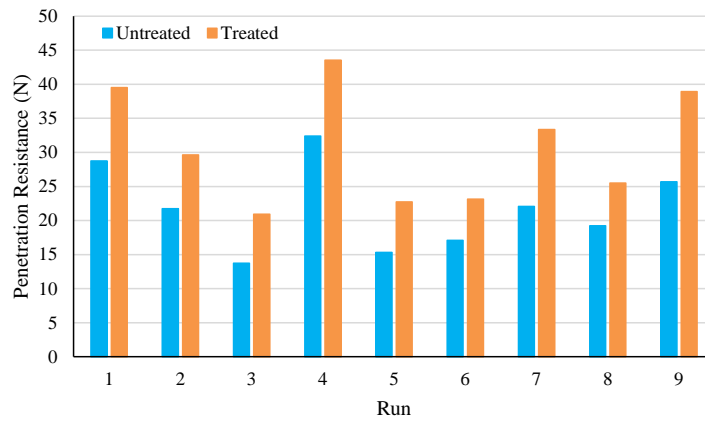
Figure 16. Penetration resistance comparison of UV treated and untreated samples

Table 11 SNK-Q test of UV aging data

Time period of UV aging		
SNK-Q		α=0.05
UV aging duration	N	1
3 days	3	0.1601
6 days	3	0.2065
9 days	3	0.2540
Significance		0.216

The data analysis of the orthogonal experimental design for wind tunnel test is illustrated in Table 12. Only the mixture concentration and the mix ratio significantly affected the crust failure time. The absolute range of mixture concentration and mix ratio are 22.77 and 6.45, respectively,

which are greater than that of the type of polymer mixtures. The crust with the longest failure time was formed by the GG-XG mixture with 1.2 wt. % concentration and 1:3 mix ratio.

Figure 17 shows the change in penetration resistance and wind tunnel failure time for solutions with different viscosities (at the shear rate of 0.33/s). It could be observed that the two-polymer mixtures with higher viscosities indicated better crust strength and advanced wind erosion resistance. Also, the relationship between the viscosity and the penetration resistance, and between the viscosity and the crust average failure time are all logarithmic. Thus, the viscosity of polymer mixtures could be used as an index to predict the final dust control performance in a cost and time effective manner. The overall ranking for the above three tests are listed as:

$GG\!:\!XG\ (1\!:\!3 - 1.2\ \text{wt.\%}) > PAM\!:\!XG\ (2\!:\!2 - 1.2\ \text{wt.\%}) > PAM\!:\!GG\ (3\!:\!1 - 1.2\ \text{wt.\%})$

$> PAM\!:\!XG\ (1\!:\!3 - 0.8\ \text{wt.\%}) > PAM\!:\!GG\ (2\!:\!2 - 0.8\ \text{wt.\%}) > GG\!:\!XG\ (3\!:\!1 - 0.8\ \text{wt.\%})$

$> PAM\!:\!GG\ (1\!:\!3 - 0.4\ \text{wt.\%}) > GG\!:\!XG\ (2\!:\!2 - 0.4\ \text{wt.\%}) > PAM\!:\!XG\ (3\!:\!1 - 0.4\ \text{wt.\%})$

Table 12 Crust failure time

Runs	Factor 1 Polymer mixture	Factor 2 Mixture concentration (wt. %)	Factor 3 Mix ratio	Failure Time (min)
1	GG:XG	0.8	3:1	19.46
2	PAM:GG	0.4	1:3	15.01
3	PAM:XG	0.4	3:1	11.71
4	GG:XG	1.2	1:3	40.46
5	PAM:GG	0.8	2:2	22.62
6	GG:XG	0.4	2:2	14.46
7	PAM:XG	0.8	1:3	27.44
8	PAM:GG	1.2	3:1	32.40
9	PAM:XG	1.2	2:2	36.62
K_1	70.03	41.18	82.91	
K_2	74.38	69.52	73.70	
K_3	75.77	109.48	63.57	
k_1	23.34	13.73	27.64	
k_2	24.79	23.17	24.57	
k_3	25.26	36.49	21.19	
Absolute Range	1.91	22.77	6.45	
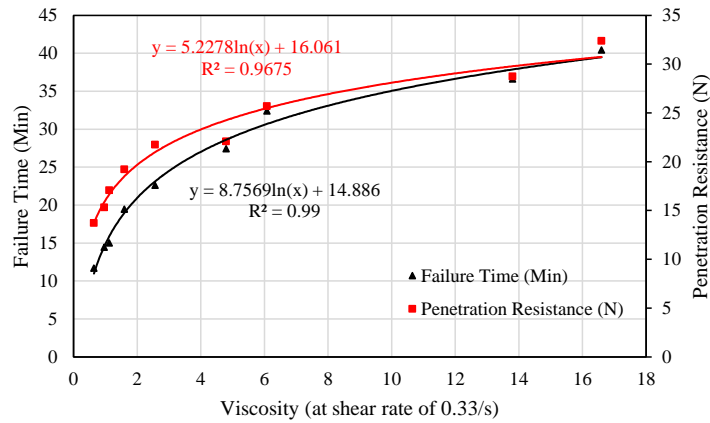
Figure 17. Relationship between the viscosity and penetration resistance and the final crust failure time

Ding et al. [179] presented study results for the individual use of the same three polymer stabilizers. These results are compared with the combined experimental data obtained in the current study in Figure 18 and Figure 19. Results revealed that two-polymer mixture is more effective in improving the structure strength and dust erosion resistance of treated sand than the individual polymer application. For example, for the concentration of 0.4 wt. %, the penetration resistance and crust failure time of two-polymer mixture treated sand was 2.23-2.99 and 1.90-2.10 times higher than those treated by individual polymers, respectively. These improvement were 3.23-3.54 and 2.21-3.09 times higher for the concentration of 0.8 wt. %, and 2.98-4.51 and 2.27 to 3.19 times higher for the concentration of 1.2 wt. %. This indicated a more significant advance of the combined application of polymers at higher concentrations.

By comparing the viscosity of each of the individual polymer stabilizers, it could also be noted that stabilizers with higher viscosity provide higher penetration and dust erosion resistance, and the only exception is the individual application of xanthan gum. One possible explanation to this phenomenon is due to the ionicity. Anionic xanthan gum is unable to react with the negatively charged sand particles via the neutralization process, which is important for better bonding performance [55]. Therefore, although xanthan gum solution has a higher viscosity, it lacked in enhancing the sand surface strength compared with the other two cationic polymers (PAM and guar gum), which have much lower viscosities.
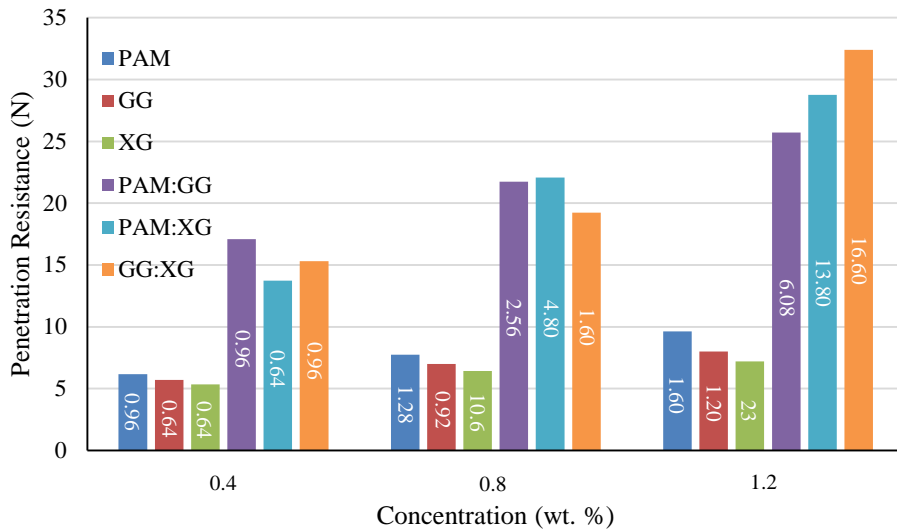
Figure 18. Penetration resistance comparison of polymer stabilizers treated samples (labels on the columns denote the viscosity values Pa·s)
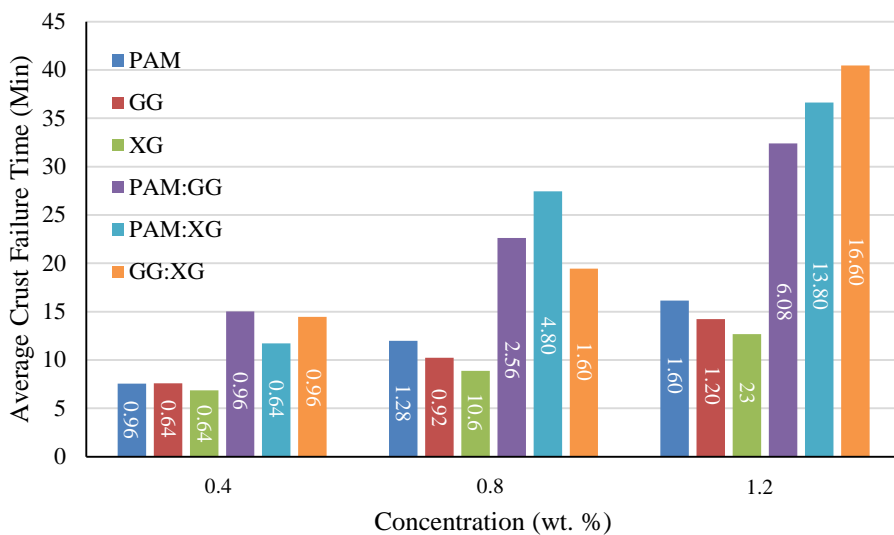
Figure 19. Average crust failure time comparison of polymer stabilizers treated samples (labels on the columns denote the viscosity values Pa·s)

7.6 Conclusions

This study illustrated that the combined application of polymer stabilizers is superior to that of the individual application. Combined application provided higher penetration resistance and prolonged crust protective period. For two-polymer mixture treated samples, an increase of 4.51 times the penetration resistance and 3.19 times the crust average failure was observed.

For environmental adaptability tests, which are quantified by the penetration resistance of the formed crust, it was noted that the penetration resistance was not affected by the number of wet-dry cycles and was improved with higher environmental temperature. Results of ultraviolent aging tests revealed that the existence of ultraviolent treatment, rather than duration of ultraviolent aging, was more significant to the penetration resistance. Crusts treated by ultraviolent for more than 3 days illustrated obvious improvements to their penetration resistances.

This study also indicated that stabilizers with higher viscosity provided higher penetration and dust erosion resistance except for the individually applied anionic xanthan gum. The penetration resistance and the wind erosion resistance were consistent with the viscosity of polymer mixtures. The polymer with higher viscosity revealed higher crust strength and better erosion resistance. Thus, the viscosity of polymer mixtures is able to predict the structure strength of formed crusts and the final erosion resistances of treated sand. guar gum-xanthan gum mixture with 1.2 wt. % concentration and 1:3 mix ratio is recommended for its outperforming penetration resistance and dust control performance.

Most notably, this is the first study to the author's knowledge that correlated the viscosity of polymer solutions to the penetration resistance and dust control performance in the field of chemical stabilization of bauxite residue. Results presented in this paper confirmed that the higher viscosity of polymer solutions produced more effective dust erosion resistance. This relationship provides compelling evidence to the reasonability of the viscosity for being an accurate and time-effective predictor of dust control performance. Findings and research methods of this study could be used as references for the extended dust control study on similar sandy materials, for it could greatly reduce the time and cost for polymer performance verification during field practise.

7.7 Acknowledgements

8. Chapter 8

Conclusions and Future Work

8.1 Conclusions

This thesis includes a review paper and several research papers which investigate a new strategy and analysing system for the purpose of bauxite residue (red sand) dust control. This provides a simple and fast way to determine the dust control performance of all the stabilizers with appropriate accuracy, which reduces the time, economical and labour cost.

A comprehensive review of the previous studies has been performed to analyse the unique advantages and shortages of each primary non-traditional stabilizers in treating bauxite residue dust pollution. It is noted that polymer stabilizers achieve the best dust control performance with the highest cost as well. Lignosulfonate stabilizers could achieve the second highest dust control performance with the lowest cost and completely environmental friendliness. The performance of the resin stabilizers is relative lower, it more suitable to be used as additives rather than primary materials for its expensive price. Results also illustrated that the dust reduction rate is closely related to physical and mechanical properties. The unconfined compressive strength and penetration resistance are key indices to predict the final dust control performance when applying lignosulfonate stabilizers.

A cost and time effective approach and effective predictors for red sand dust control by applying non-traditional stabilizers has been developed and evaluated in this thesis. Firstly, the study of lignosulfonate stabilizers presented in Chapter 4 illustrated that utilization of lignosulfonate stabilizers significantly improves the structure properties and wind erosion resistance of treated sand. Better dust control performance was observed at higher penetration resistance and unconfined compressive strength. Thus, the penetration resistance or unconfined compressive strength could be used as index for evaluating LS dust control performance instead of in-situ practise which requires long-term and high cost. Secondly, the studies presented in Chapter 5 to Chapter 7 which investigated the individual application and the combination of polymer stabilizers in treating red

sand dust control demonstrated that the application of polymer stabilizer can greatly improve the structure strength and reduce dust erosion of treated red sand, and synthetic polymer performs better that natural polymers. The combination of different polymer stabilizer revealed superior performance than individual application. As better penetration resistance and higher solution viscosity resulted by higher stabilizer concentration benefit enhanced dust erosion resistance. The penetration resistance and the viscosity of polymer stabilizers could be utilized as key indices to predict the structure strength of formed crust and the final erosion resistance of treated sand.

For lignosulfonate stabilizers, bauxite residue is better controlled by higher penetration resistance and unconfined compressive strength of treated sand, as they are effective indices to predict dust control performance. For polymer stabilizer, better bauxite residue dust control is achieved by the combined application of different polymers with higher penetration resistance of treated sand and higher viscosity of polymer solutions, as penetration resistance and viscosity can accurately predict dust control performance.

Most notably, findings and research methods of this study can be used as references for the extended dust control study on similar sandy materials, for it can greatly reduce the time and cost for polymer performance verification during field practise.

8.2 Highlights of Accomplished Studies

The research presented in this thesis is proved to be successful in providing a more efficient and accuracy strategy and evaluation system for the bauxite residue (red sand) dust control by applying non-traditional stabilizers. Key highlights of the accomplished studies are:

- The mechanism of dust emission and how non-traditional stabilizers enhance the forces and energy of bonding between sand particles has been well illustrated.

- The mechanical properties and the dust erosion resistance of non-traditional stabilizers treated sand are systematically investigated and correlated. Key indices for predicting

the actual performance of each kind of stabilizers has been nominated and proved. This suggested a timely and cost effective method for bauxite residue dust control.

- The combined effect of different stabilizers has been studies alongside the individual application. Results is sound that the stabilizers mixture could achieve better dust control efficiency than each single stabilizer when applied to red sand.

- One hypothesis that the performance of a stabilizer is not only determined by its ionicity, but also relies on its viscosity, has been proved. The viscosity could be regarded as another significant index for dust control performance prediction when applying polymer stabilizers. Higher viscosity of stabilizer solution could result in better dust control performance.

8.3 Limitations and Future Work

Although the studies presented in this thesis is significant to bauxite residue mining industry that provided a most effective method for residue sand dust control, some limitations still exist which need to be improved in future works.

Due to the confidential policy of bauxite mining companies, the source of bauxite residue (red sand) is restricted. Thus, one red loam sand was used as a substitute for making test sample. Although the physical properties and chemical components of the red loam sand is found to be similar with actual sand. The small difference existed is still believed to bring uncertain effect to the final test results. Therefore, the adoption of actual red sand to further prove the findings presented in this thesis is necessary for a sound dust control strategy.

The studies in this thesis mainly focused on two primary non-traditional stabilizers which are polymers and lignosulfonates. However, as discussed in Chapter 2, resin stabilizers include synthetic and natural resins also have the potential to reduce red sand dust erosion for their excellent water retention property, high unit efficiency (small quantity could achieve good performance) and high adaptability to wet conditions. Meanwhile, other kinds of non-traditional stabilizers such as

salts and bio-stabilizers also attracted more attention in recent decades. Thus, more work needs to be done on investigating their performance for a more comprehensive dust control strategy.

As illustrated in Chapter 2, the combination of different non-traditional chemical stabilizers may achieve better performance than using a single stabilizer. However, the study of the combination effect was only performed on different polymer stabilizers. Whether this conclusion is general to other kind of stabilizer still need further studies.

References

[1]   IAI. 2013. Background information on typical bauxite residue. European Aluminium Association.

[2]   WorldBank. 2017. Commodity Markets Outlook.

[3]   Alcoa. 2007. Dust management plan for the Alcoa Pinjarra bauxite residue disposal area.

[4]   Howe PL, Clark MW, Reichelt-Brushett A, Johnston M. 2011. Toxicity of raw and neutralized bauxite refinery residue liquors to the freshwater cladoceran Ceriodaphnia dubia and the marine amphipod Paracalliope australis. *Environmental toxicology and chemistry* 30:2817-2824.

[5]   Li Y, Haynes R, Zhou Y-F, Chandrawana I. 2016. Chemical and physical properties of seawater-neutralized bauxite residue mud and sand and the effects of leaching. *International Journal of Environmental Science and Development* 7:273.

[6]   Klauber C, Gräfe M, Power G. 2011. Bauxite residue issues: II. options for residue utilization. *Hydrometallurgy* 108:11-32.

[7]   Evans K. 2016. The history, challenges, and new developments in the management and use of bauxite residue. *Journal of Sustainable Metallurgy* 2:316-331.

[8]   Lombi E, Zhao F-J, Zhang G, Sun B, Fitz W, Zhang H, McGrath SP. 2002. In situ fixation of metals in soils using bauxite residue: chemical assessment. *Environmental pollution* 118:435-443.

[9]   Lombi E, Zhao F-J, Wieshammer G, Zhang G, McGrath SP. 2002. In situ fixation of metals in soils using bauxite residue: biological effects. *Environmental Pollution* 118:445-452.

[10]   Power G, Grafe M, Klauber C. 2011. Bauxite residue issues: I. current management, disposal and storage practices. *Hydrometallurgy* 108:33-45.

[11]   Klebercz O, Mayes WM, Anton ÁD, Feigl V, Jarvis AP, Gruiz K. 2012. Ecotoxicity of fluvial sediments downstream of the Ajka red mud spill, Hungary. *Journal of Environmental Monitoring* 14:2063-2071.

[12]   Ruyters S, Mertens J, Vassilieva E, Dehandschutter B, Poffijn A, Smolders E. 2011. The red mud accident in Ajka (Hungary): plant toxicity and trace metal bioavailability in red mud contaminated soil. *Environmental science & technology* 45:1616-1622.

[13]   Pagano G, de Biase A, Iaccarino M, Meric S, Petruzzelli D, Tünay O, Warnau M, Trieff NM. 2002. Bauxite manufacturing residues from Gardanne (France) and Portovesme (Italy) exert different patterns of pollution and toxicity to sea urchin embryos. *Environmental toxicology and chemistry* 21:1272-1278.

[14]   Latifi N, Marto A, Eisazadeh A. 2013. Structural Characteristics of Laterite Soil Treated by SH-85 and TX-85 (Non-Traditional) Stabilizers. *EJGE* 18:1707-1718.

[15]   Liu J, Shi B, Jiang H, Bae S, Huang H. 2009. Improvement of water-stability of clay aggregates admixed with aqueous polymer soil stabilizer. *CATENA* 77:175-179.

[16]   Chen Y, Tan Y. 2012. Test Study on Road Performance of Soils Stabilized by Liquid Stabilizer in Seasonally Frozen Regions. *Advanced Engineering Forum* 5:310-315.

[17]   Han Z, Wang T, Dong Z, Hu Y, Yao Z. 2007. Chemical stabilization of mobile dunefields along ahighway in the Taklimakan Desert of China. *Journal of Arid Environments* 68:260-270.

[18]   Genis A, Vulfson L, Ben-Asher J. 2013. Combating wind erosion of sandy soils and crop damage in the coastal deserts: Wind tunnel experiments. *Aeolian RESEARCH* 9:69-73.

[19]   Lentz RD, Sojka RE. 2000. Applying polymers to irrigation water: Evaluating strategies for furrow erosion control. *Transactions of the ASAE* 43:1561.

[20]   Yan L, Yang J. 2009. Research Status and Prospect of Novel Chemical Sand-fixing Materials. *Materials Review* 23:51-54.

[21]   Tingle JS, Newman JK, Larson SL, Weiss CA, Rushing JF. 2007. Stabilization Mechanisms of Nontraditional Additives. *Transportation Research Record: Journal of the Transportation Research Board*:59-67.

[22]   Indraratna B, Athukorala R, Vinod JS. 2013. Estimating the rate of erosion of a silty sand treated with lignosulfonate. *Journal of Geotechnical and Geoenvironmental Engineering* 139:701-714.

[23]   Rollings RS, Burkes JP, Rollings MP. 1999. Sulfate Attack on Cement-Stabilized Sand. *Journal of Geotechnical and Geoenvironmental Engineering* 125:364-372.

[24]   Vinod JS, Indraratna B, Mahamud MAA. 2010. Stabilisation of an erodible soil using a chemical admixture. *Institution of Civil Engineers Proceedings Ground Improvement* 163:43-52.

[25]   Biggs AJW, Mahony KM. 2004. IS SOIL SCIENCE RELEVANT TO ROAD INFRASTRUCTURE? , *13th International Soil Conservation Organisation Conference*. Brisbane, pp 1-7.

[26]   Perry JP. 1977. Lime treatment of dams constructed with dispersive clay soils. *Transactions of the ASAE* 20:1093-1099.

[27]   Kitchen NR, Sudduth KA, Drummond ST. 1996. Mapping of sand deposition from 1993 midwest floods with electromagnetic induction measurements. *Journal of Soil and Water Conservation* 51:336-340.

[28]   Nalbantoglu Z, Tuncer ER. 2001. Compressibility and hydraulic conductivity of a chemically treated expansive clay. *Canadian Geotechnical Journal* 38:154-160.

[29]   Shawqui LM, Neaz A. 1998. Effect of new soil stabilizers on the compressive strength of dune sand. *Construction and building Materials* 12:321-328.

[30]   Razavi M. 2013. Chemical Soil Stabilization. pp 1-28.

[31]   Evans K, Nordheim E, Tsesmelis K. 2012. Bauxite residue management. *Light Metals*:63-66.

[32]   Gräfe M, Power G, Klauber C. 2011. Bauxite residue issues: III. alkalinity and associated chemistry. *Hydrometallurgy* 108:60-79.

[33]   Cooling D. 2007. Improving the sustainability of residue management practices-Alcoa World Alumina Australia. *Paste and Thickened Tailings: A Guide*:3-16.

[34]   Power G, Grafe M, Klauber C. 2009. Review of current bauxite residue management, disposal and storage: practices, engineering and science. *National Research* 18.

[35]   Xue S, Zhu F, Kong X, Wu C, Huang L, Huang N, Hartley W. 2016. A review of the characterization and revegetation of bauxite residues (Red mud). *Environmental Science and Pollution Research* 23:1120-1132.

[36]   Klauber C, Harwood N, Hockridge R, Middleton C. 2016. Proposed mechanism for the formation of dust horizons on bauxite residue disposal areas. *Light Metals*:951-956.

[37]   Mayes W, Burke I, Gomes H, Anton Á, Molnár M, Feigl V, Ujaczki É. 2016. Advances in understanding environmental risks of red mud after the Ajka spill, Hungary. *Journal of Sustainable Metallurgy* 2:332-343.

[38]   Gelencsér As, Kováts Nr, Turóczi B, Rostási Ag, Hoffer As, Imre Kl, Nyirő-Kósa I, Csákberényi-Malasics D, Tóth Adm, Czitrovszky Ar. 2011. The red mud accident in Ajka (Hungary): characterization and potential health effects of fugitive dust. *Environmental science & technology* 45:1608-1615.

[39]   Dauvin J-C. 2010. Towards an impact assessment of bauxite red mud waste on the knowledge of the structure and functions of bathyal ecosystems: The example of the Cassidaigne canyon (north-western Mediterranean Sea). *Marine Pollution Bulletin* 60:197-206.

[40]   Santoni RL, Tingle JS, Webster SL. 2002. Stabilization of silty sand with nontraditional additives. *Transportation Research Record: Journal of the Transportation Research Board* 1787:61-70.

[41]   Tingle JS, Santoni RL. 2003. Stabilization of clay soils with nontraditional additives. *Transportation Research Record: Journal of the Transportation Research Board* 1819:72-84.

[42]   Shi B, Ning W, Xu W, Dai S. 2013. Application of con-aid soil stabilizer in expedient airfield pavement. *Journal of Traffic and Transportation Engineering* 13:25-33.

[43]   Jones D, Mitchley M. 2001. A reassessment of the use of ligno sulphonate as an additive for unsealed roads. *20th ARRB Conference*. Australia.

[44]   Koohpeyma HR, Vakili AH, Moayedi H, Panjsetooni A, Nazir R. 2013. Investigating the Effect of Lignosulfonate on Erosion Rate of the Embankments Constructed with Clayey Sand. *The Scientific World Journal* 2013:1-6.

[45]   Indraratna B, Athukorala R, Vinod JS. 2014. Erosion mitigation of lignosulfonate treated unstable soils. *7th International Congress on Environmental Geotechnics*:793-800.

[46]   Armbrust DV, Lyles L. 1975. Soil Stabilizers to Control Wind Erosion. *Soil Conditioner*:77-82.

[47]   Han Z, Hu Y, Chen G, Yao Z, Shao G. 2000. The Suitability of Chemical Engineering Stabilization in Controlling Aeolian Hazard Along the Highway in Tarim Basin. *Envionmental Science* 21:86-88.

[48]   Lentz RD, Sojka RE, Carter DL, Shainberg I. 1992. Preventing irrigation furrow erosion with small applications of polymers. *Soil Science Society of America Journal* 56:1926-1932.

[49]   Santoni RL, Tingle JS, Nieves M. 2002. Accelerated Strength Improvement of Silty Sand Using Nontraditional Additives. *TRB 2003 Annual Meeting*:1-19.

[50]   Mainfort R. 1955. Soil stabilization with resins and chemicals. *Highway Research Board Bulletin*.

[51]   Alazigha DP. 2015. The efficacy of lignosulfonate in controlling the swell potential of expansive soil and its stabilization mechanisms. Doctor of Philosophy thesis. University of Wollongong.

[52]   Lai J, Zhang K, Wang W, Wang Y, Xu X, Qu J, Xiao J. 2017. Research advances and prospect in chemical sand-fixing materials. *Journal of Desert Research* 37:644-658.

[53]   Zang Y-X, Gong W, Xie H, Liu B-L, Chen H-L. 2015. Chemical sand stabilization: A review of material, mechanism, and problems. *Environmental Technology Reviews* 4:119-132.

[54]   Liu J, Shi B, Jiang H, Huang H, Wang G, Kamai T. 2011. Research on the stabilization treatment of clay slope topsoil by organic polymer soil stabilizer. *Engineering Geology* 117:114-120.

[55]   Iyengar SR, Masad E, Rodriguez AK, Bazzi HS, Little D, Hanley HJM. 2013. Pavement subgrade stabilization using polymers: characterization and performance. *Journal of Material in Civil Engineering* 25:472-483.

[56]   Naeini SA, Ghorbanalizadeh M. 2010. Effect of Wet and Dry Conditions on Strength of Silty Sand Soils Stabilized with Epoxy Resin Polymer. *Journal of Applied Science* 10:2839-2846.

[57]   Zandieh AR, Yasrobi SS. 2010. Study of factors affecting the compressive strength of sandy soil stabilized with polymer. *Geotechnical and Geological Engineering* 28:139-145.

[58]   Naeini SA, Mahdavi A. 2009. Effect of Polymer on Shear Strength of Silty Sand. *EJGE* 14:1-11.

[59]   Huang H, Shi B, Liu J, Jiang H. 2008. Experimental study on application of STW ecotypic soil stabilizer in windbreak and sand fixation. *Chinese Journal of Geotechnical Engineering* 30:1900-1904.

[60]   Gao W, Wu Z, Wu Z. 2012. Study of mechanism of the W-OH sand fixation. *Journal of Environmental Protection*:1025-1033.

[61]   Yu J, Lei T, Shainberg I, Mamedov AI, Levy GJ. 2003. Infiltration and erosion in soils treated with dry PAM and gypsum. *Soil Science Society of America Journal* 67:630-636.

[62]   Aase JK, Bjorneberg DL, Sojka RE. 1998. Sprinkler irrigation runoff and erosion control with polyacrylamide - laboratory tests. *Soil Science Society of America Journal* 62:1681-1687.

[63]   He J, Cai Q, Tang Z. 2008. Wind tunnel experimental study on the effect of PAM on soil wind erosion control. *Environmental monitoring and assessment* 145:185-193.

[64]   Bjorneberg DL, Aase JK. 2000. Multiple polyacrylamide applications for controlling sprinkler irrigation runoff and erosion. *Applied Engineering in Agriculture* 16:501.

[65]   Jiang C, Shi B, Liu F, Liu J, Huang H. 2009. Study on soil improvement of expansive soil slope with ecotypic soil stabilizer in Ning-Huai Expressway. *Journal of Disaster Prevention and Mitigation Engineering* 29:507-512.

[66]   Huang H, Shi B, Liu J, Gao W, Jiang H. 2008. Experimental study on the strength of soil modified by STW ecotypic soil stabilizer. *Journal of Disaster Prevention and Mitigation Engineering* 28:87-97.

[67]   Chen Q, Indraratna B, Carter J, Rujikiatkamjorn C. 2014. A theoretical and experimental study on the behaviour of lignosulfonate-treated sandy silt. *Computers and Geotechnics* 61:316-327.

[68]   Gaëtan B, Olivier C, Farimah M. 2014. Soil treatment with organic non-traditional additives for the improvement of earthworks. *Acta Geotech* 9:1111-1122.

[69]   Rasika A. 2013. Geotechnical characteristics of an erodible soil stabilised by lignosulfonate–an analytical perspective. University of Wollongong.

[70]   Chen Q, Indraratna B. 2014. Shear behaviour of sandy silt treated with lignosulfonate. *Canadian Geotechnical Journal* 52:1180-1185.

[71]   Shulga G, Rekner F, Varslavan J. 2001. SW—Soil and Water: Lignin-based Interpolymer Complexes as a Novel Adhesive for Protection against Erosion of Sandy Soil. *Journal of Agricultural Engineering Research* 78:309-316.

[72]   Li J, Song Z. 2002. Study on Lignosulfonate and Its Grafted Polymers as Sandy Soil Stabilizers. *Chemistry and Industry of Forest Products* 22:17-20.

[73]   Li Y, Chen J, Zuo S, Ye M. 2014. Effect of Lignin Content on the Direct Shear Strength of Sprayed Soil Base Layer in Slope Restorations. *Soil Eng and Foundation* 28:121-123.

[74]   Ram G, Jeevan S, Ghanshyam D. 2013. Chemical stabilisation of sand: Part VII Natural resins as dune sand stabiliser. *Defence Science Journal* 38:169-175.

[75]   Yang J, Wang F, Fang L, Tan T. 2007. Synthesis, characterization and application of a novel chemical sand-fixing agent-poly(aspartic acid) and its composites. *Environmental Pollution* 149:125-130.

[76]   Anagnostopoulos CA, Kandiliotis P, Malvina L, Sarafianos K. 2014. Improving Properties of Sand Using Epoxy Resin and Electrokinetics. *Geotechnical and Geological Engineering* 32:859-872.

[77]   Aksoy HS, Gor M. 2013. Effect of Natural Resin on Strength Parameters of Sandy Soil. *International Journal of Environmental Science and Development* 4:11.

[78]   Hsu C-l, Dai S-y, Chiang S-w, Chan C-y. 2010. Erosion control for mudstone soil with ventilation and watertight resin. *International Journal of Sediment Research* 25:194-201.

[79]   State of California - Business TaHA. 2000. California Test 221: Unconfined Compressive Strength of Soil. pp 1-4.

[80]   ASTM. 2016. D2166/D2166M-16. *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*. American Society for Testing and Materials International.

[81]   Sivakugan N, Arulrajah A, Bo MW. 2011. *Laboratory testing of soils, rocks and aggregates*. J. Ross, Fort Launderdale, FL, USA.

[82]   Al-Khanbashi A, El-Gamal M. 2002. Modification of sandy soil using water-borne polymer. *Journal of Applied Polymer Science* 88:2484-2491.

[83]   ASTM. 2016. D4253-16. *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*. American Society for Testing and Materials International.

[84]   Australian Standard. 1998. AS1289.6.2.2. *Soil strength and consolidation tests—Determination of the shear strength of a soil—Direct shear test using a shear box: Methods of testing soils for engineering purposes*. Australian Standards

[85]   ASTM. 2011. D3080/D3080M-11. *Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions*. American Society for Testing and Materials International.

[86]   GB/T. 1999. *Standard for soil test method, GB/T 50123-1999*.

[87]   Feng G, Sharratt B, Vaddella V. 2013. Windblown soil crust formation under light rainfall in a semiarid region. *Soil & Tillage Research* 128:91-96.

[88]   Gillette DA, Adams J, Muhs D, Kihl R. 1982. Threshold friction velocities and rupture moduli for crusted desert soils for the input of soil particles into the air. *Journal of Geophysical Research* 87:9003-9015.

[89]   Pluis JLA, Boxel JHv. 1993. Wind velocity and algal crusts in dune blowouts. *CATENA* 20:581-594.

[90]   Williams JD, Dobrowolski JP, West NE, Gillette DA. 1995. Microphytic crust and influence on wind erosion. *Transactions of the ASAE* 38:131-137.

[91]   Neuman CM, Maxwell CD, Boulton JW. 1996. Wind transport of sand surfaces with photoautotropic microoganisms. *CATENA* 27:229-247.

[92]   Reynolds R, Belnap J, Reheis M, Lamothe P, Luiszer F. 2001. Aeolian dust in Colorado Plateau soils: nutrient inputs and recent change in source. *Proceedings of the National Academy of Sciences* 98:7123-7127.

[93]   Zobeck TM, Popham TW. 1992. Influence of microrelief aggregate size, and precipitation on soil crust properties. *Transactions of the ASAE* 35:487-492.

[94]   Zobeck TM. 1991. Abrasion of Crusted Soils: Influence of Abrader Flux and Soil Properties. *Soil Science Society of America Journal* 55:1091-1097.

[95]   Chepil WS, Neal PW, Zingg AW. 1955. Field study of wind erosion in Western Texas.

[96]   Zobeck TM. 1991. Soil properties affecting wind erosion. *Journal of Soil and Water Conservation* 46:112-118.

[97]   Goossens D. 2010. Wind tunnel calibration of the USGS dust deposition sampler: Sampling efficiency and grain size correction. *Aeolian Research* 2:159-170.

[98]   Zingg AW. 1951. A Portable Wind Tunnel and Dust Collector Developed to Evaluate the Erodibility of Field Surfaces. *AGRONOMY JOURNAL*:pp. 189-191.

[99]   Chiou S-F, Tsai C-J. 2001. Measurement of emission factor of road dust in a wind tunnel. *Powder Technology* 118:10-15.

[100]   Roney JA, White BR. 2006. Estimating fugitive dust emission rates using an environmental boundary layer wind tunnel. *Atmospheric Environment* 40:7668-7685.

[101]   Neuman CM, Boulton JW, Sanderson S. 2009. Wind tunnel simulation of environmental controls on fugitive dust emissions from mine tailings. *Atmospheric Environment* 43:520-529.

[102]   Faria R, Ferreira AD, Sismeiro JL, Mendes JCF, Sousa ACM. 2011. Wind tunnel and computational study of the stoss slope effect on the aeolian erosion of transverse sand dunes. *Aeolian Research* 3:303-314.

[103]   Ellison WD. 1945. Soil Erosion of Raindrops and surface - Flow on soil Erosion and infiltration. *Transactions, American Geophysical Union* 26:415-429.

[104]   Fox DM, Bryan RB, Fox CA. 2004. Changes in pore characteristics with depth for structural crusts. *Geoderma* 120:109-120.

[105]   Philip JR. 1998. Infiltration into crusted soils *Water Resources Research* 34:1919-1927.

[106]   Mutchler CK, Murphree CE, Mcgregor KC. 1994. Laboratory and field plots for soil erosion studies. *Soil erosion research methods*:11-37.

[107]   Hudson NW. 1993. Field measurement of soil erosion and runoff. *Fao soils bull* 68:139.

[108]   Ben-Hur M, Faris J, Malik M, Letey J. 1989. Polymers as Soil Conditioners Under Consecutive Irrigations and Rainfall. *Soil Science Society of America Journal* 53:1173-1177.

[109]   Quinton JN, Edwards GM, Morgan RPC. 1997. The influence of vegetation species and plant properties on runoff and soil erosion: results from a rainfall simulation study in south east Spain *Soil use and management* 13:143-148.

[110]   Vinod JS, Indraratna B. 2011. A conceptual model for lignosulfonate treated soils. *the 13th International Conference of the International Association for Computer Methods and Advances in Geomechanics*. Melbourne, Australia.

[111]   Tie S, Jiang X, Wang C. 2013. Progress in Chemical Sand-fixing Materials in Desertification Combating. *Reviews* 31:106-111.

[112]   Al-Khanbashi A, Abdalla SW. 2006. Evaluation of three waterborne polymers as stabilizers for sandy soil. *Geotechnical & Geological Engineering* 24:1603-1625.
[113]   Lahalih SM, Hovakeemian G. 1988. Development of novel polymeric soil stabilizers. *Industrial & engineering chemistry research* 27:1806-1810.
[114]   Arthur G, Leonid V, Jiftah B-A. 2013. Combating wind erosion of sandy soils and crop damage in the coastal deserts: Wind tunnel experiments. *Aeolian Research* 9:69-73.
[115]   Musselman J, Forsha C. 2009. RAPID STABILIZATION/POLYMERIZATION OF WET CLAY SOILS; LITERATURE REVIEW
[116]   Karol RH. 2003. *Chemical grouting and soil stabilization, revised and expanded*. Crc Press.
[117]   Xiao B, Sun XF, Sun R. 2001. The chemical modification of lignins with succinic anhydride in aqueous system. *Polymer Degradation and Stability* 71:223-231.
[118]   Dong Z, Wang L, Zhao S. 2008. A potential compound for sand fixation synthesized from the effluent of pulp and paper mills. *Journal of arid environments* 72:1388-1393.
[119]   Addo JQ, Sanders TG. 1995. Effectiveness and environmental impact of road dust suppressants.
[120]   Telysheva G, Shulga G. 1995. Silicon-Containing Polycomplexes for Protection Against Wind Erosion of Sandy Soil. *Journal of Agricultural Engineering Research* 62:221-227.
[121]   Anagnostopoulos CA, Papaliangas T, Manolopoulou S, Dimopoulos T. 2011. Physical and mechanical properties of chemically grouted sand. *Tunnelling and Underground Space Technology* 26:718-724.
[122]   Power G, Gräfe M, Klauber C. 2009. Review of current bauxite residue management, disposal and storage: practices, engineering and science. *CSIPO Document DMR 3608, Australian Government* 18.
[123]   Jones B, Haynes R, Phillips I. 2010. Effect of amendment of bauxite processing sand with organic materials on its chemical, physical and microbial properties. *Journal of Environmental Management* 91:2281-2288.
[124]   Cooling D. 2007. Improving the sustainability of residue management practices–Alcoa World Alumina Australia. *Paste and Thickened Tailings: A Guide*:3-16.
[125]   Liu J, Shi B, Jiang H, Bae S, Huang H. 2009. Improvement of water-stability of clay aggregates admixed with aqueous polymer soil stabilizers. *Catena* 77:175-179.
[126]   A. B, Davis W, Reinhold VN. 1992. *Air Pollution Engineering Manual*, New York.
[127]   Yang J, Wang F, Fang L, Tan T. 2007. The effects of aging tests on a novel chemical sand-fixing agent – Polyaspartic acid. *Composites Science and Technology* 67:2160-2164.
[128]   Han Z, Wang T, Dong Z, Hu Y, Yao Z. 2007. Chemical stabilization of mobile dunefields along a highway in the Taklimakan Desert of China. *Journal of arid environments* 68:260-270.
[129]   Keith DR. 1985. *Dust Control at Hazardous Waste Sites*.
[130]   Stunder BB, Arya S. 1988. Windbreak effectiveness for storage pile fugitive dust control: a wind tunnel study. *JAPCA* 38:135-143.
[131]   Faria R, Ferreira AD, Sismeiro JL, Mendes JCF, Sousa ACM. 2011. Wind tunnel and computational study of the stoss slope effect on the aeolian erosion of transverse sand dunes. *Aeolian Research* 3:303-314.
[132]   Ferreira AD, Oliveira RA. 2009. Wind erosion of sand placed inside a rectangular box. *Journal of Wind Engineering and Industrial Aerodynamics* 97:1-10.
[133]   Turpin C, Harion JL. 2009. Numerical modeling of flow structures over various flat-topped stockpiles height: Implications on dust emissions. *Atmospheric Environment* 43:5579-5587.
[134]   Badr T, Harion JL. 2005. Numerical modelling of flow over stockpiles: Implications on dust emissions. *Atmospheric Environment* 39:5576-5584.
[135]   Sinclair Knight Merz (SKM). 1997. Dust Assessment - Pinjarra Bauxite Stockpile Area. Report, Prepared for Alcoa of Australia, Pinjarra.
[136]   José CMF, Esteban Altabella J, García Darás F, Gallardo Izquierdo A. 2013. Influence of the design on slope stability in solid waste landfills.

[137]   Roe DC. 2003. Recent Innovations in Controlling Dust Emissions in the Bauxite/Alumina Industry. *GE Water & Process Technologies Technical Paper*:pp. 1-6.

[138]   George E. P. Box, J. Stuart Hunter, Hunter WG. 2005. *Statistics for Experimenters*, 2nd ed, United States of America.

[139]   Xu G, Ding X, Kuruppu M, Zhou W, Biswas W. 2018. Research and application of non-traditional chemical stabilizers on bauxite residue (red sand) dust control, a review. *Science of The Total Environment* 616-617:1552-1565.

[140]   Vakili AH, Kaedi M, Mokhberi M, Selamat MRb, Salimi M. 2018. Treatment of highly dispersive clay by lignosulfonate addition and electroosmosis application. *Applied Clay Science* 152:1-8.

[141]   Ta'negonbadi B, Noorzad R. 2017. Stabilization of clayey soil using lignosulfonate. *Transportation Geotechnics* 12:45-55.

[142]   Australian Standard. 2005. 1289.2.1.1. *Methods of testing soils for engineering purposes-Soil moisture content tests-Determination of the moisture content of a soil-oven drying method (standard method)*. Australian Standards.

[143]   Australian Standard. 2009. 1289.3.6.1. *Standard method of analysis by sieving in Methods of testing soils for engineering purposes—Soil classification tests—Determination of the particle size distribution of a soil*. Australian Standards.

[144]   ASTM. 2011. D2487-17. *Standard Practice for Classification of Soils for Engineering Purposes (unified Soil Classification System)*
American Society for Testing and Materials International.

[145]   Arel HŞ, Aydin E. 2017. Effects of Ca-, Mg-, K-, and Na-lignosulfonates on the behavior of fresh concrete. *Construction and Building Materials* 157:1084-1091.

[146]   Lemes AP, Soto-Oviedo MA, Mei LHI, Duran N. 2003. Processing, chemical structure and morphology of poly(hydroxybutyrate-co-valerate)/ lignosulfonate composites. *4th Mercosur Congress on Process Systems Engineering*:1-6.

[147]   Onyejekwe S, Ghataora GS. 2015. Soil stabilization using proprietary liquid chemical stabilizers: sulphonated oil and a polymer. *Bulletin of Engineering Geology and the Environment* 74:651-665.

[148]   Australian Standard. 2007. AS 1289.5.4.2. *Methods of Testing Soils for Engineering Purposes: Soil compaction and density tests - Compaction control test - Assignment of maximum dry density and optimum moisture content values*. Australian Standards.

[149]   Ding X, Xu G. 2016. Innovative sample preparation apparatus and method to construct cylindrical specimen for mechanical properties test of sandy materials. In Office TAP, ed. Vol 2016102039, Australia.

[150]   Khatami HR, O'Kelly BC. 2012. Improving mechanical properties of sand using biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering* 139:1402-1406.

[151]   Chen R, Ramey D, Weiland E, Lee I, Zhang L. 2016. Experimental investigation on biopolymer strengthening of mine tailings. *Journal of Geotechnical and Geoenvironmental Engineering* 142:06016017.

[152]   Chang I, Cho G-C. 2012. Strengthening of Korean residual soil with β-1, 3/1, 6-glucan biopolymer. *Construction and Building Materials* 30:30-35.

[153]   Chang I, Im J, Cho G-C. 2016. Geotechnical engineering behaviors of gellan gum biopolymer treated sand. *Canadian Geotechnical Journal* 53:1658-1670.

[154]   Australian Standard. 2003. AS-1289.5 *Methods of testing soils for engineering purposes, Method 51 1: Soil compaction and density tests—Determination of the dry density/moisture content relation of a soil using standard compactive effort*. Australian Standards.

[155]   Orts WJ, Roa-Espinosa A, Sojka RE, Glenn GM, Imam SH, Erlacher K, Pedersen JS. 2007. Use of synthetic polymers and biopolymers for soil stabilization in agricultural, construction, and military applications. *Journal of materials in civil engineering* 19:58-66.

[156]   Chao-Yin D, Fa-Hu L, Wu L. 2012. Soil erosion as affected by polyacrylamide application under simulated furrow irrigation with saline water. *Pedosphere* 22:681-688.

[157]   Roa-Espinosa A, Bubenzer G, Miyashita E. 2000. Sediment and runoff control on construction sites using four application methods of polyacrylamide mix. Proceedings of the National Conference on Tools for Urban Water Resource Management and Protection USEPA Office of Research and Development EPA/625/R-00/001, pp 278-283.

[158]   Casas JA, Mohedano AF, García-Ochoa F. 2000. Viscosity of guar gum and xanthan/guar gum mixture solutions. *Journal of the Science of Food and Agriculture* 80:1722-1727.

[159]   ASTM. 2006. D2166/D2166M-16. *Standard test method for unconfined compressive strength of cohesive soil*. American Society for Testing and Materials International.

[160]   Montgomery DC. 2017. *Design and analysis of experiments*. John wiley & sons.

[161]   Zhu F, Hou J, Xue S, Wu C, Wang Q, Hartley W. 2017. Vermicompost and gypsum amendments improve aggregate formation in bauxite residue. *Land Degradation & Development* 28:2109-2120.

[162]   Kong X, Tian T, Xue S, Hartley W, Huang L, Wu C, Li C. 2018. Development of alkaline electrochemical characteristics demonstrates soil formation in bauxite residue undergoing natural rehabilitation. *Land Degradation & Development* 29:58-67.

[163]   Zhu F, Cheng Q, Xue S, Li C, Hartley W, Wu C, Tian T. 2018. Influence of natural regeneration on fractal features of residue microaggregates in bauxite residue disposal areas. *Land Degradation & Development* 29:138-149.

[164]   Thombare N, Jha U, Mishra S, Siddiqui M. 2016. Guar gum as a promising starting material for diverse applications: A review. *International journal of biological macromolecules* 88:361-372.

[165]   Chen R, Lee I, Zhang L. 2014. Biopolymer stabilization of mine tailings for dust control. *Journal of Geotechnical and Geoenvironmental Engineering* 141:04014100.

[166]   Bergmann D, Furth G, Mayer C. 2008. Binding of bivalent cations by xanthan in aqueous solution. *International journal of biological macromolecules* 43:245-251.

[167]   Comba S, Sethi R. 2009. Stabilization of highly concentrated suspensions of iron nanoparticles using shear-thinning gels of xanthan gum. *Water research* 43:3717-3726.

[168]   Zhu F, Zhou J, Xue S, Hartley W, Wu C, Guo Y. 2016. Aging of bauxite residue in association of regeneration: a comparison of methods to determine aggregate stability & erosion resistance. *Ecological Engineering* 92:47-54.

[169]   Zhu F, Xue S, Hartley W, Huang L, Wu C, Li X. 2016. Novel predictors of soil genesis following natural weathering processes of bauxite residues. *Environmental Science and Pollution Research* 23:2856-2863.

[170]   Zhu F, Liao J, Xue S, Hartley W, Zou Q, Wu H. 2016. Evaluation of aggregate microstructures following natural regeneration in bauxite residue as characterized by synchrotron-based X-ray micro-computed tomography. *Science of The Total Environment* 573:155-163.

[171]   Xue S, Kong X, Zhu F, Hartley W, Li X, Li Y. 2016. Proposal for management and alkalinity transformation of bauxite residue in China. *Environmental Science and Pollution Research* 23:12822-12834.

[172]   Bouazza A, Gates WP, Ranjith PG. 2009. Hydraulic conductivity of biopolymer treated silty sand. *Geotechnique* 59:71-72.

[173]   Ayeldeen MK, Negm AM, El Sawwaf MA. 2016. Evaluating the physical characteristics of biopolymer/soil mixtures. *Arabian Journal of Geosciences* 9:371.

[174]   Bjorneberg D. 1998. Temperature, concentration, and pumping effects on PAM viscosity. *Transactions of the ASAE* 41:1651.

[175]   Eldaw G. 1998. A study of guar seed and guar gum properties (Cyamopsis tetragonoloba (L). M. Sc Thesis, Faculty of Agriculture, U of K, Sudan.

[176]   Alshaal T, Domokos-Szabolcsy É, Márton L, Czakó M, Kátai J, Balogh P, Elhawat N, El-Ramady H, Fári M. 2013. Phytoremediation of bauxite-derived red mud by giant reed. *Environmental chemistry letters* 11:295-302.

[177]   Mudgil D, Barak S, Khatkar BS. 2014. Guar gum: processing, properties and food applications—a review. *Journal of food science and technology* 51:409-418.

[178]   Santos J, Calero N, Guerrero A, Munoz J. 2015. Relationship of rheological and microstructural properties with physical stability of potato protein-based emulsions stabilized by guar gum. *Food hydrocolloids* 44:109-114.

[179]   Ding X, Xu G, Zhou W, Kuruppu M. 2018. Effect of synthetic and natural polymers on reducing bauxite residue dust pollution. *Environmental technology*:1-10.

[180]   Entry JA, Sojka R. 2000. The efficacy of polyacrylamide and related compounds to remove microorganisms and nutrients from animal wastewater. *Journal of Environmental Quality* 29:1905-1914.

[181]   Barakat MA. 2011. New trends in removing heavy metals from industrial wastewater. *Arabian Journal of Chemistry* 4:361-377.

[182]   Zendehdel M, Barati A, Alikhani H, Hekmat A. 2010. Removal of methylene blue dye from wastewater by adsorption onto semi-inpenetrating polymer network hydrogels composed of acrylamide and acrylic acid copolymer and polyvinyl alcohol. *Iranian Journal of Environmental Health Science & Engineering* 7:431.

[183]   García-Ochoa F, Santos VE, Casas JA, Gómez E. 2000. Xanthan gum: production, recovery, and properties. *Biotechnology Advances* 18:549-579.

[184]   Chang I, Im J, Prasidhi AK, Cho G-C. 2015. Effects of Xanthan gum biopolymer on soil strengthening. *Construction and Building Materials* 74:65-72.

[185]   Laneuville SI, Turgeon SL, Sanchez C, Paquin P. 2006. Gelation of native β-lactoglobulin induced by electrostatic attractive interaction with xanthan gum. *Langmuir* 22:7351-7357.

[186]   Plank J. 2004. Applications of biopolymers and other biotechnological products in building materials. *Applied microbiology and biotechnology* 66:1-9.

[187]   Sakhale BK, Badgujar JB, Pawar VD, Sananse SL. 2011. Effect of hydrocolloids incorporation in casing of samosa on reduction of oil uptake. *Journal of food science and technology* 48:769.

[188]   Manna PJ, Mitra T, Pramanik N, Kavitha V, Gnanamani A, Kundu P. 2015. Potential use of curcumin loaded carboxymethylated guar gum grafted gelatin film for biomedical applications. *International journal of biological macromolecules* 75:437-446.

[189]   Prabaharan M. 2011. Prospective of guar gum and its derivatives as controlled drug delivery systems. *International journal of biological macromolecules* 49:117-124.

[190]   Mishra MM, Mishra DK, Mishra P, Behari K. 2015. Synthesis and characterization of a novel graft copolymer of partially carboxymethylated guar gum and N-vinylformamide. *Carbohydrate polymers* 115:776-784.

[191]   Pal S, Ghorai S, Dash M, Ghosh S, Udayabhanu G. 2011. Flocculation properties of polyacrylamide grafted carboxymethyl guar gum (CMG-g-PAM) synthesised by conventional and microwave assisted method. *Journal of hazardous materials* 192:1580-1588.

[192]   Gupta V, Pathania D, Singh P, Kumar A, Rathore B. 2014. Adsorptional removal of methylene blue by guar gum–cerium (IV) tungstate hybrid cationic exchanger. *Carbohydrate polymers* 101:684-691.

[193]   Pal S, Patra AS, Ghorai S, Sarkar AK, Mahato V, Sarkar S, Singh R. 2015. Efficient and rapid adsorption characteristics of templating modified guar gum and silica nanocomposite toward removal of toxic reactive blue and Congo red dyes. *Bioresource technology* 191:291-299.

[194]   Maier H, Anderson M, Karl C, Magnuson K, Whistler RL. 1993. CHAPTER 8 - GUAR, LOCUST BEAN, TARA, AND FENUGREEK GUMS. In Whistler RL, Bemiller JN, eds, *Industrial Gums (Third Edition)*. Academic Press, London, pp 181-226.