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P30: Bagasse Ash and Fibres in Pavement Construction in Queensland

SUMMARY

Queensland is one of the largest sugarcane producing regions in the world. The process of producing sugar results in large quantities of a fibrous by-product known as bagasse, which is often incinerated to generate energy for the sugarcane processing plant and/or fed back to the municipal power grid. The residual by-product, bagasse ash, is currently considered a waste material requiring long-term storage in large stockpiles or disposal in landfills.

Bagasse ash and fibres are currently used in pavement construction in other sugar-producing countries; most notably India, Nigeria and Brazil. The most common treatment applied is to blend bagasse into expansive subgrade soils, taking advantage of the pozzolanic effect of the ash, in much the same way as other industrial by-products such as fly ash and blast-furnace slag have been utilised. This treatment will often require blending the bagasse ash with a traditional chemical stabilising agent such as lime. The vast quantities of excess bagasse ash and fibre produced and stored along the coastal regions of Queensland present opportunities for an alternative treatment option for expansive subgrades while providing both environmental and economic benefits.

The first year of this study focussed initially on reviewing the health and safety requirements involved in working with and testing bagasse ash and fibres. A number of potential health issues had been identified with bagasse in the past, which meant that it was critical to ensure that all the appropriate precautions were taken before embarking on a major laboratory and/or field testing program. This review concluded that the safety concerns identified are not dissimilar to the typical concerns with products of this nature, such as fly ash, lime and Portland cement, provided that appropriate safety procedures and protection are used when handling the product. It is recommended that internal procedures are developed before handling and testing the material in laboratories, and that field safety and handling procedures are developed before moving to a potential field trial.

The principal stakeholders of this research effort include TMR, ARRB Group, Arup, the Australian Sugar Milling Council (ASMC) and the University of Technology Sydney (UTS). In addition to the review of health and safety requirements, the testing plan includes assessment of the impact of bagasse ash on a Queensland black soil. Preliminary results suggest that large quantities of ash are required to produce significant improvements in the strength and expansive properties of the black soil. Bagasse ash blended with lime in a 3:1 ratio showed more promise, with large reductions in linear shrinkage and much greater strength after several days curing. The second year of the project will look to explore the use of bagasse products in Queensland through further laboratory testing and a field trial.

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1 INTRODUCTION

The natural foundation of large areas of Queensland is characterised by expansive soils, with properties that can lead to considerable swelling in wet conditions and shrinking in dry conditions. This presents a design problem for pavement engineers. Thick overlays of pavement materials or chemical stabilising additives are commonly used to minimise the risk of volumetric change induced cracking of the pavement. Due to high material supply and haulage costs, often making thick overlays unfeasible, designs in expansive soil regions generally require significant additions of a chemical stabilising agent to be added to the in situ materials. Traditionally, this additive has been Portland cement or lime, but recently the need to minimise costs has led to the introduction of various blended products incorporating supplementary cementitious materials (SCM) such as fly ash or blast-furnace slag.

Sugarcane bagasse is a fibrous by-product of sugarcane processing. Bagasse ash is the residual material after the bagasse fibres are incinerated for electricity generation. There is potential for this ash to be used as an additive in expansive soil stabilisation in Queensland, likely as a part of a blended end-product incorporating lime. Some studies have also looked into the potential for using the bagasse fibres in road construction, an approach which was also explored during this study.

The widespread uptake of bagasse fibre/ash products in road stabilisation works can reduce the quantity of traditional chemical stabilising agents used and introduce a new plentiful and readily available stabilisation additive. Both economic and environmental benefits result from reduced material costs during construction and also reduced quantities of waste bagasse material held by sugar mills.

In order to best understand the benefits and limitations of bagasse before introducing it as a road construction material, this review has been undertaken to summarise the potential uses for bagasse in pavements, as well as investigate the safety concerns associated with the use of bagasse fibres and ash.

1.1 Methodology

The technical approach taken for this project was as follows:

- Explore the background to the sugarcane industry in Queensland and the current uses for bagasse material (Section □)
- Conduct a literature review on the use of bagasse ash and fibres in pavement construction internationally, with a particular focus on studies that have included laboratory trials comparing various chemical stabilising agents (Section 3)
- Outline the various health and safety concerns associated with bagasse, in terms of the chemical composition and practical considerations of using bagasse in the laboratory and field (Section 4)
- Summarise the laboratory testing program as undertaken by the University of Technology Sydney (Section 5)
- Develop future action items for the bagasse research project, including recommendations for laboratory testing and field trials in Queensland (Section 6).

2 BACKGROUND

2.1 Sugarcane in Queensland

Australia was among the top ten sugarcane producers in 2011 as shown in Table 2.1, with by far the smallest population among the top ten producers, which also places Australia high on the list of sugarcane production per capita.

Table 2.1: Top ten sugarcane producers, 2011

Country	Production (thousand metric tonnes)
Brazil	734 000
India	342 382
China	115 124
Thailand	95 950
Pakistan	55 309
Mexico	49 735
Philippines	34 000
United States	26 656
Australia	*25 182*
World total	1 794 359

Source: Food and Agricultural Organization of United Nations (2011).

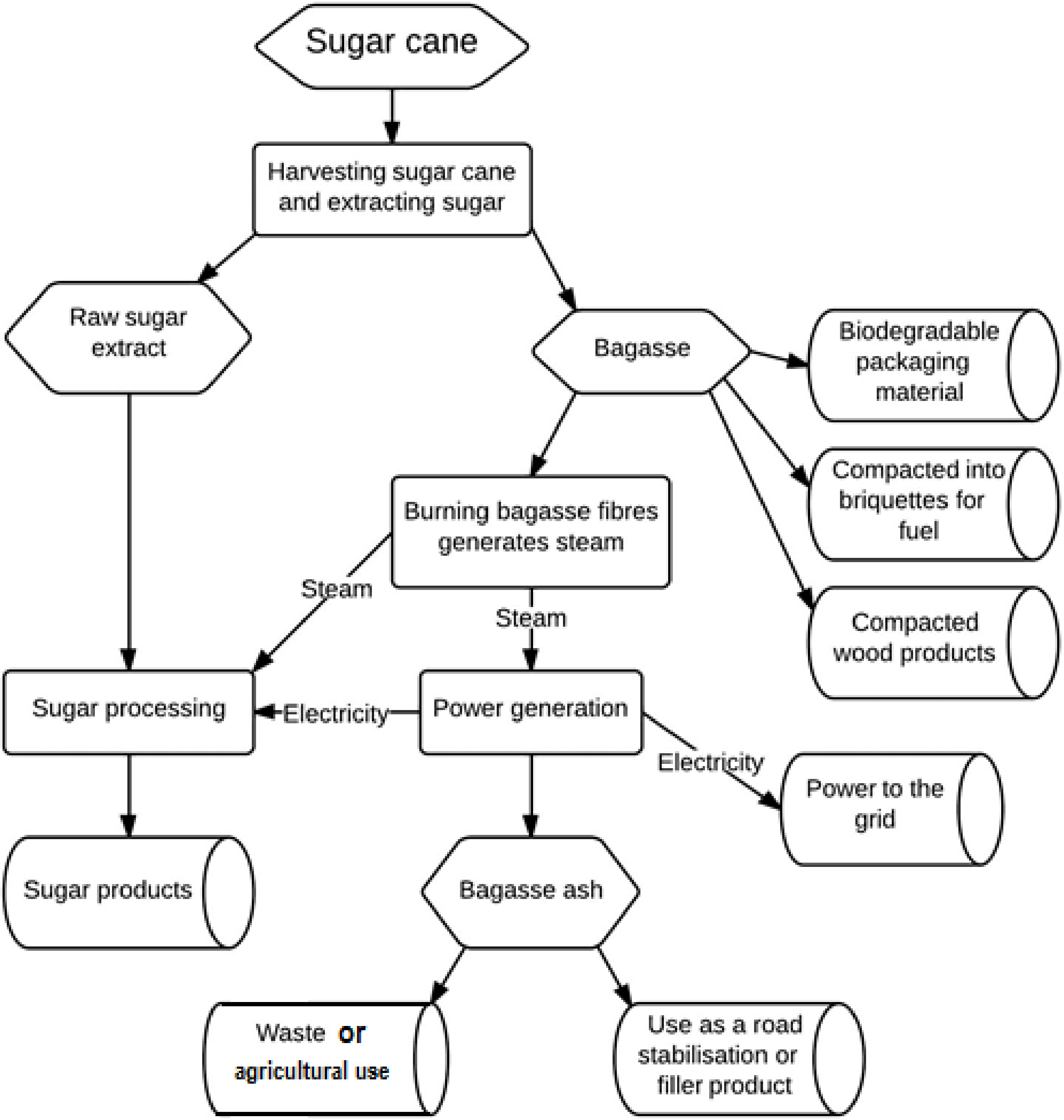
Within Australia, the key production regions are along the northern Queensland coast between Cairns and Mackay, as well as in areas further south such as Bundaberg and Maryborough, in addition to the Northern Rivers region of New South Wales. Most sugarcane farms are located close to ports, as a significant proportion of sugar is sent interstate or overseas by ship. Sugarcane is processed into a number of components. The principal component is cane sugar, but bagasse, molasses, and filtercake are also produced.

2.2 Uses for Bagasse

After extracting the sugar from raw sugarcane, the leftover bagasse fibres can either be sent away as waste or recycled in a number of ways. Landfilling the residual bagasse is expensive and environmentally damaging, so there is a significant benefit in utilising the bagasse material in a productive manner. Figure 2.1 shows the sugarcane industrial process and potential uses of bagasse.

In Australia, the most common application is burning the bagasse to produce the steam and electricity required in the sugar production process, with the excess electricity being fed back into the electricity grid. India and Brazil lead the world in the conversion of bagasse waste to fuel and electricity. As a result of burning bagasse, large quantities of bagasse ash are produced, a material that is currently treated as a waste product or used as an agricultural fertiliser on sugarcane crops or other crops in the area.

Figure 2.1: Sugarcane and by-products – production flowchart



As with fly ash and blast-furnace slag, residues produced during combustion (e.g. in coal power plants and the steel industry), bagasse may have potential use as a more commercially and environmentally friendly replacement for traditional fillers and additives. To this point, much of the research into bagasse ash recycling has focussed on the potential for the ash to be used as an SCM with Portland cement in concrete structures. These applications will not be explored in depth in this report, with the focus here instead being on the use of bagasse in Queensland pavement applications.

3 BAGASSE IN PAVEMENT CONSTRUCTION

The following section details a number of studies into the use of bagasse ash and fibres in pavement construction. The majority of research comes out of India, where significant volumes of bagasse are used to generate power for sugar production and the municipal electricity grid.

3.1 Bagasse Ash as a Chemical Stabilisation Agent

Expansive soils, commonly referred to as black soil in Queensland, contain clay minerals that swell in the presence of water and shrink when dried out. This can lead to deep cracks forming within the soil mass when moisture is lost during extended hot, dry weather. This can also have an effect on overlying pavement layers in the case of sealed roads. Chemical stabilisation agents such as lime have been used to reduce this effect in black soils, although lime is relatively expensive and not readily available in some regions. If the same level of performance can be achieved by replacing some or all of the lime with an industrial by-product, significant cost savings may be achieved.

Kharade et al. (2014) investigated the use of bagasse ash as a stabilising material in the western Maharashtra region of India. The region has the highest concentration of sugar production in India, with much of the bagasse being incinerated for electricity production. As such, disposal of the high quantities of bagasse ash has become an environmental and logistical challenge.

The study tested a black soil without added bagasse ash, and at replacement rates of 3%, 6%, 9% and 12% bagasse ash. The results suggested that adding 3% and 6% bagasse has the effect of increasing the maximum dry density and optimal moisture content, but after this point, additional bagasse saw these values drop rapidly to below the baseline values. Kharade et al. (2014) suggested that this may be due to the low specific gravity of the bagasse compared to the soil. The study tested the strength of the blends using both the California Bearing Ratio (CBR) and unconfined compressive strength (UCS) tests as shown in Table 3.1.

Table 3.1: CBR and UCS results at various bagasse ash replacement levels

% replacement	CBR values
0	12.88
3	15.93
6	22.04
9	17.39
12	12.58

% replacement	UCS values (kN/m^2)
0	138.58
3	152.15
6	245.65
9	220.03
12	187.52

Source: Kharade et al. (2014).

The biggest improvement in both CBR and UCS occurred at 6% replacement rate, with CBR 41.5% higher than the baseline level and UCS at 43.6% higher than baseline. The study concluded that adding bagasse, even without the addition of further cementing or stabilisation agents, can be an economic approach to improving the properties of black soil.

Kiran and Kiran (2013) added bagasse ash and cement to 'black cotton' soils and found that the UCS more than doubled for an 8% bagasse ash with 8% cement mix, from 84.92 kN/m^2 up to 174.91 kN/m^2.

Gandhi (2012) studied the effect of adding between 3% and 10% bagasse ash to soil samples from the Surat region in India, an area known for expansive black cotton soils. Initial testing showed that adding bagasse led to a reduction in all soil moisture properties, including the free swell, plastic and shrinkage indexes (Table 3.2).

Table 3.2: Test results on material properties

Ash (%)	Liquid limit (%)	Plastic limit (%)	Plastic Index (%)	Shrinkage limit (%)	Free swell index	Swelling pressure (kg/cm^2)	Shrinkage Index (%)
0	72	30	42	21	143	0.120	21
3	67	29	38	19	127	0.099	19
5	63	28	35	17	103	0.084	18
7	58	26	32	15	85	0.074	17
10	52	25	27	12	80	0.046	15

Source: Gandhi (2012).

The results show that the key property of the free swell index drops from 143 with no ash, steadily down as more ash is added, to a low of 80 with 10% ash. Similarly, the swelling pressure of 0.120 kg/cm^2 drops down to 0.046 kg/cm^2 with 10% ash added. Gandhi (2012) concluded that this was due to the bagasse ash replacing volume held by expansive clay minerals, and by providing cementitious properties to the soil. Bagasse ash was found to be effective at improving existing poor and expansive subgrade soils in India, especially considering it is often freely available through the local sugar industry.

Sabat (2012) studied the effects of bagasse ash and lime sludge on the strength, moisture and constructability of expansive soils. Lime sludge is a by-product of the paper manufacturing industry and contains a high proportion of lime. The conclusions were that adding bagasse ash decreased the maximum dry density and increased the optimum moisture content of the expansive soil at all proportions of ash. However, lime sludge without the addition of bagasse ash had similar effects.

The highest strength characteristic was found with a mix ratio of 76% soil, 8% bagasse ash and 16% lime sludge. As with the previous study, the swelling pressure dropped as more additive was mixed with the soil, and with the optimum blend found to be at a level low enough to be compatible with flexible pavements. In was found to be important to compact the mixed soil promptly and as close to the optimum moisture content as possible to avoid construction problems. The paper concluded that these two waste products can be effective at strengthening the subgrade of flexible pavements in expansive soil areas and can lead to significant cost savings (Sabat 2012).

Osinubi et al. (2009) conducted a similar study in Nigeria to investigate the effect of bagasse ash on the properties of expansive soils. This study used between 0 and 8% bagasse ash, in addition to between 2% and 8% lime, to stabilise a black soil from north-eastern Nigeria. The optimal combination was found to be 8% lime and 4% bagasse ash, which led to a drop in the liquid limit from 73% to 56% and the plasticity index from 50% down to 15%. The CBR increased for the optimum blend compared to the natural soil, but did not reach the minimum criteria required for use as a basecourse layer. The CBR values of 20% are however suitable for use as a subgrade material in Nigeria.

The research in India and Nigeria suggests that a lime/bagasse ash blend may be suitable as a stabilising agent for black soils, however the quantity of lime required could be prohibitively costly, especially if this technology was applied to Queensland pavements.

3.2 Bagasse Fibres in Stone Mastic Asphalt

Various studies have investigated the effects of fibrous and/or organic material in stone mastic asphalt (SMA) mixes. SMA mixes have characteristically high binder contents, and as such it is often necessary to add fibre to the mix to provide added stability to the binder and to prevent binder drain-down during mixing, transportation and placement (AAPA 2000). Materials that have been used as fibre in SMA include cellulose, rock wool, glass fibre and other organic sources.

Trials using fibre from various environmentally sustainable sources have taken place in recent years. Coconut fibres were found to be a viable replacement for cellulose to reduce binder drain-down in SMA mixes (Colares do Vale et al. 2014). Jute fibres have also been trialled and performed equally well to the traditional cellulose fibres (Kumar et. al. 2007). Banana and sisal fibres have also been successfully used in SMA mixes, although not tested in comparison to traditional fibre additives (Dikshith 2012).

Soren (2012) tested sugarcane bagasse fibres in SMA mixes to determine whether they could be used to prevent drain-down of binder in rich SMA mixes. Mixes were prepared with and without bagasse fibre at various binder contents to compare the mix properties, namely the stability, flow, voids, density, drain-down and tensile strength. The results suggest that SMA with bagasse fibre performs well overall, and drain-down was observed to be negligible for mixes with bagasse fibre added. The tests would have to be run with proper control samples in order to gain a complete understanding of the impact of bagasse fibres on SMA mixes, and whether or not they are comparable to traditional fibres.

3.3 Summary

A survey of the literature suggests that the most beneficial applications for bagasse material in pavements in Queensland are likely to come in terms of using bagasse ash as a chemical stabilising agent in expansive soils. The most convincing research results are in cases where bagasse ash is used in conjunction with lime.

Many stabilisation projects in recent years have utilised blended cements and SCM in order to increase working times during construction and reduce the risk of early shrinkage cracking in the pavement (AustStab 2011). Materials such as fly ash from the coal industry and blast-furnace slag from the steel industry have been used in these blends, and bagasse ash may be used in a similar fashion, should it possess the required chemical properties.

Not all sources of fly ash and slag are suitable for use in road construction, and while these products are effectively a waste material, they still come at a cost and are sometimes difficult to source. Bagasse may therefore be a suitable alternative in some regions of Queensland, provided it has been proven to perform to an equivalent standard. Laboratory testing in this project will include tests on a bagasse ash/lime blend, in addition to tests using straight bagasse ash and bagasse fibres.

4 HEALTH AND SAFETY REVIEW

The following section outlines the research conducted into the chemical composition of bagasse and subsequently the effect that this has on occupational health and safety (OH&S) in the laboratory and field. Procedures put in place by the University of Technology Sydney (UTS) are detailed further in Section 5.2.

4.1 Chemical Composition

Many of the chemicals contained in bagasse ash are also present in fly ashes which are heavily used in road construction, particularly as a cement replacement in road stabilisation. These fly ashes are produced during the burning of coal in pulverised fuel furnaces. The chemical composition of ashes from a number of prominent Australian power stations is shown in Table 4.1 (CPEE 2012). These plants all burn black coal, which contains high percentages of silica and alumina, low percentages of calcium and carbon and the material is pozzolanic. Brown coals from Victoria contain high percentages of soluble salts and are not suitable for stabilisation.

Table 4.1: Principal chemical components and loss of ignition (LOI) of fly ashes and other materials

	Source	Percentage										
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	P_2O_5	LOI
Fly ash	Vales Point, NSW	58.0	26.5	3.2	1.6	0.9	0.4	NA	0.1	A	A	3.0
	Eraring, NSW	69.2	21.8	3.5	1.2	0.7	0.5	1.4	<0.1	A	A	0.9
	Mt Piper, NSW	65.0	23.0	5.0	0.2	0.3	0.4	1.8	0.2	A	A	<1.0
	Swanbank, Qld	57.2	29.7	2.7	1.5	0.8	0.2	0.5	0.1	A	A	3.7
	Gladstone, Qld	49.1	26.7	6.0	5.8	0.7	NA	NA	0.3	A	A	4.2
	Tarong, Qld	61.6	32.9	0.6	0.1	0.1	0.1	0.1	NA	A	A	A
	Callide, Qld	49.8	32.8	12.3	0.8	0.8	0.1	0.1	0.1	A	A	0.8
	Port Augusta, SA	39.2	26.7	5.2	10.5	3.0	5.7	1.3	2.5	A	A	2.8
Other	Portland cement	17.84	3.88	3.71	66.83	1.40	0.17	0.67	4.10	0.26	0.07	0.90
	Clinker	19.09	4.02	4.22	68.14	1.49	0.19	0.78	1.11	0.26	0.06	0.48
	Gypsum	2.12	0.87	0.46	42.48	0.13	NA	0.02	50.28	0.06	NA	3.48
Sugarcane bagasse ash	Kaset Thai Factory, Thailand *(Muangtong et al. 2012)*	64.11	5.26	2.78	5.75	1.28	0.32	2.59	0.41	0.38	1.37	15.09
	Nigeria *(Osinubi and Stephan 2005)*	57.12	29.73	2.75	3.23	A	A	8.72	0.02	1.10	A	17.57
	Dan Chang Bio-Energy, Thailand *(Janjaturaphan and Wansom 2010)*	75.78	5.06	2.23	3.68	1.06	0.02	2.85	0.20	0.34	0.96	7.46
	Unknown *(Singh and Juwaid 2013 & Srinivasan and Sathiya 2010)*	78.34	8.55	3.61	2.15	A	0.12	3.46	A	0.50	1.07	0.42

A – Not available
Source: CPEE (2012).

Studies on bagasse ash have revealed that the main component of the ash is silica dioxide (SiO_2), also known as silica. While silica is also a component of other additives, the concentration is relatively high in bagasse ash, at around 64% by weight. This is comparable to the proportion of silica in fly ash from several Australian power stations, including the Stanwell power station in Tarong which has 61.6% silica in its fly ash by-product. Free silica is important as it reacts with calcium hydroxide (lime) through a series of processes to form calcium silicate hydrates (CSH). The silica requires a source of calcium (e.g. lime) to complete this reaction.

Bagasse ash also contains small quantities of phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O), which are considered dangerous corrosive materials. P_2O_5 reacts with water to form phosphoric acid, a highly corrosive acid which can cause severe chemical burns. Fumes can also cause irritation to eyes and the respiratory tract. Muangtong et al. (2013) found that bagasse ash contains approximately 1.37% P_2O_5 by mass.

Many of the other particulate materials are also potentially hazardous, as is the case for most materials with very fine components. The particle grading of bagasse ash is similar to that of Portland cement, with around half of the material passing the 45 µm sieve opening.

4.2 Handling, Transport and Practical Considerations

While bagasse ash may not appear to be more or less harmful than many other common materials used in road construction, there are a number of other OH&S considerations to take into account.

Vicki Patteson (personal communication, 22 July 2014), Senior Materials Technologist at TMR, noted that there are a number of operational, production and technical concerns surrounding the use of bagasse ash and fibres, and that the material should be treated with caution. Specific concerns include:

- The incomplete combustion of bagasse fibre in the mill boiler results in organic fibres in the bagasse, which would need to be separated at some stage.
- Some of the material originally consigned from Isis Central Mill was boiler ash which had been stored in a ‘pond’ and had the potential to have associated health risks – none of which were investigated prior to the despatch of the material to the TMR laboratory.
- The sugar industry has a long history of and are practised at dealing with the various issues associated the handling and storage of bagasse, however using bagasse in the road industry would introduce parties that are not familiar with the material and would need appropriate training.
- The transportation and storage of the product needs to be investigated to ensure it is as safe as possible.
- The product is approximately a quarter of the density of hydrated lime, and would therefore need appropriate risk assessments conducted as it can become airborne very easily.
- Bagasse can contain a significant proportion of crystalline silica, a hazardous material that can cause respiratory problems due to its extremely low density and any attempt to use extraction systems in the laboratory to keep workers safe would tend to suck significant amounts of ash away during any application or mixing process. Similarly, this would be problematic during field application due to wind and material transfer.

4.3 Bagassosis from Bagasse Fibres

The dangers surrounding bagasse have been known since the early days of its use in industrial processes. Bagasse was used as an insulating material, and was in heavy demand in war-time England (Castleden & Hamilton-Paterson 1942). Waste bagasse fibres were transported in bales where they were broken apart for processing. Under dry conditions, this led to high dust levels for factory staff. Several cases of what was termed ‘bagassosis’ were identified in workers that were in regular close contact with the fine bagasse particles. This condition manifested as an industrial lung disease, causing inflammation to the lungs, coughing with sputum, shortness of breath and fibrosis on the lungs. In each case, the worker had significant exposure to the fibres and those with greater exposure had the worst symptoms (Castleden & Hamilton-Paterson 1942). The researchers concluded that the symptoms and various phases of the illness were not consistent with silicosis, despite the presence of silica in bagasse fibres. This led to the labelling of this disease as bagassosis. Bagassosis was first documented in the United States around the same time (Jamison & Hopkins 1941).

Some 25 years after the disease was first identified, there was still controversy over the basic nature of the process, the mechanisms of development and the ultimate resolution of the pathological process (Sodeman 1967). The World Health Organisation (2010) classifies bagassosis as a ‘hypersensitivity pneumonitis due to organic dust’, where pneumonitis is a broad collection of diseases characterised by inflammation to the lungs.

The sugar industry of Australia recognises the health risks associated with bagassosis (State of Queensland 2011). Documentation from the sugar industry suggests that bagassosis is not caused by the bagasse itself, but that *thermoactinomycetes sacchari* spores can propagate in the damp storage conditions, and it is these spores than can cause an allergic reaction in lung tissue.

Park (2011) indicates bagassosis can be avoided by following several precautionary measures:

- dust control: methods of prevention/suppression of dust such as wet process, enclosed apparatus, exhaust ventilation etc. should be used
- personal protection: masks/respirators
- medical control: initial medical examination and periodical check-ups of workers
- bagasse control: keep moisture content above 20% and spray bagasse with 2% propionic acid.

The State of Queensland (2011) documents possible control measures for bagasse (Table 4.2).

While many of these precautions are typical of any industrial process involving fine material, many of the countries where sugarcane is a primary industry are in the developing world, where occupational health and safety is not of foremost concern. Thus, some of the health concerns associated with bagasse ash and fibres may be preventable if proper safety procedures are followed. For example, while wetting the stored bagasse fibres may be an important safety precaution, this step may be ignored as it slows down further processing of the material, as wet material is heavier and requires drying before burning. This could lead to increased levels of air-borne particles and fibres.

Table 4.2: Possible control measures for bagasse

Controlling and minimising bagasse dust	▪ High standards of housekeeping ▪ Covered conveyers and transfer points ▪ Local exhaust ventilation ▪ Provision of personal protective equipment ▪ Training and supervision
Reclamation or de-baling of stored bagasse	▪ Involving the minimum number of workers ▪ Conducting the activities only when weather conditions are suitable ▪ Providing air conditioned cabins on machinery used for these activities ▪ Providing suitable P2 class respirators (minimum) and goggles to workers who are exposed
Additional control measures	▪ Health checks of workers normally involved in activities generating levels of atmospheric contaminants ▪ Identification of sources of dusts ▪ Assessment of measures to minimise the generation of dusts ▪ Site inspections to assess housekeeping standards ▪ Suitability and use of personal protective equipment provided

Source: The State of Queensland (2011).

5 LABORATORY RESEARCH PROGRAM

The early work on using bagasse as a chemical stabilisation agent for expansive subgrade soils was undertaken by Arup consultants, in conjunction with TMR. This research was progressing towards a laboratory evaluation at the TMR laboratory in Herston when issues were documented regarding material handling and safety. At this stage, it was decided to push back testing until a thorough OH&S audit could be undertaken. TMR engaged the ARRB Group to complete an initial health and safety review (see Section 4). Upon completion of this review, it was decided that the OH&S risks could be mitigated with appropriate measures in place, allowing the project to progress to the laboratory assessment phase.

5.1 Initial Discussions

On 25 September 2014, a project meeting was held between the key stakeholders in this research project, namely TMR, ARRB Group, Arup and the Australian Sugar Milling Council (ASMC). This meeting was called to bring the stakeholders up-to-date with the state of the bagasse research project and to clarify issues surrounding the health and safety requirements for bagasse products. As an outcome of this meeting, it was decided that the initial laboratory research program would be undertaken by the University of Technology in Sydney (UTS).

The Queensland Department of Environmental and Heritage Protection (EHP) has also become involved in this project, considering that bagasse is currently designated as a registered waste product in Queensland. This means that strict waste management practices must be undertaken with the product. Should bagasse be a candidate for use in road stabilisation, a beneficial use acceptance (BUA) would be sought. This alternative use for the product would be beneficial to the sugar industry as it removes a waste material, and would be similarly beneficial to the road construction industry due to improved material availability and potentially reduced costs.

A follow-up meeting was held with the original stakeholders as well as the EHP. This meeting led to the development of testing plans and it was agreed that materials for testing would be sourced and provided at no cost to UTS.

5.2 Test Methods and Safety Procedures

This research program would only be supported by ARRB and TMR under the condition that all appropriate OH&S precautions would be taken by UTS in transporting, handling and processing bagasse materials. UTS has since prepared health and safety guidelines and procedures for bagasse ash and the other materials used in the initial laboratory testing phase. Further work on the health and safety implications for field staff, the community and the environment will need to be undertaken before the material can be used in any trials.

UTS has prepared two new *Safe Work Method Statements* (SWMS) for the sampling and handling of bagasse material, which are presented in Appendix A.

5.3 Laboratory Testing

It was necessary to obtain a large quantity of black soil material to conduct these tests, which was sourced from the Darling Downs region in Queensland. The Isis Central Sugar Mill in the Bundaberg region provided bagasse ash and fibre samples for testing. The testing was conducted by two research students in the Civil and Environmental Engineering Department at UTS.

The testing was broken down into seven stages, summarised briefly below, that highlighted the important results in terms of viability as a road construction material. All the preliminary testing results are presented in Appendix B. It is important to note that testing has not been completed, and a full analysis of results will be provided early in Year 2 of the research project.

The first phase of laboratory testing determined the natural soil characteristics of the Darling Downs black soil (Table 5.1). The soil displays typical properties of an expansive Queensland subgrade material, with very high silt/clay content and high plasticity. A subgrade soil with these properties would typically require either a thick overlay of imported material or some form of stabilisation with a chemical additive (e.g. lime) in order to limit volumetrically induced cracking of the pavement.

Table 5.1: Characteristics of the Darling Downs soil

Test		Result
Characteristics (%)	Gravel	0.06
	Sand	18.30
	Silt/clay	81.64
Natural water content (%)		30.76
Liquid limit		86
Plastic limit		37
Plasticity index		49
Linear shrinkage		21.67
Specific gravity		2.62–2.65
USCS classification of the soil		Clay of high plasticity, fat clay (CH)

The full set of tests is scheduled to be completed with an untreated sample, with bagasse ash added at several content rates, with a combination of lime and bagasse at several different rates and with lime only. Another series of tests will also be conducted on material treated with bagasse fibres. At the time of writing, the series of tests with bagasse only were completed, as well as several of the tests with the bagasse/lime blend and lime only.

Important findings from the preliminary laboratory testing include:

- a moderate reduction in linear shrinkage of the soil when treated with bagasse ash only
- a more significant reduction in linear shrinkage when treated with a combination of lime and bagasse ash in a 3:1 ratio
- equivalent performance of bagasse/lime blend and hydrated lime only, at a point which equates to a 37% saving in hydrated lime, based on two case studies:
  - to bring linear shrinkage down to 6.9%, treat with either 15.6% bagasse/lime blend or 6.25% lime
  - to bring linear shrinkage down to 11.56%, treat with 25% bagasse ash, 8.7% bagasse/lime blend or 3.15% lime
- some improvement in UCS when adding bagasse ash, but much greater improvement when adding the bagasse/lime blend
- CBR shows relatively minor improvement when adding only bagasse, but the bagasse/lime blends show a large increase in strength, jumping from 7% to 26% with the addition of 10% bagasse/lime blend
- the free swell potential of the soil drops from 10% to 2.5% after adding 6% bagasse and curing for 7 days while there are also improvements in terms of the rate of heave after adding 6% bagasse ash.

As previously stated, some of these tests need to be completed with the bagasse/lime blend and with straight lime added. This will allow for a more balanced comparison of the options.

The testing to date suggests that bagasse ash, most likely in some sort of blended product with hydrated lime, could prove to be a viable alternative for stabilising expansive subgrade soils. If the quantity of lime used in pavement construction can be reduced by one-third or more, this will lead to significant cost savings.

The results do suggest that it may take large quantities of bagasse to offset the lime, which may have consequences in terms of other soil properties. It would also increase the total transport cost of additives and require a larger quantity of additive to be mixed into the treated material layer. These additional costs will have to be weighed up against the savings by using less hydrated lime. A key assumption in this calculation is that the bagasse will be either very cheap or free (supplied by industry as a means of removing waste).

At this stage, there is no data on the impact of bagasse fibres on pavement construction, so it is not proposed to pursue this technology. Should laboratory results show significant benefits from adding fibres, then this may be explored further.

6 NEXT STEPS

Following the promising results detailed in Section 5.3, and subject to the finalisation of testing, it is proposed that the project now focuses on the use of the material in a range of treatment options for stabilisation of expansive soils in Queensland pavements. It is recommended that this process consist of two phases, broadly outlined below.

6.1 Implementation Phase 1

A consultation with laboratory staff from UTS and TMR will help in the development of standard SWMS and laboratory testing methods for using bagasse ash and fibres.

In order to move towards a field trial, it will be necessary to refine the design so that the most economical solution can be trialled. If the laboratory results continue to point towards the blended product being the most appropriate use of bagasse ash, then a range of blend ratios should be examined.

For slag/lime or fly ash/lime blends, a range of different ratios have been used across various projects. AustStab (2011) notes that an 85/15 slag/lime blend is typically available for use, as is a 75/25 fly ash/lime blend. The UTS testing program used a 75/25 bagasse ash/lime blend, so this is likely to be near the higher end of viable blended products. It may be worthwhile trialling a 60/40 or 50/50 blend to determine the optimal ratio. The tests will ideally be undertaken on a sample of soil from a potential trial site.

A hold point would be reached at this stage, where the test results are to be analysed and results discussed with the project team. If the results indicate a significant increase in performance, it will be recommended that the project moves to Phase 2.

6.2 Implementation Phase 2

The second phase will consist of a field trial in an expansive subgrade soil region of Queensland. As a part of this process, a safety review will be completed for the use of bagasse material in the field. This will include the development of SWMS for construction teams to educate them about the properties and handling of this new material.

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APPENDIX A SAFE WORK METHOD STATEMENTS

A.1 Mixing Bagasse with Soil for Testing

SAFE WORK METHOD STATEMENT

UNIVERSITY OF TECHNOLOGY SYDNEY

Principal Researcher / Lab or Workshop Manager: Antonio Reyno	
Faculty: Faculty of Engineering and IT	
Location(s): Geotechnical/Soils Laboratories, Building 2 Level 2 room 211	
Name of Assessor: Antonio Reyno	**Date:** Dec 2014

1) Work Description: Mixing bagasse with soil for testing.
Notify the Lab. manager to access the Soils Lab. Storage Room, as required

2) Before you start

Make sure:
You are wearing personal protective equipment (viz. gloves and respirator or dust mask).
You have the necessary container and scoop to get the desired amount of bagasse and soil.

3) Always

- Mix sample under dust extraction hood
- Avoid inhalation of dust, and skin or eye contact. Maintain high standards of personal hygiene i.e. washing hands prior to eating, drinking, or using toilet facilities.
- Prevent the build-up of dust in the room, and sweep-up material avoiding dust generation or dampen spilled material with water to avoid airborne dust.
- Transfer material to a suitable container, discharging the bagasse as close as possible to the bottom of the container. Wash surfaces well with soap and water. Seal all wastes in labelled plastic containers for subsequent disposal.

4) Never

- Breathe the dust.
- Access the room without any personal protective equipment.

5) Personal Protective Equipment Required

[✓] Gloves	[] Face shield
[✓] Safety glasses/goggles or Face shield	[✓] Respirator
[✓] Safety footwear	[] Protective clothing
[] Hearing protection	Other:

6) Define the Projects/Tasks

Mixing bagasse with soil for compaction and UCS tests. Atterberg, consolidation, triaxial and other typical soils test will be conducted. Hydrated lime or cement may be added to increase the strength/reduce the swell potential.	

7) When you finish

- Make sure that you seal/close the lid of the drum containing the opened bag of bagasse.
- If opening a new bag, disposed of the empty bag and place the newly-opened bag into the drum and close the lid after use.
- Close the door when finished.

8) Specific Assessments

[]Plant licenses

[ ] Certification/licensing of operator

Supervisors signature	Printed name	Date
	A/Prof. Hadi Khabbaz	
	Dr. Behzad Fatahi	

Prepared by: Antonio Reyno June 2012

A.2 Getting Bagasse for Testing

SAFE WORK METHOD STATEMENT

UNIVERSITY OF TECHNOLOGY SYDNEY

Principal Researcher / Lab or Workshop Manager: Antonio Reyno	
Faculty: Faculty of Engineering and IT	
Location(s): Geotechnical/Soils Laboratories, Building 2 Level 2 room 211	
Name of Assessor: Antonio Reyno	**Date:** Dec 2014

1) Work Description: Getting bagasse for testing.
Notify the Lab. manager to access the Soils Lab. Storage Room.

2) Before you start

Make sure:
You are wearing personal protective equipment (viz. gloves and respirator or dust mask).
You have the necessary container and scoop to get the desired amount of bagasse.

3) Always

- Avoid inhalation of dust, and skin or eye contact. Maintain high standards of personal hygiene i.e. washing hands prior to eating, drinking, or using toilet facilities.
- Prevent the build-up of dust in the room, and sweep-up material avoiding dust generation or dampen spilled material with water to avoid airborne dust.
- Then transfer material to a suitable container, discharging the bagasse as close as possible to the bottom of the container. Wash surfaces well with soap and water. Seal all wastes in labelled plastic containers for subsequent disposal.

4) Never

- Breathe the dust.
- Access the room without any personal protective equipment.

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[✓] Gloves	[] Face shield
[✓] Safety glasses/goggles or Face shield	[✓] Respirator
[✓] Safety footwear	[] Protective clothing
[] Hearing protection	Other:

6) Define the Projects/Tasks

Mixing bagasse with soil for compaction and UCS tests. Atterberg, consolidation, triaxial and other typical soils test will be conducted. Hydrated lime or cement may be added to increase the strength/reduce the swell potential.	

7) When you finish

- Make sure that you seal/close the lid of the drum containing the opened bag of bagasse.
- If opening a new bag, disposed of the empty bag and place the newly-opened bag into the drum and close the lid after use.
- Close the door when finished.

8) Specific Assessments

[]Plant licenses

[ ] Certification/licensing of operator

Supervisors signature	Printed name	Date
	A/Prof. Hadi Khabbaz	
	Dr. Behzad Fatahi	

APPENDIX B UTS TEST RESULT SUMMARY (TO DATE)

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

SOIL DATA REPORT

1 Atterberg Limits
1.1 Liquid Limit
1.1.1 Liquid Limit (Fall Cone method)

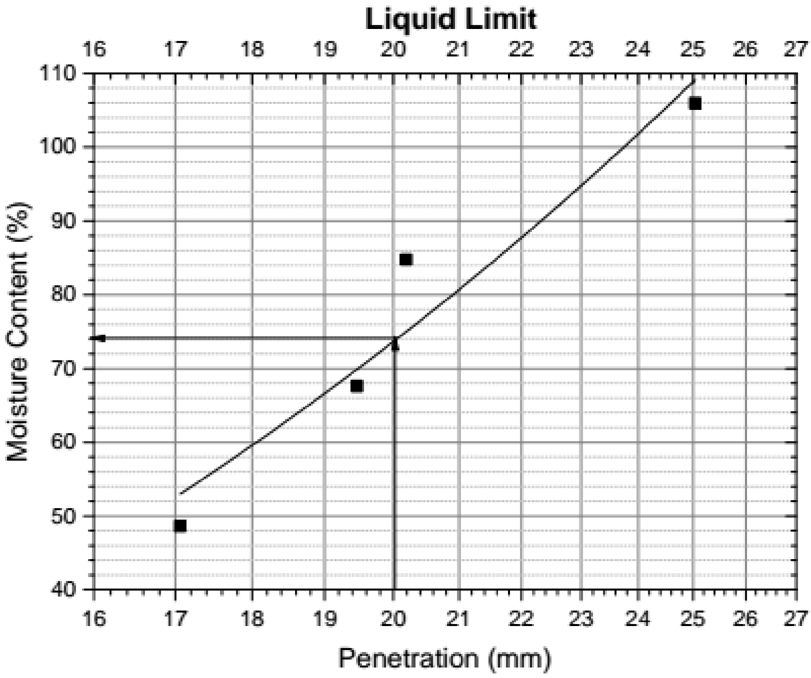

Figure 1 Liquid limit chart by fall cone method for natural soil

Table 1 Liquid Limit (Fall Cone) data for natural soil

No.	Mass of container + wet soil (gram)	Mass of container + dry soil (gram)	Moisture content W %	Penetration (mm)
1	54.2	41.8	48.63%	17.06
2	53.1	38.9	67.62%	19.46
3	64.9	46	84.75%	20.19
4	66.3	45	105.97%	25.04

1

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

1.1.2 Liquid Limit (Casagrande method)

(Sample 1)

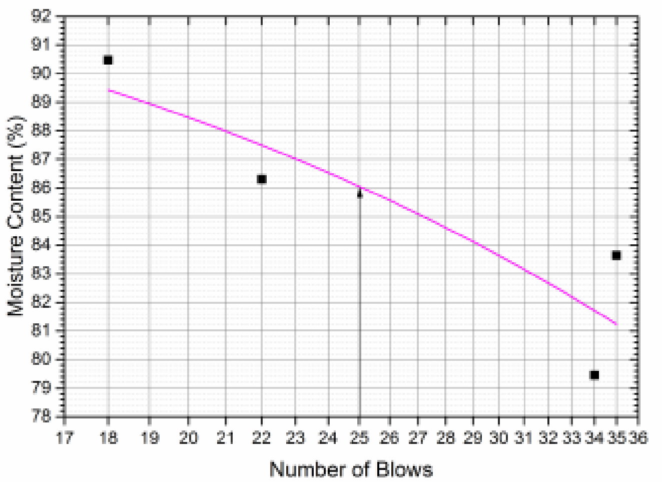

Figure 2 Liquid limit chart by Casagrande method for natural soil

Table 2 Liquid Limit (Casagrande method) data for natural soil

No.	Blows	Mass of Container (gram)	Mass of container + wet soil (gram)	Mass of container + dry soil (gram)	Water Content (%)
1	18	21.1	37.1	29.5	90.48
2	22	25.9	39.5	33.2	86.30
3	34	22.9	36	30.2	79.45
4	35	22.4	32.5	27.9	83.64

2

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

(Sample 2)

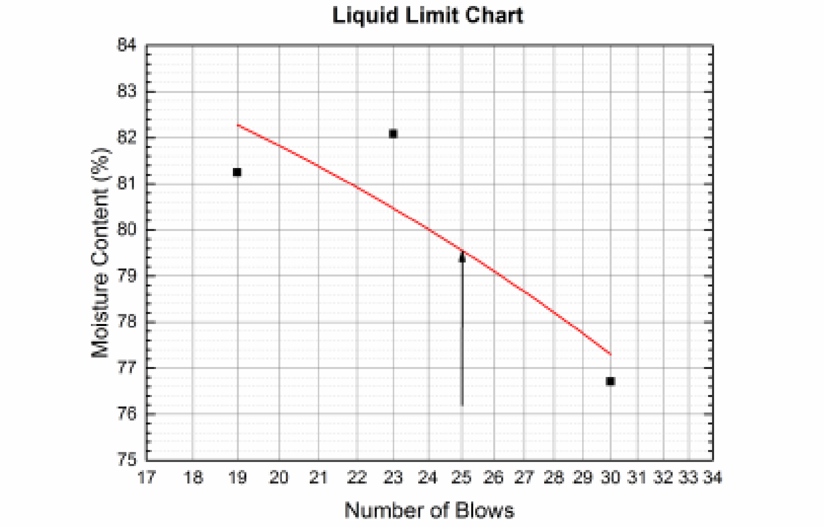

Figure 3 Liquid limit chart by Casagrande method for natural soil

Table 3 Liquid Limit (Casagrande method) data for natural soil

No.	Blows	Mass of Container (gram)	Mass of container + wet soil (gram)	Mass of container + dry soil (gram)	Water Content (%)
1	19	27.3	44.7	36.9	81.25
2	23	19.7	31.9	26.4	82.09
3	30	25.6	38.5	32.9	76.71

3

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

(Sample 3)

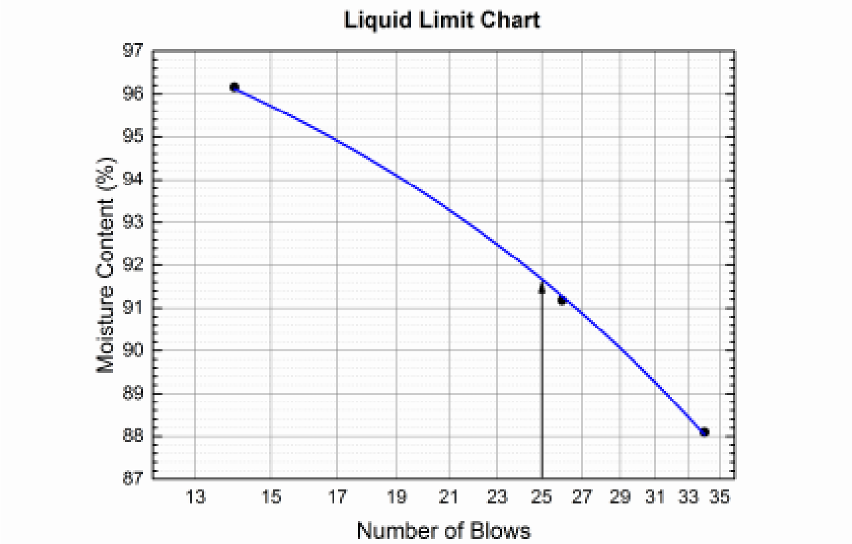

Figure 4 Liquid limit chart by Casagrande method for natural soil

Table 4 Liquid Limit (Casagrande method) data for natural soil

No.	Blows	Mass of Container (gram)	Mass of container + wet soil (gram)	Mass of container + dry soil (gram)	Water Content (%)
1	14	22.1	37.4	29.9	96.15
2	26	25.5	32	28.9	91.18
3	34	25.6	41.4	34	88.10

➔ **Liquid Limit in average (Casagrande method):** $\frac{(86+79.6+91.6)}{3} = 85.73 = 86\%$

4

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

1.2 Plastic Limit

Table 5 Plastic Limit data for natural soil

No.	Mass of Container (gram)	Mass of container + wet soil (gram)	Mass of container + dry soil (gram)	Water Content (%)
1	19.8	28.6	26.4	33.33%
2	23.2	29.5	27.8	36.96%
3	22.6	30.9	28.8	33.87%
4	25.8	30.5	29.2	38.24%
5	22.1	29.6	27.3	44.23%
6	21.0	25.9	24.5	40.00%
7	25.6	33.4	31.2	39.29%
8	27.3	34.2	32.2	40.82%
9	19.8	26.8	24.8	40.00%
10	25.5	31.7	30.2	31.91%
11	25.5	31.5	30.2	27.66%
12	27.3	34.3	32.5	34.62%
13	25.5	33.9	31.6	37.70%
	Average			**36.82%**
	Standard deviation			**4.41%**

1.3 Sieving Analysis

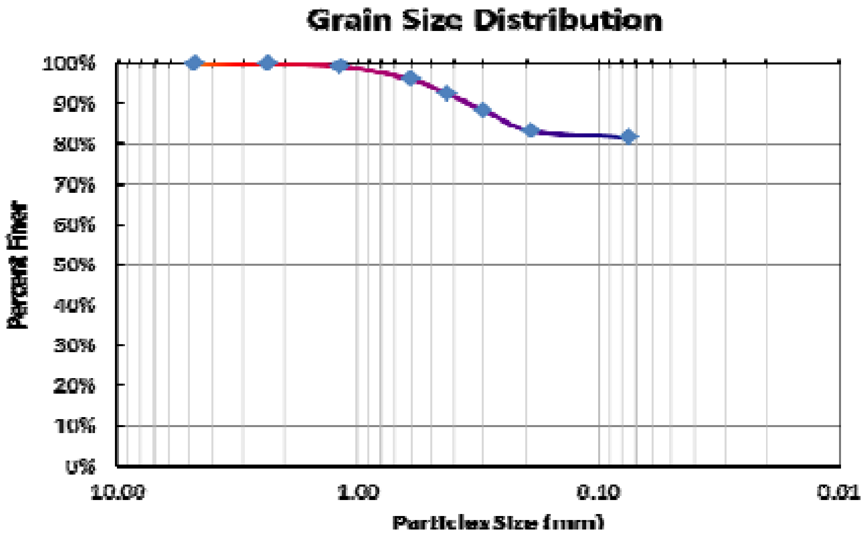

Figure 5 Grain size distribution chart by washing method for natural soil

5

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

Table 6 Grain size distribution data for natural soil

Sieve No.	Retained Dry Weight (gram)	Per cent Finer	Accumulated per cent Finer
4.75			100.00%
2.36	0.3	0.06%	99.94%
1.18	3	0.60%	99.34%
0.6	16.1	3.22%	96.12%
0.425	18.6	3.72%	92.40%
0.3	20.1	4.02%	88.38%
0.19	25.7	5.14%	83.24%
0.075	8	1.60%	81.64%
<0.075	408.2	81.64%	
Σ	**500**		

1.4 Natural Soil Moisture Content

Table 7 Moisture content data for natural soil

No.	Mass of Container (gram)	Mass of container + wet soil (gram)	Mass of container + dry soil (gram)	Water Content (%)
1	27.7	76.3	64.4	32.43%
2	25.3	79.0	66.3	30.98%
3	27.2	79.9	66.6	33.76%
4	22.9	69.8	58.2	32.86%
5	22.9	83.5	68.8	32.03%
6	25.5	71.7	59.7	35.09%
7	22.3	86.6	71.6	30.43%
8	22.2	58.9	50.3	30.60%
9	22.1	69.9	58.0	33.15%
10	22.3	68.8	57.5	32.10%
11	23.0	78.2	65.1	31.12%
12	25.5	85.8	71.1	32.24%
13	20.9	82.3	68.1	30.08%
14	25.4	69.2	59.0	30.36%
15	21.0	90.3	74.8	28.81%
16	25.8	72.2	61.4	30.34%
17	25.9	84.1	70.9	29.33%
18	22.6	87.6	73.4	27.95%
19	21.7	68.5	58.2	28.22%
20	23.2	61.5	52.4	31.16%
21	25.8	76.3	64.6	30.15%
22	25.6	76.8	65.2	29.29%
23	25.6	67.9	57.9	30.96%

24	25.5	91.5	76.1	30.43%
25	19.7	65.7	55.4	28.85%
26	22.6	60.7	52.0	29.59%
27	20.1	64.4	54.5	28.78%
28	55.5	116.6	102.2	30.84%
29	54.1	113.6	100.3	28.79%
30	54.0	118.9	103.1	32.18%
	AVERAGRE			**30.76%**
			STD	1.71%

1.5 Linear Shrinkage

Table 8 Linear Shrinkage data of black soil

No.	Length of the mould L mm	Longitudinal Shrinkage of samples L_S mm	Linear Shrinkage LS mm	Average LS (%)	Comments
1	150.36	32.43	21.57%	21.67%	
2	150.28	33.02	21.97%		
3	126.79	27.22	21.47%		

Table 9 Characteristics of natural soil

Characteristics (%)	
Gravel	0.06
Sand	18.30
Silt/Clay	81.64
Natural water content (%)	30.76
Liquid limit	86
Plastic limit	37
Plasticity index	49
Linear Shrinkage (%)	21.67
Specific gravity	2.62-2.65
USCS classification of the soil	CH

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

2 Bagasse Ash and Fibre

2.1 Bagasse Fibre Moisture Content

Table 10a Bagasse Fibre Moisture Content

No.	Mass of Container (gram)	Mass of container + wet soil (gram)	Mass of container + dry soil (gram)	Water Content (%)
1	54.0	92.9	73.5	99.49%
2	55.5	121.6	88.3	101.52%
3	54.8	113.8	84.6	97.99%
			Average	**99.67%**

Table 10b Bagasse fibre Moisture Content (second time check)

No.	Mass of Container (gram)	Mass of container + wet soil (gram)	Mass of container + dry soil (gram	Moisture Content W (%)		Oven Type (°C)
					Average	
1	25.8	55.2	40.4	101.37	100.10	105
2	50.7	135.2	93.2	98.82		105
3	25.6	61.6	44.5	90.48	90.98	50
4	55.6	141	100.2	91.48		50

2.2 Bagasse Ash Analysis

Table 11 Bagasse Ash Sieving Test data

No.	Mass of Sieve (gram)	Mass of Sieve + BA (gram)	Retained Bagasse Ash (gram)	Retained Per cent Finer	Accumulated Per cent Finer
0.425mmn	300.0	307.8	7.8	7.22%	92.78%
0.075mm	259.7	303.8	44.1	40.83%	51.94%
Pan	302.8	358.9	56.1	51.94%	
	Σ		108.0		

Specific gravity of bagasse ash G_s: 2.32

8

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

3 Soil Compaction Test

3.1 Soil Compaction Test for Natural Soil only

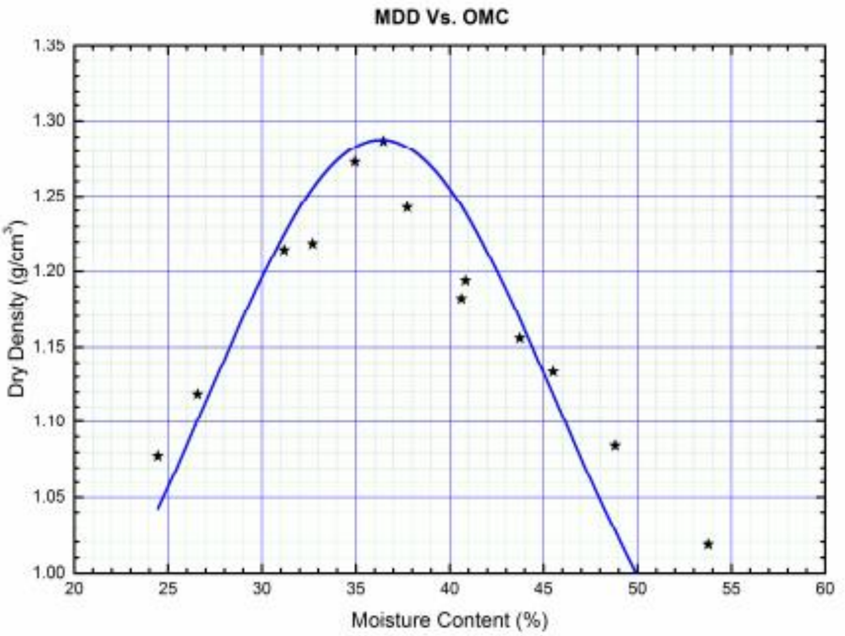

Figure 6 Relationship of dry density versus moisture content of black soil

Table 12 Compaction test data of black soil

No.	Description	Determination No.												
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
1	Internal dia. of mould in mm	104.79	104.79	104.79	104.79	104.8	104.79	104.79	104.79	104.79	104.79	104.79	104.79	104.79
2	Internal height of mould in mm	115.53	115.53	115.53	115.53	115.5	115.53	115.53	115.53	115.53	115.53	115.53	115.53	115.53
3	Volume of mould (V) in cm^3	996.34	996.34	996.34	996.34	996.3	996.34	996.34	996.34	996.34	996.34	996.34	996.34	996.34
4	Weight of mould (W_1) in gr	4097.6	4097.6	4097.4	4097.6	4097.4	4097.4	4097.6	4104.8	4097.4	4104.8	4097.6	4104.8	4104.8
5	Weight of mould + wet soil (W_2) in gr	5433.9	5508	5685.1	5709	5809	5847.5	5802.4	5760.9	5772.8	5760.1	5740.8	5712.5	5665
6	Weight of soil (W_2-W_1) in gr	1336.3	1410.4	1587.7	1611.4	1711.6	1750.1	1704.8	1656.1	1675.4	1655.3	1643.2	1607.7	1560.2
7	Bulk Density of soil $\gamma=(W_2-W_1)/V$, g/cm^3	1.34	1.42	1.59	1.62	1.72	1.76	1.71	1.66	1.68	1.66	1.65	1.61	1.57
8	Moisture Content (W) in %	24.45	26.57	31.19	32.7	35	36.47	37.74	40.63	40.84	43.74	45.51	48.81	53.77
9	Dry Density of Soil $\gamma_d=\gamma_w/(1+W)$, g/ cm^3	1.08	1.12	1.21	1.22	1.27	1.29	1.24	1.18	1.19	1.16	1.13	1.08	1.02

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

3.2 Compaction test: Black Soil mixed with Bagasse Ash at 36.5% Moisture Content of Bagasse Ash & Dry Weight of Soil

(16 Feb 2015)

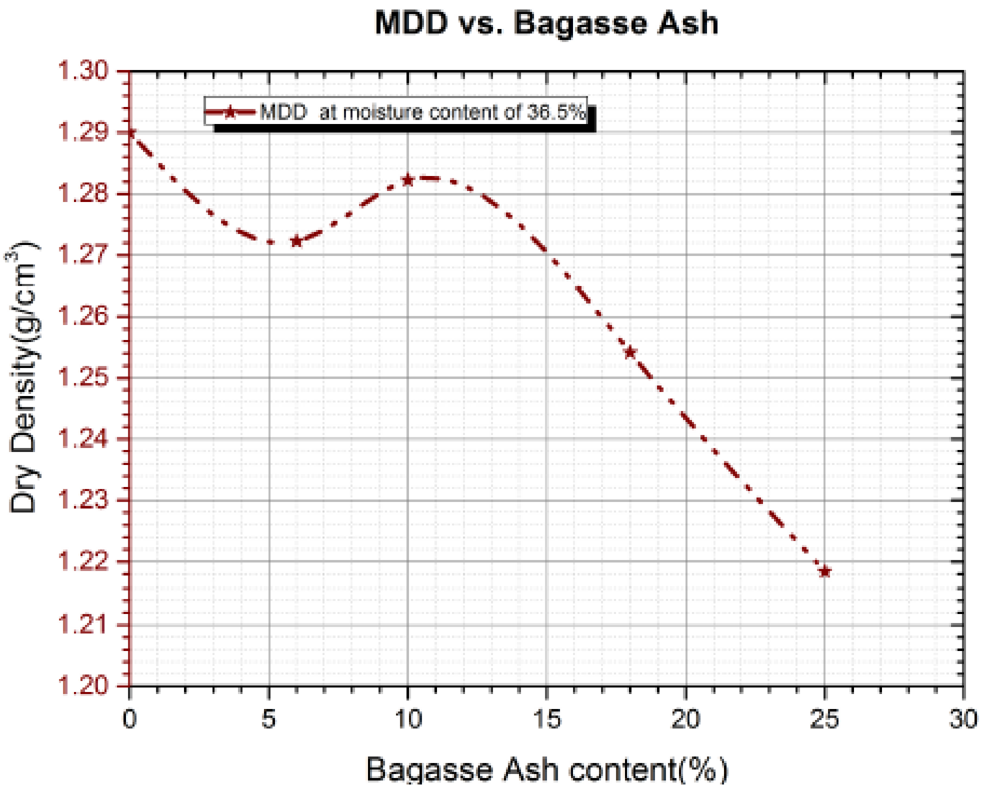

Figure 7 Relationship of dry density of black soil mixed with various bagasse ash contents at 36% moisture content of solid mass

Table 13 Data for dry density of black soil mixed with various bagasse ash contents at 36.5% moisture content of BA and black soil

No.	Description	Determination No.				
		0	6% BA	10% BA	18% BA	25% BA
1	Internal dia. of mould in mm	104.79	104.6	104.6	104.6	104.6
2	Internal height of mould in mm	115.53	115.6	115.6	115.6	115.6
3	Volume of mould (V) in cc	996.34	993.3	993.3	993.3	993.3
4	Weight of mould (W_1) in gr	4097.4	4097.5	4097.5	4097.5	4097.5
5	Weight of mould + wet soil (W_2) in gr	5847.5	5834.6	5837.7	5804.2	5756.9
6	Weight of soil γ=(W_2-W_1)in gr	1750.1	1737.1	1740.2	1706.7	1659.4
7	Bulk Density of soil γ=(W_2-W_1)/V, g/cc	1.76	1.749	1.752	1.718	1.671
8	Moisture Content (W) in %	36.47	0.375	0.366	0.370	0.371
9	Dry Density of Soil $\gamma d=\gamma/(1+W)$, g/cc	1.29	1.272	1.282	1.254	1.218
10	Bagasse Ash Content	0	6%	10%	18%	25%

Note: BA means Bagasse Ash

11

Project: Bagasse Ash and Black Soil Stabilisation Date: 30 April 2015

3.3 Compaction test: Black Soil mixed with Bagasse Ash and Hydrated Lime (23 March 2015)

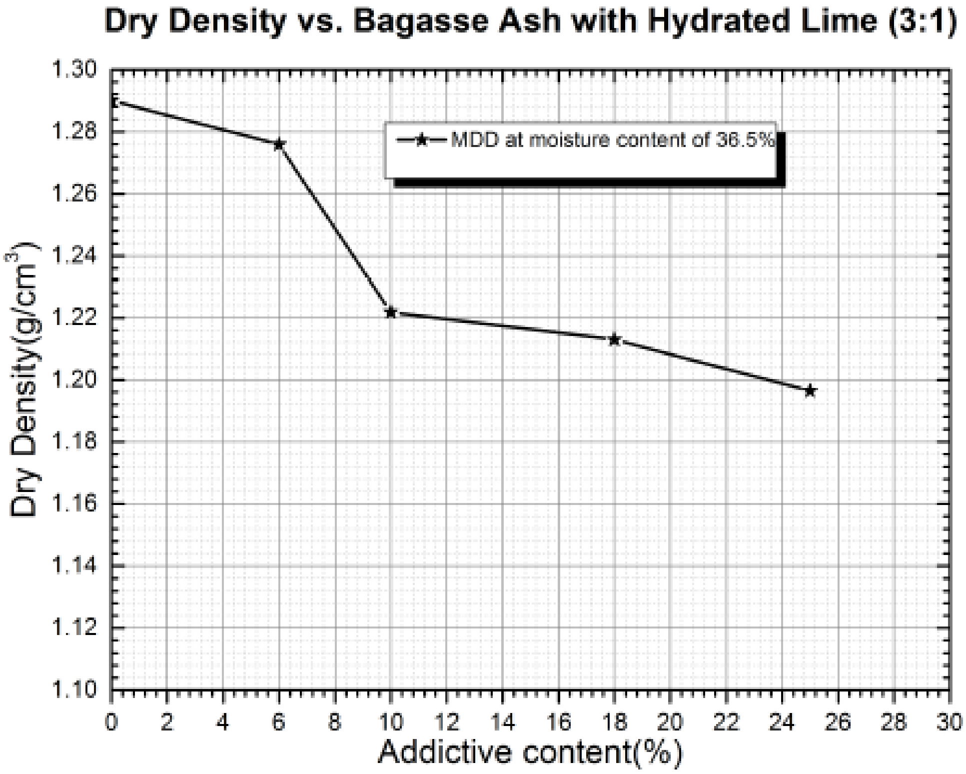

Figure 8 Effect of bagasse ash with lime on compaction characteristics

Table 14 Data for dry density of black soil mixed with various bagasse ash and lime contents at 36.5% moisture content of BA+ lime + black soil

No.	Description	0	Determination No.			
			6% BA+L	10% BA+L	18% BA+L	25% BA+L
1	Internal dia. of mould in mm	104.79	104.99	104.99	104.99	104.99
2	Internal height of mould in mm	115.53	115.65	115.65	115.65	115.65
3	Volume of mould (V) in cc	996.34	1001.29	1001.29	1001.29	1001.29
4	Weight of mould (W_1) in gr	4097.4	4443.20	4443.20	4443.20	4444.20
5	Weight of mould + wet soil (W_2) in gr	5847.5	6183.10	6110.20	6099.71	6082.70
6	Weight of soil (W_2-W_1) in gr	1750.1	1739.90	1667.00	1656.51	1638.50
7	Bulk Density of soil $\gamma=(W_2-W_1)/V$, g/cc	1.76	1.738	1.665	1.654	1.636
8	Moisture Content (W) in %	36.47	36.20%	36.26%	36.39%	36.78%
9	Dry Density of Soil $\gamma_d=\gamma/(1+W)$, g/cc	1.29	1.276	1.222	1.213	1.196
10	Hydrated Lime Content	0	1.50%	2.50%	4.50%	6.25%
11	Bagasse Ash Content	0	4.50%	7.50%	13.50%	18.75%

12

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3.4 Compaction Test: Soil mixed with Hydrated Lime Only

(12 April 2015)

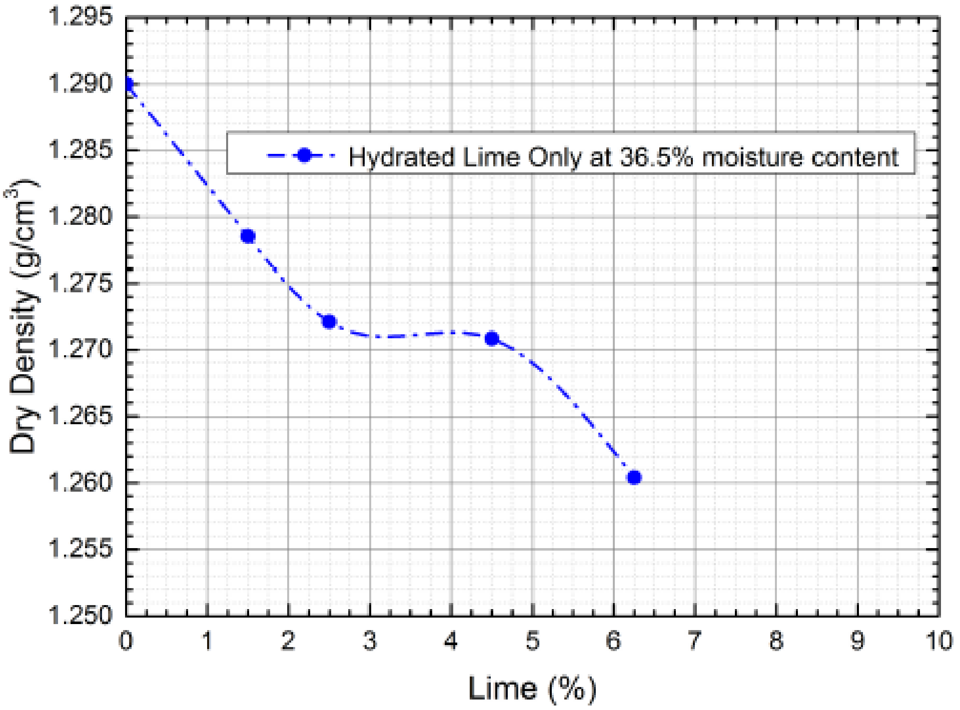

Figure 9 Effect of hydrated lime content on compaction characteristics

Table 15 Data for dry density of black soil mixed with hydrated lime contents alone at 36.5% moisture content of lime + black soil

No.	Description	Determination No.				
		0	(1.5% L)	(2.5% L)	(4.5% L)	(6.25% L)
1	Internal dia. of mould in mm	104.79	104.8	104.8	104.8	104.8
2	Internal height of mould in mm	115.53	115.4	115.4	115.4	115.4
3	Volume of mould (V) in CC	996.34	995.7	995.7	995.7	995.7
4	Weight of mould (W_1) in gr	4097.4	4423.3	4423.3	4423.3	4423.3
5	Weight of mould + wet soil (W_2) in gr	5847.5	6143.9	6136.9	6134.1	6127.3
6	Weight of soil (W2-W1) in gr	1750.1	1720.6	1713.6	1710.8	1704.0
7	Bulk Density of soil γ=(W2-W1)/V, g/cc	1.76	1.728	1.721	1.718	1.711
8	Moisture Content (W) in %	36.47	35.2%	35.3%	35.2%	35.8%
9	Dry Density of Soil $\gamma d=\gamma/(1+W)$, g/cc	1.29	1.279	1.272	1.271	1.260
10	Hydrated lime Content	0	1.50%	2.50%	4.50%	6.25%

13

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4 Linear Shrinkage

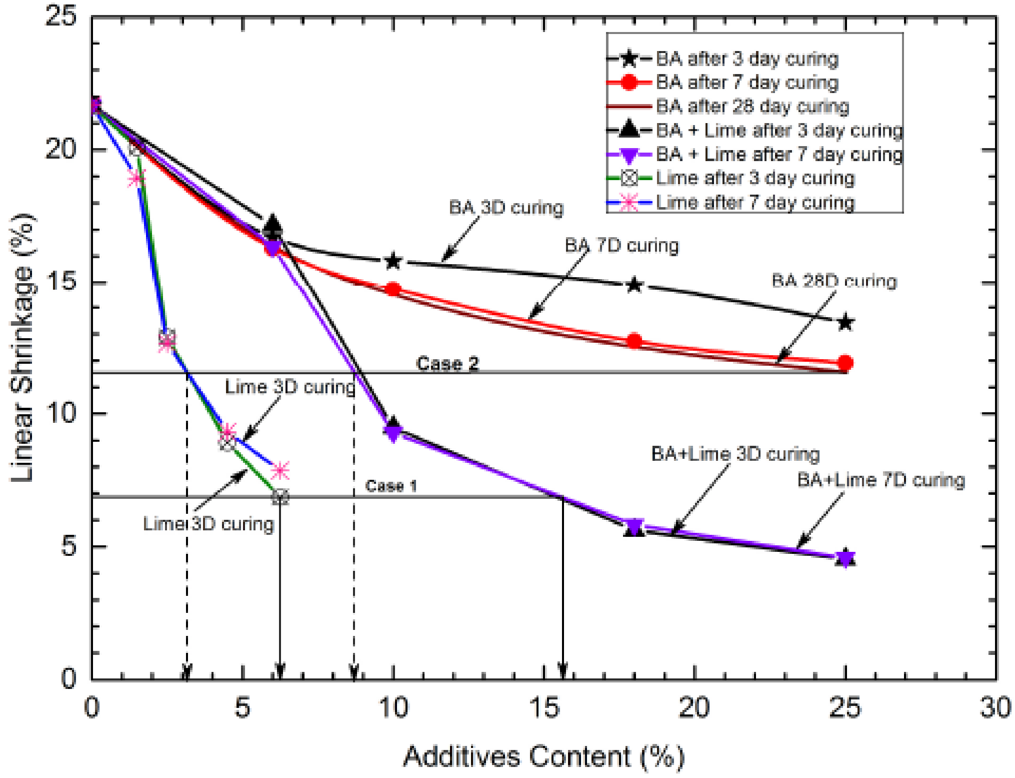

Figure 10 Linear Shrinkage of black soil mixed various bagasse ash (BA), Lime(L), and (BA + L) combination contents

Table 16 Comparison of linear shrinkage with different additives contents

Case No.	Linear Shrinkage (%)	Option 1	Option 2	Option 3
		Bagasse Ash (%)	Bagasse Ash + Lime (3:1)	Hydrated Lime (%)
1	6.9	-	11.7%BA + 3.91%L	6.25
2	11.56	25	6.53%BA + 2.18%L	3.15

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Table 17 Linear Shrinkage data of black soil mixed various bagasse ash content at 3 days curing

No.	Length of the mould	Longitudinal Shrinkage of samples	Linear Shrinkage	Average LS (%)	Admixture Content (%)
	L mm	L_s mm	LS mm		
1	150.4	32.4	21.57%	21.67%	Soil
2	150.3	33.0	21.97%		
3	126.8	27.2	21.47%		
4	150.0	24.8	16.55%	16.72%	6%BA
5	150.0	25.2	16.77%		
6	150.0	25.3	16.83%		
7	250.0	39.1	15.65%	15.82%	10%BA
8	250.0	40.2	16.08%		
9	250.0	39.3	15.74%		
10	500.0	74.9	14.98%	14.88%	18%BA
11	500.0	70.7	14.14%		
12	250.5	38.8	15.51%		
13	150.6	17.5	11.60%	13.43%	25%BA
14	150.4	21.9	14.57%		
15	127.0	17.9	14.13%		

Table 18 Linear Shrinkage data of black soil mixed various bagasse ash content at 7 days curing

No.	Length of the mould L mm	Longitudinal Shrinkage of samples L_s mm	Linear Shrinkage LS (%)	Bagasse Ash Content (%)
0	150.355	32.425	21.57%	0
1	150.275	33.015	21.97%	0
2	126.79	27.22	21.47%	0
3	150.5	24.510	16.29%	6
4	250.0	36.775	14.71%	10
5	250.0	31.825	12.73%	18
6	250.0	29.775	11.91%	25

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Table 19 Linear Shrinkage data of black soil mixed various bagasse ash content at 28 days curing

No.	Length of the mould L mm	Longitudinal Shrinkage of samples L_s mm	Linear Shrinkage LS (%)	Bagasse Ash Content (%)
1	150.62	24.69	16.39%	6
2	500.00	72.50	14.50%	10
3	500.00	62.58	12.52%	18
4	500.00	57.80	11.56%	25

Table 20 Linear Shrinkage data of black soil mixed various bagasse ash and lime content at 3 days curing

No.	Length of the mould L mm	Longitudinal Shrinkage of samples L_s mm	Linear Shrinkage LS mm	BA + L Content (%)	Comments
1	251.00	43.107	17.17%	6	
2	254.0	24.107	9.49%	10	
3	254.0	14.273	5.62%	18	
4	254.25	11.61	4.57%	25	

Table 21 Linear Shrinkage data of black soil mixed various bagasse ash and lime content at 7 days curing

<table>
<tr><th>No.</th><th>Length of the mould L mm</th><th>Longitudinal Shrinkage of samples L_s mm</th><th>Linear Shrinkage LS mm</th><th>Average LS (%)</th><th>BA + L Content (%)</th><th>Comments</th></tr>
<tr><td>1</td><td>250.00</td><td>40.923</td><td>16.37%</td><td>16.37%</td><td>6</td><td></td></tr>
<tr><td>2</td><td>254.25</td><td>23.617</td><td>9.29%</td><td>9.29%</td><td>10</td><td></td></tr>
<tr><td>3</td><td>254.0</td><td>14.800</td><td>5.83%</td><td>5.83%</td><td>18</td><td></td></tr>
<tr><td>4</td><td>254.00</td><td>12.00</td><td>4.73%</td><td rowspan="3">4.59%</td><td rowspan="3">25</td><td rowspan="3"></td></tr>
<tr><td>5</td><td>150.31</td><td>6.93</td><td>4.61%</td></tr>
<tr><td>6</td><td>150.45</td><td>6.66</td><td>4.43%</td></tr>
</table>

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Table 22 Linear Shrinkage data of black soil mixed various hydrated lime content only at 3 days curing

No.	Length of the mould L mm	Longitudinal Shrinkage of samples L_s mm	Linear Shrinkage LS mm	Hydrated Lime Content (%)	Comments
1	254.25	48.150	18.94%	1.5	
2	251.00	31.760	12.65%	2.5	
3	251.10	23.393	9.32%	4.5	
4	254.50	20.00	7.86%	6.25	

Table 23 Linear Shrinkage data of black soil mixed various hydrated lime content only at 7 days curing

No.	Length of the mould L mm	Longitudinal Shrinkage of samples L_s mm	Linear Shrinkage LS mm	Hydrated Lime Content (%)	Comments
1	150.51	30.24	20.09%	1.5	
2	126.93	16.34	12.88%	2.5	
3	150.54	13.41	8.91%	4.5	
4	126.89	8.71	6.86%	6.25	

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5 Unconfined Compressive Strength (UCS) Tests

Time

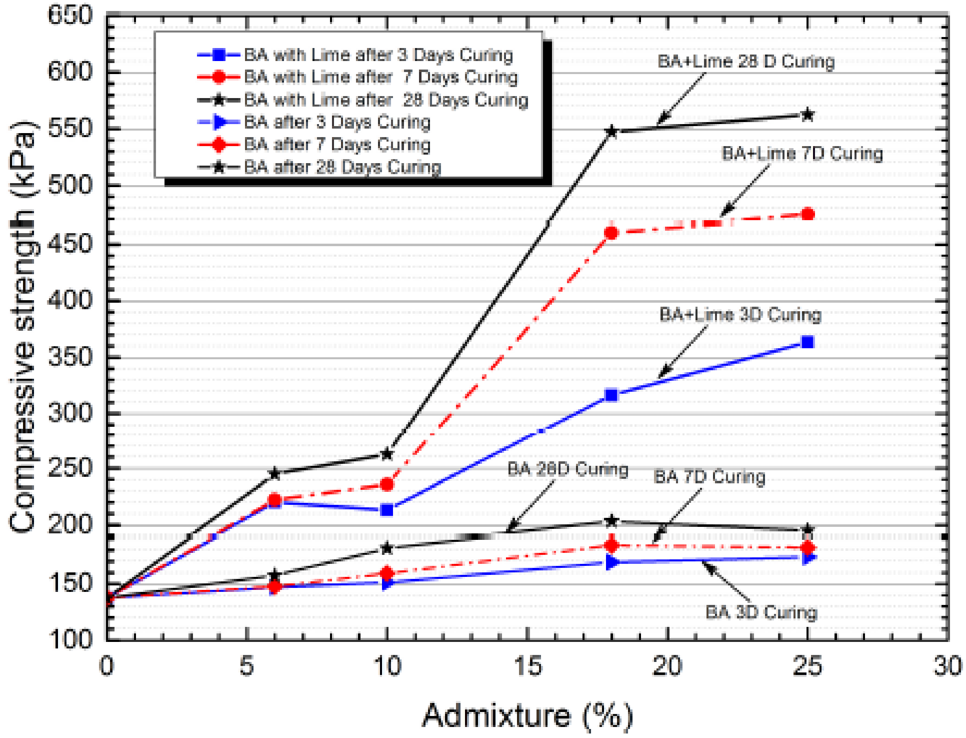

Figure 11 Effects of Admixture on Average UCS of Treated Black Soil with Various Curing Time

Table 17 UCS values of black soil mixed with variations of additives at different days curing

No.	Admixture Content (%)	3 Days Curing Strength (kPa)	7 Days Curing Strength (kPa)	28 Days Curing Strength (kPa)
1	Black Soil	137.6	137.6	137.6
2	6%BA	147.0	147.7	157.5
3	10%BA	151.2	159.3	181.5
4	18%BA	169.2	184.1	203.3
5	25%BA	173.7	182.1	195.1
6	4.5%BA+1.5%L	220.3	222.2	245.0
7	7.5%BA+2.5%L	213.1	235.8	262.5
8	13.5%BA+4.5%L	316.5	460.3	547.4
9	18.75%BA+6.25%L	363.6	474.6	562.6

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6 Free Swell Potential Test

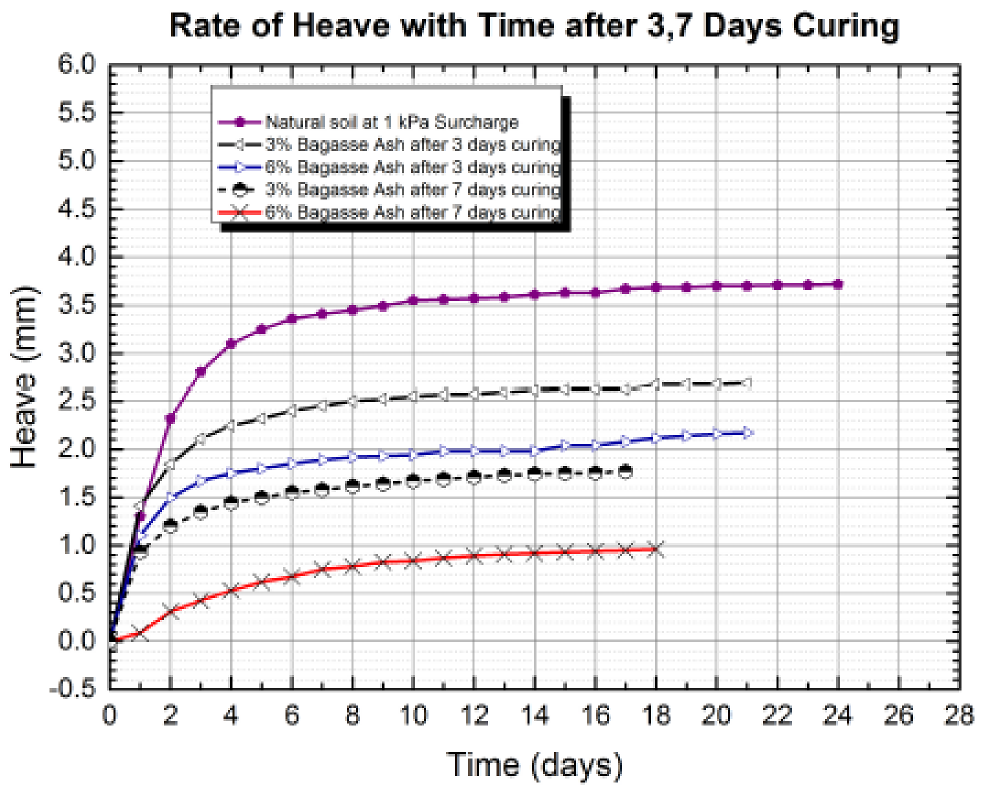

Figure 12 Effects of Bagasse Ash-Reinforced Black Soil on Rate of Heave with Various Curing Time

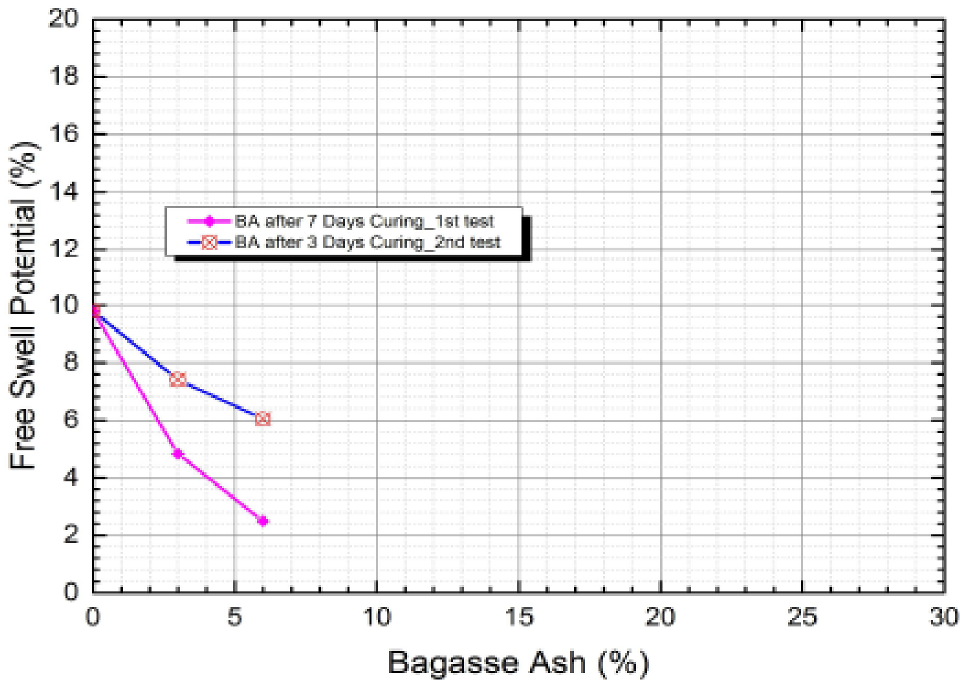

Figure 13 Effect of Bagasse Ash on Swell Potential in Per cent

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Table 24 Effects of Bagasse Ash-Reinforced Black Soil on Rate of Heave with Various Curing Time

No.	Description	sp0	sp1	sp2	sp3	sp4
1	**Bagasse Ash Content (%)**	Black Soil only	3	6	3	6
2	Curing Days	0	3	3	7	7
3	Internal dia. of mould in mm	152.18	150.73	151.65	151.86	152.13
4	Internal height of mould in mm	37.95	36.34	35.96	36.62	38.60
5	Volume of mould (V) in cm^3	690.27	648.49	649.46	663.25	701.67
6	initial surcharge in gr ~ 1 kPa	1854.11	1818.95	1841.16	1846.38	1852.89
7	Weight of mould (W_1) in gr	26469.00	27187.10	27044.20	27064.20	27021.00
8	Mass of mould + wet soil (W_2) in gr	27681.50	28268.64	28119.53	28170.36	28207.30
9	Mass of wet soil (W_2-W_1) in gr	1212.50	1081.54	1075.33	1106.16	1161.79
10	Bulk Density of soil $\gamma_\omega=(W_2-W_1)/V$, g/ cm^3	1.76	1.67	1.66	1.67	1.66
11	Moisture Content (W) in %	36.50%	36.50%	36.50%	36.50%	36.50%
12	Dry Density of Soil $\gamma_d=\gamma/(1+W)$, g/ cm^3	1.287	1.222	1.213	1.222	1.213
13	**Free Swell Potential**	**9.80%**	**7.40%**	**6.03%**	**4.83%**	**2.49%**

Table 25 Effect of Bagasse Ash on Swell Potential in Per cent

No.	Height (mm)	Diameter (mm)	Heaving (mm)	Swell Potential (%)	Bagasse Ash Content (%)	Curing Days
1	37.95	152.18	3.72	9.80%	0	0
2	36.34	150.73	2.69	7.40%	3	3
3	35.96	151.65	2.17	6.03%	6	3
4	36.62	151.86	1.77	4.83%	3	7
5	38.60	152.13	0.96	2.49%	6	7

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7 California Bearing Ratio (CBR) Test

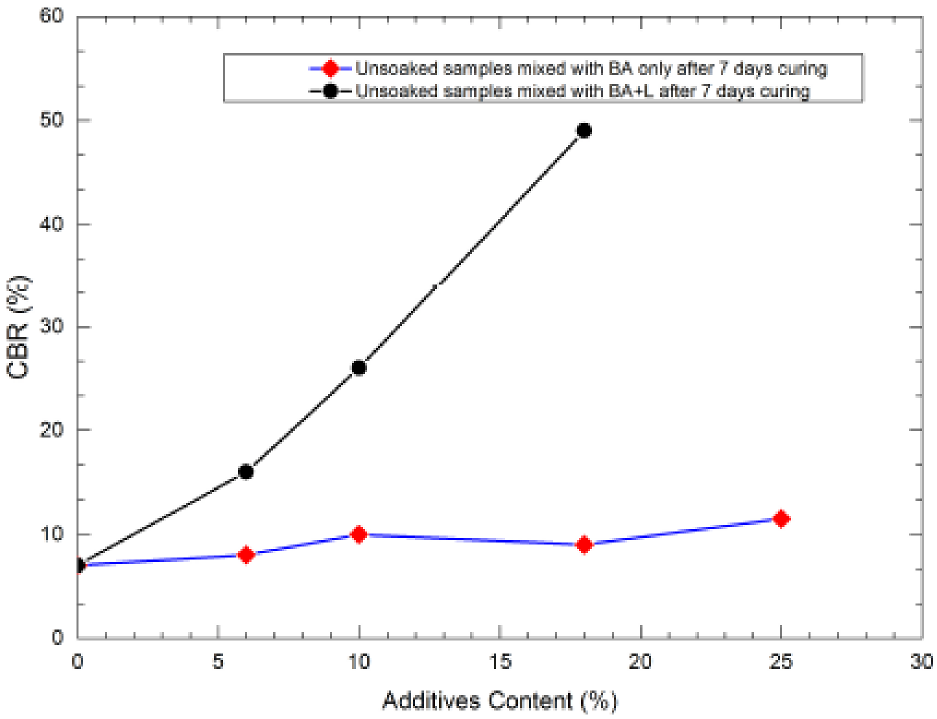

Figure 14 Summary of CBR of Treated Black Soil after 7 Days Curing

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Table 26 Effect of Bagasse Ash on CBR of Treated Black Soil

No	Description	Determination No.					
		Sample 1 soaked	Sample 2 unsoaked	Sample 3 unsoaked	Sample 4 unsoaked	Sample 5 unsoaked	Sample 6 unsoaked
1	Additives (BA Only)	Black soil only	Black soil only	6%	10%	18%	25%
2	Internal dia. of mould in mm	151.70	151.46	152.19	151.62	151.62	152.00
3	Internal height of mould in mm	115.69	118.15	115.94	119.71	119.71	117.93
4	Volume of mould (V) cm^3	2091.07	2128.82	2108.95	2161.42	2161.42	2139.94
5	initial surcharge	4500	4500	4500	4500	4500	4500
6	Weight of mould (W_1) in gr	16802.90	16427.80	16556.70	15772.40	16407.60	16355.70
7	Weight of mould + wet soil (W_2) in gram	20483.19	20191.46	20219.50	19499.80	20107.30	19913.50
8	Weight of soil (W2-W1) in gr	3680.29	3763.66	3662.80	3727.40	3699.70	3557.80
9	Bulk Density of soil γ=(W2-W1)/V, g/ cm^3	1.768	1.768	1.737	1.725	1.712	1.663
10	Moisture Content (W) in %	41.10%	36.50%	35.98%	37.61%	35.87%	37.57%
11	Dry Density of Soil $\gamma d=\gamma/(1+W)$, g/ cm^3	1.290	1.290	1.277	1.253	1.254	1.218
12	CBR (%)	**4.0**	**7.0**	**8.0**	**10.0**	**9.0**	**12.0**

Table 27 Effect of Lime-Bagasse Ash Additives on CBR of Treated Black Soil

No.	Description	Determination No.			
		SP1	Sp2	SP3	SP4
1	Additives (Lime/BA: 1/3)	6%	10%	18%	25%
2	Internal dia. of mould in mm	151.5825	152.185	151.7	
3	Internal height of mould in mm	117.225	115.973	117.85	
4	Volume of mould (V) in cm^3	2115.48	2109.54	2130.01	
5	initial surcharge	4500	4500	4500	
6	Weight of mould (W_1) in gr	16802.9	16556.7	1577.4	
7	Weight of mould + wet soil (W_2) in gram	20487.51	20075.48	5104.15	
8	Weight of soil (W2-W1) in gr	3684.61	3518.78	3526.75	
9	Bulk Density of soil γ=(W2-W1)/V, g/ cm^3	1.742	1.668	1.656	
10	Moisture Content (W) in %	35.48%	35.65%	35.45%	
11	Dry Density of Soil $\gamma d=\gamma/(1+W)$, g/ cm^3	1.276	1.222	1.213	
12	**CBR (%)**	**16**	**26**	**49**	

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