AN EVALUATION OF THE COMPRESSIVE AND SHEAR STRENGTH OF AN ALTERNATIVE MATERIAL: STABILIZED FINE-GRAINED FLY ASH

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ABSTRACT

The potential use of alternative materials is sometimes limited by the lack of performance data. Appropriate laboratory studies can provide information on their performance. Two grades of fine grained fly ash samples without course fractions are being investigated for potential and appropriate application as road construction material. In the current phase of the study, the samples are treated with the minimum required amounts of lime and cement as well as an enzyme-based liquid stabilizer. The bulk mechanical properties are quantified using the unconfined compressive strength and static triaxial tests. The results show that moderate to high compressive and shear strength values are achievable with the minimum required amounts of cement and lime to stabilise the unclassified fine grained fly ash. The stabilisation with the enzyme-based liquid stabiliser has potential for application.

1. INTRODUCTION

Major initiatives have been underway over the years on the international scene by highway authorities to manage the use of alternative materials in road construction. The term, alternative materials, refers to recovered materials from road rehabilitation projects, industrial, municipal or the mining sector. Typical examples of alternative materials include fly-ash, slag, dam tailings, recycled asphalt pavements, construction and demolition waste (rubble) and any other materials with potential for use in road construction.

Based on the data extracted from the national waste information baseline report (DEA, 2012), large stockpiles of industrial and mine discard occur in South Africa. A total of 43 165 963.00 tonnes of generated waste per a year is landfilled which potentially can be used in road construction. Table 1 presents the composition of unclassified waste. Only 6% of the fly ash produced in 2011 was recycled. While the utilization of fly ash in road construction cannot dramatically reduce the quantities being produced, increasing the utilisation alternative potential of the fly ash should greatly contribute towards conserving landfill capacity requirements.

Table 1: Unclassified waste by management option - 2011 (DEA, 2012)

Description	Generated	Recycled	Treated	Landfilled	Recycled
	Tonnes				%
Brine	4 166 129	-	-	4 166 129	0
Fly ash and dust from miscellaneous filter sources	31 420 488	1 885 229	-	29 535 259	6
Bottom ash	5 717 324	-	-	5 717 324	0
Slag	5 370 968	2 685 484		2 685 484	50
Mineral waste	369 000	-	-	369 000	0
Waste of Electric and electronic Equipment	64 045	6 884		57 161	11
Sewage sludge	673 360	130 160	42 624	500 508	19

The use of alternative materials, including re-use by recycling is beneficial not only in terms of reducing construction costs but as the most appropriate response to the requirements of sustaining the environment, as naturally occurring materials will be conserved and energy requirements during construction will also be reduced and therefore reduce impact to the environment.

The initiatives in the use of alternative materials in road construction are aimed at providing guidance on how and when alternative materials can be used in road pavements. The Institute for Recyclable Materials (IRM) was established in a cooperative agreement between CSIR and University of Pretoria in the late 90s to facilitate such a process (Jones, 2003). A project has been initiated at the CSIR to formally assemble information on the use of alternative materials in road construction in South Africa in order to revive this initiative. The current study therefore builds upon previous work carried out during the past several years by other researchers at the CSIR Built Environment, in particular within the Transport Infrastructure Engineering competence area. The objective is to collate information, review and where necessary develop methods/standards based on experiences learned on the performance of these materials from both laboratory and field conditions for better use by industry.

2. INITIATIVES IN THE UTILISATION OF ALTERNATIVE MATERIALS IN ROAD CONSTRUCTION IN RECENT YEARS AT THE CSIR

Heath and Jones (1997) investigated the environmental implications of using Sasol ash as a road construction material. They carried out toxicity testing and chemical analyses on leachate obtained from shake tests performed with the ash. They also assessed performance under field conditions by monitoring trial sections constructed using the ash as basecourse aggregate. The conclusion was that the use of Sasol ash as a basecourse or subbase material would not have a significant effect on the surrounding environment. They however recommended that the use of the ash as a bulk fill material for road construction required investigations for each case by taking site specific conditions into account

Heath et al. (1997) undertook a detailed laboratory testing programme. They investigated the use of unstabilized, lime stabilized and bitumen emulsion treated course and fly ash blend for use in basecourse, subbase and fill applications. In addition, they investigated the use of the ash as an asphalt, slurry seal and concrete aggregate. They found that the Sasol ash could be effectively used as an aggregate in unstabilized basecourse layers.

The emulsion stabilized ash achieved good strengths and engineering properties. The ash was unlikely to be used as asphalt and slurry seal aggregate due to its high absorption and therefore high binder content requirement, making it more expensive than using natural materials. Lightweight concrete using Sasol ash as an aggregate was found to be a cost effective alternative to conventional concrete, if the project site was within a distance of 256 km from the source.

Lea (1999) examined a number of possible applications of waste materials. The materials were grouped into three categories, namely granular, processed materials and liquids. In the study, processed material referred to materials which had to undergo significant processing before they can be used in road construction. Granular materials such as mine tailings, ash, slag and phosphogypsum were deemed more promising followed by processed materials from pavement recycling. With respect to liquids, the recommendation was that more detailed investigation was required into their potential use. A four stage process, from assessment to implementation/technology transfer, to fast track the utilisation of waste in road construction was proposed. The process comprised of feasibility study, detailed testing, field testing and implementation/technology transfer.

Paige-Green and Gerber (2000) report on the preliminary results of a laboratory investigation and a number of field trials on road building properties using the by-product phosphogypsum (BPG) in the Lethabong Metropolitan Local Council (MLC) area. Field trial sections were constructed in Edenvale and Tembisa. The BPG was stabilised with 7 per cent (by mass) of Ordinary Portland Cement (OPC), an effective stabiliser content of about 5 per cent by volume due to the low density of BPG. Laboratory results showed that the material was comparable in strength and durability with any C4 type material and could be obtained cost-effectively. Field monitoring of the trial sections over a period of 18 months indicated that the materials performed well and that the strength of the stabilised BPG continued to increase over time. The strength of the stabilised BPG subbase increased by between 86 and 121 per cent, while the strengths of the stabilised natural gravel control subbases increased by between only 30 and 50 per cent over the same period.

Denneman and Paige-Green (2007) presented an overview of the waste stockpiles available in South Africa and the state of the art of the technology of utilizing this waste in road pavements. Their report highlights some of the barriers to waste utilization, often related to the conservative nature of the Civil Construction sector. The role of CSIR in advancing the use of recycled materials in pavement construction is also discussed. Unlike Lea’s recommendation in 1999 to pursue research projects in the utilization of waste materials, they suggest that the CSIR should respond to specific requests for research to be carried out. The CSIR Transport Infrastructure Engineering group was therefore to take every opportunity to assist companies that want to investigate the use of waste materials in pavement construction and no pro-active steps in research on the utilization of waste material be taken.

However, current challenges call for development of technology and innovation in support of sustainable development. Despite the fact that it is more than three decades ago, since Horak and Maree (1982) reported on trial sections of projects in South Africa where slag, an industrial by-product, was used as a base material, there exist no official tool that provides guidance on how and when alternative materials can be used in road pavement. To this end, the revival of the project on alternative materials at the CSIR, from which both laboratory and field performance of these materials can be established and specific methods/standards be developed is the appropriate response.

The approach is to focus on a specific material at a time. The construction of new power stations by ESKOM will increase the production of fly ash in South Africa, of which currently only 6% being recycled. In spite of the fact that a number of options for alternative use of fly ash are being implemented and studied around the world and in South Africa, like in cement, concrete, bricks, soil stabilisation, road base or embankment, ground consolidation, land reclamation, agriculture, and even a possible remediation option for acid mine drainage, there is a need to increase the utilisation potential of the fly ash in road construction in order to contribute to sustainable development by reducing the capacity to landfills.

The common practice is to use fly ash in combination with other materials in road construction, for example the study by Santos et al. (2011). However, the paper focuses on initial work on characterising treated fine grained fly ash. This involved testing the fly ash treated with cement, lime and an enzyme-based liquid stabiliser. The aim of the current study is to supplement the information on fly ash performance. Previous studies (Heath et al., 1996) on fly ash at the CSIR focused on coarse Sasol fly ash mixed with different proportions of natural soil. In this study 100% fly ash available from Lethabo Power Station in Vereeniging was used.

3. MATERIAL TESTING

3.1. Material preparation

Two grades of fly ash, a classified and unclassified fly ash available from Lethabo Power Station in Vereeniging were used in the study. According to the data provided by the supplier, the classified fly ash has a mean particle size of 25 micron, typically 90% of the product's particles pass through a 45 micron sieve. The unclassified fly ash comprises of particles ranging in size from 120 micron to sub-micron in size.

Specimen preparation consisted of four steps: material preparation, moulding, compaction, and curing in case of unconfined compression and triaxial test specimens. Material preparation involved the determination of the required mix proportions of the cement, lime or enzyme-based liquid stabiliser to fly ash quantity. In practice, the recommendation is that the demand for stabilizer by a material being treated should be satisfied and excess stabilizer provided so that there is sufficient stabilizer to allow for completion of the early reactions (Paige-Green 2008). In the current study, the minimum strength for the minimum required amounts/concentrations for cement, lime and enzyme-based liquid stabiliser in order to achieve effective reaction was being investigated. This was done through the determination of the initial cement and lime content consumption tests for the cement and lime treated samples respectively. The concentration level for the enzyme-based liquid stabiliser is the one normally recommended for use with fine grained materials by the Manufacturer of the product. As a result of the ICC and ICL tests, samples were prepared with 2 per cent cement, 1 per cent lime and 0.033 $m\ell/m^3$ enzyme-based liquid stabiliser as per Manufacturer's recommendation.

3.2. Compaction test

Compaction tests were carried out to define the relationship between moisture and density. Compaction curves were developed for the specimens of each sample. The optimum moisture content and maximum density properties were then determined for the untreated and treated fly ash samples as reference values for moulding the samples for both the unconfined compression test and triaxial tests.

3.3. Unconfined Compression test

The unconfined compression test used to approximate the compressive strength of stabilised material was also conducted on the treated and untreated samples. Compacted specimens were placed in a plastic bag and then left to cure under room temperature. In the conventional unconfined compressive strength test; samples are cured for 7 days and soaked prior to testing. However, modification to the test was necessary, in that all samples were not soaked prior to testing as it was expected that samples treated with the enzyme-based product were most likely to crumble during soaking, based on previous experiences and therefore this approach ensured similar testing conditions. Specimens were therefore tested “dry”.

The effect of curing age was assessed over 28 days. In addition, the effect of moulding moisture was assessed by preparing samples at three compaction moisture contents: dry of optimum moisture content, at 2 per cent below, wet of optimum moisture content, at 2 per cent above and at optimum moisture content level.

3.4. Triaxial test

In order to assess the shear strength of the stabilised fly ash compositions, a set of samples were prepared for the triaxial tests. The set consisted of four specimens and the specimens were cured for 7 days. Each specimen was loaded until failure at different confining pressures (0, 20 kPa, 50 kPa and 100 kPa). Only the unclassified fly ash was tested under the triaxial test programme as the results of the UCS consistently showed higher strength values for the unclassified treated fly ash compared with the unclassified fly ash.

4. RESULTS AND ANALYSIS

4.1. Unconfined Compressive Strength

The unconfined compressive strength test was used as a ranking indicator of the strength relative to minimum acceptable values for pavement application following the treatment with the three stabilizers and also to assess the effect of moulding moisture on the unconfined compressive strength of the investigated material compositions.

4.1.1. Effect of type of treatment and age

The samples are represented by the following identification labels: CTCFA for cement treated classified fly ash; CTUFA for cement treated unclassified fly ash. Thus LTCFA, LTUFA, ETCFA and ETUFA for the lime treated and enzyme-based liquid stabiliser treated samples respectively.

The effects of the type of treatment on the unconfined compressive strength are shown in Figure 1 for all the material compositions. It can be observed that the maximum compressive strength is dependent on the type of treatment, with the cement treated samples showing the greatest strength followed by the lime treatment and then enzyme-based liquid stabiliser.

Figure 1 also shows the effect of curing age. All sample compositions show an increase in strength over time, with cement treated samples showing relatively higher strength values. It can also be observed that for all sample compositions, the achieved strength values for the unclassified samples are higher than those obtained for the classified fly ash samples

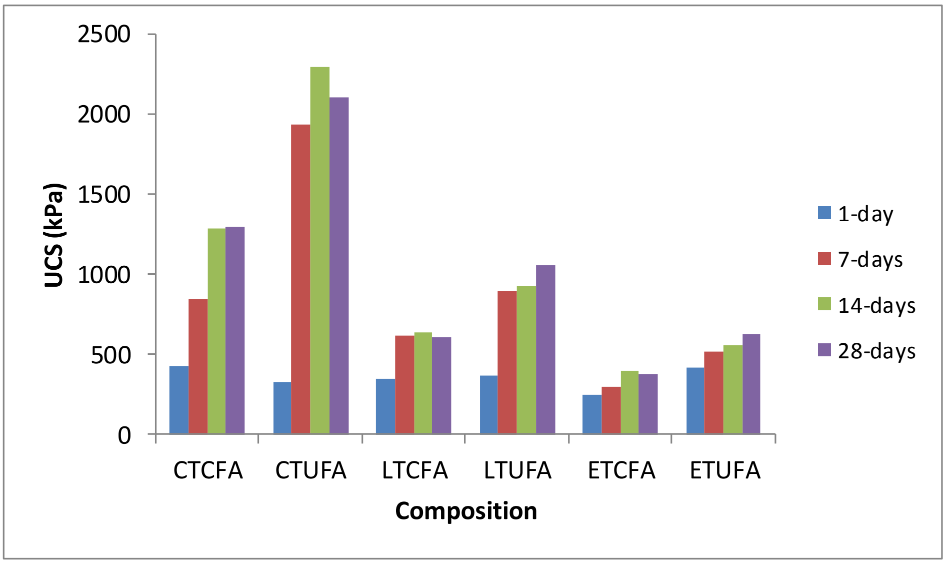


Figure 1: Unconfined compressive strength for the different material compositions at different curing ages.

The cement and lime treated samples show a relatively significant increase in unconfined compressive strength between day 1 and day 7, particularly for the unclassified fly ash samples. Between day 7 and day 14 the rate of increase is much smaller. Cement treated samples for day 28 testing had noticeable surface hairline cracks and probably these cracks extended deeper in the specimens leading to the weakened internal zones. Although, small, the enzyme treated samples show a steady increase in strength over time, particularly with the unclassified fly ash samples.

As the primary objective is to quantify the minimum practical strength of the treated fly ash samples, special attention is paid to the test results at the curing age of 7 days. At this curing age, the strength values range from low average values of 298 kPa and 523 kPa, respectively for the classified fly ash and unclassified fly ash samples treated with enzyme-based liquid stabiliser to high average values of 844 kPa and 1934 kPa, respectively for the classified fly ash and unclassified fly ash samples treated with cement. Comparatively, the strength values for the lime treated samples at 7 days are 622 kPa and 897 kPa for the classified fly ash and unclassified fly ash samples respectively. The lower strength values of the lime treated samples are not surprising as previous studies found that South African fly ashes do not appear to react strongly with the lime (TRH13).

A comparison in strength gain of treated samples against the untreated unclassified fly ash (UTUFA) samples is shown in Figure 2. The average UCS for the untreated samples at day 7 was 490.3 kPa and 564 kPa at day 14. The results show no significant difference in strength between these samples and those treated with the enzyme-based liquid stabiliser. The treatment with lime resulted in an increase in strength to nearly twice the strength of the untreated fly ash samples, while treatment with cement resulted in an increase in strength of four times the value of the untreated samples. The observed magnitude in strength gain due to treatment was the same for the samples tested on day 7 and day 14.

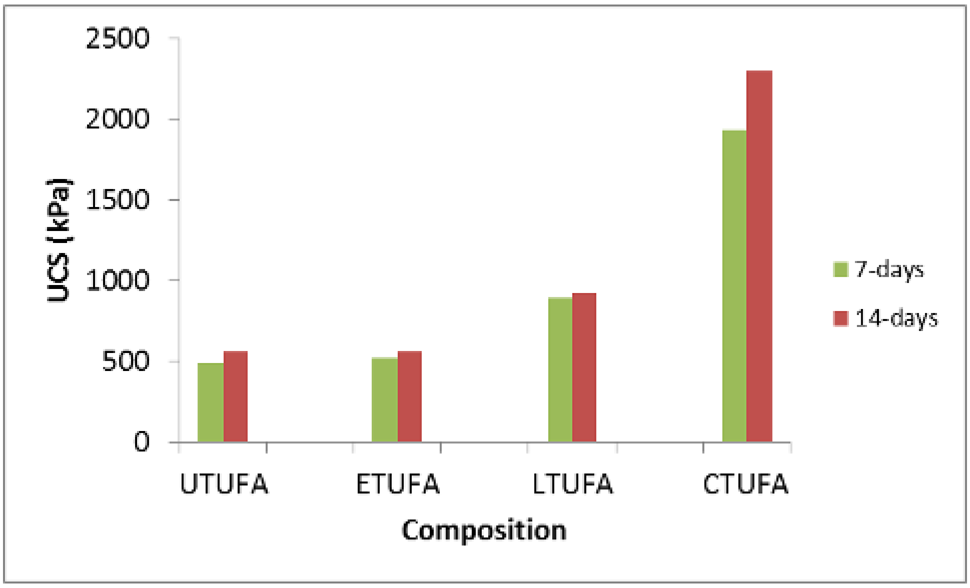


Figure 2: Unconfined compressive strength for unclassified fly ash

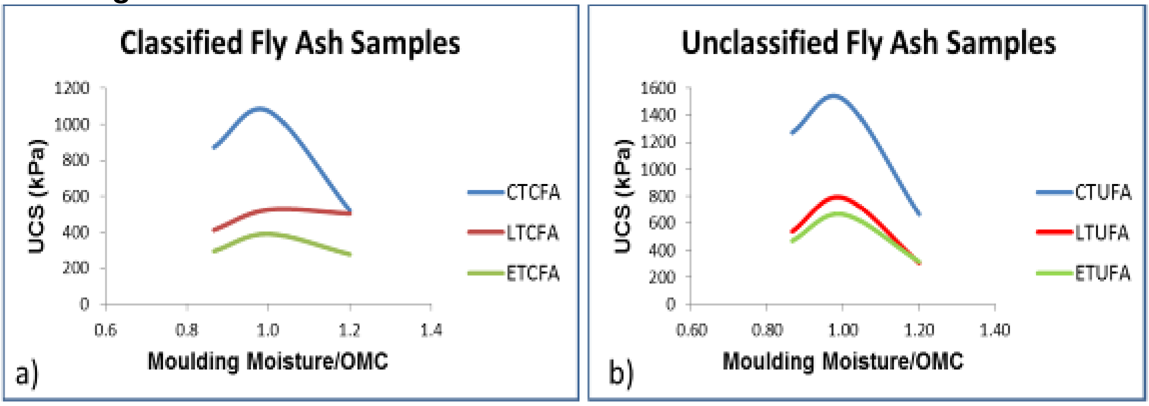
The test results indicate that cement treated unclassified fly ash achieved strength values of a "C3 quality" material from compressive strength point of view. The lime treated unclassified fly ash and cement treated classified fly ash achieved a "C4 quality" material. It should however be appreciated that these tests were carried out "dry".

The variation in the achieved strength between the two grades of the fly ash can probably be explained by the chemical composition and particle size difference. According to Shehata et.al (1999), the composition of the pozzolanic reaction products vary considerably depending on the composition of the fly ash. The main difference in the chemical composition between the unclassified and the classified fly ash is the CaO and SiO_2 content. The silica content for the unclassified fly ash ranges between 51% and 65% compared to 47% – 55% for the classified fly ash. The CaO ranges between 1 and 6 per cent for the unclassified fly ash, while the values for the classified fly ash ranges from 4 to 10 per cent. The other difference is the particle size distribution, with unclassified fly ash being courser than the classified fly ash.

4.1.2. Effect of moulding moisture

The effect of moulding moisture level relative to the optimum moisture content on UCS values is shown in Figure 3. For all sample compositions the maximum UCS values are obtained when the moulding moisture level is equal to or near to optimum moisture content, as expected. Worth noting is that, the effect of moulding moisture content wet of the optimum is more pronounced in cement treated samples. Also notable is that unclassified fly ash samples seem to be affected much more by the level of moulding moisture wet of the optimum compared to the classified fly ash.

Figure 3: Effect of molding moisture on the unconfined compressive strength



4.2. Shear strength

4.2.1. Measured shear strength

The measurement of shear strength is essential as it is one of the fundamental material properties that influence the behaviour of materials. The evaluation of the effective shear strength results presented in this Section is specifically for the testing conditions outlined in Section 3.4. The results are only for the unclassified fly ash cured for 7 days. Figure 4 presents critical values of the maximum octahedral shear stress values with respect to confining pressure for the different compositions. As expected the maximum mobilised octahedral shear stress increases with increasing confining pressure and that the maximum mobilised shear strength is dependent on the type of treatment, with the cement treated samples showing the greatest strength compared to both the lime treated and enzyme treated samples.

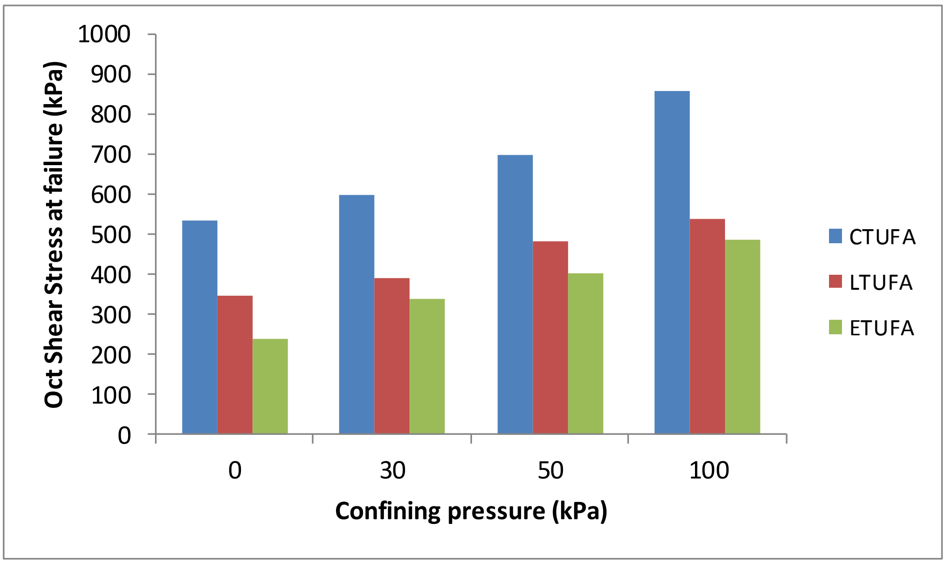


Figure 4: Octahedral shear stress at failure at different confining pressures

Determination of the maximum shear strength is only one aspect of characterising the shear properties of a material. Of particular interest in the characterisation of material strength are the shear strength parameters that will define the response of a material to induced shearing stresses for a given initial condition. These parameters are presented in the next Section.

4.2.2. Shear strength properties

Figure 5 shows the q-p diagram representing the variation of the deviatoric stress (q) as a function of the octahedral normal stress (p). The stress state in Figure 5 is used to define the Mohr-Coulomb failure envelope in terms of the principal stresses, corresponding to the maximum stresses. The results indicate a linear relationship for the stress levels that have been considered in this study. The slopes of the lines defining the maximum deviatoric stresses define the characteristic slope of the failure envelope: $M_p = q/p$. The values of M_p are 2.1152, 1.7769 and 1.8886 for cement treated, lime treated and enzyme treated samples respectively. These values correspond to the internal friction angle (φ) values at peak strength of 51.4º, 43.4º and 45.9º for the respective values of M_p with corresponding cohesion values of 170 kPa, 160 kPa and 108 kPa.

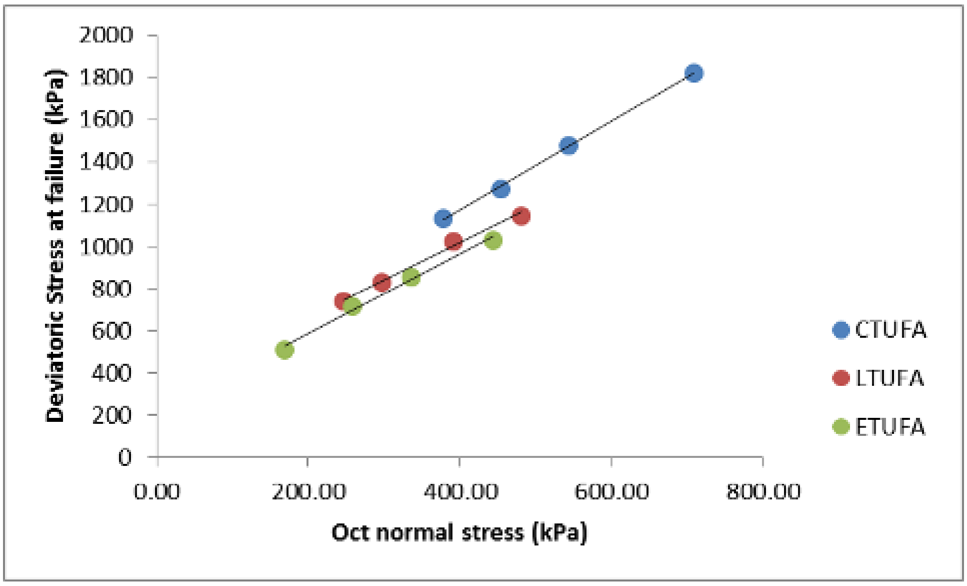


Figure 5: Deviatoric stress variation for the different compositions

An alternative failure criterion of the general form of the generalized Hoek-Brown criterion (Hoek, 1990; Hoek and Brown, 1997; Hoek et. al., 2002) was investigated for defining the strength of the compositions for different confining stresses. One of the advantages of the Hoek-Brown criterion is that the general stress state is described in terms of principal stresses, as shown in equation 1, from which corresponding tensile strength of the material can be estimated and thus the static triaxial test is adequate for parameter determination:

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a \quad (1)$$

In the equation, m_b is the material constant, while a and s are constants and for s = 1, σ_{ci} is equal to the uniaxial compressive strength. By setting $\sigma_1' = \sigma_3' = \sigma_t$ in equation 1, the tensile strength is given by

$$\sigma_t = -\frac{s\,\sigma_{ci}}{m_b} \quad (2)$$

Since no tensile test was carried out and the fact that Hoek-Brown material characteristics were developed for rocks, the form of the equation 1 is what is of interest. A curve fitting process was therefore done to first obtain the equivalent values of m_b and σ_{ci}. Using equation 2, the equivalent tensile strength was then determined. The tensile strength calculated and the data from the triaxial test were then used in a second phase curve fitting process to define the envelope. The results presented below, in Figures 6, 7 and 8, have been obtained by assuming s = 1 (intact) and *a* = 0.5 in equation 1. The final values of the parameter m_b were 18.563, 10.87 and 15.203 for cement, lime and enzyme treated samples respectively.

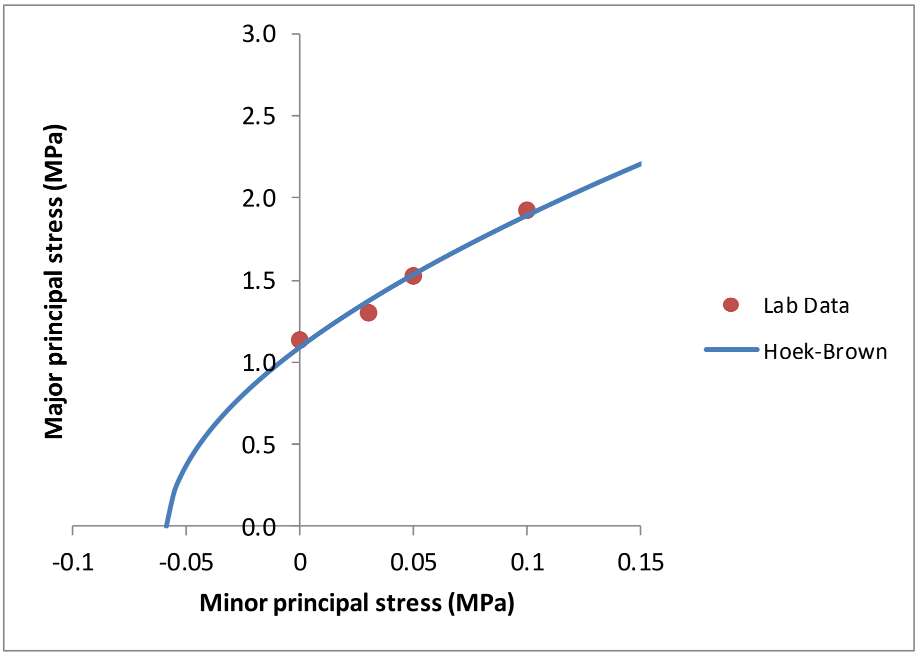


Figure 6: Hoek-Brown failure envelop for CTUFA

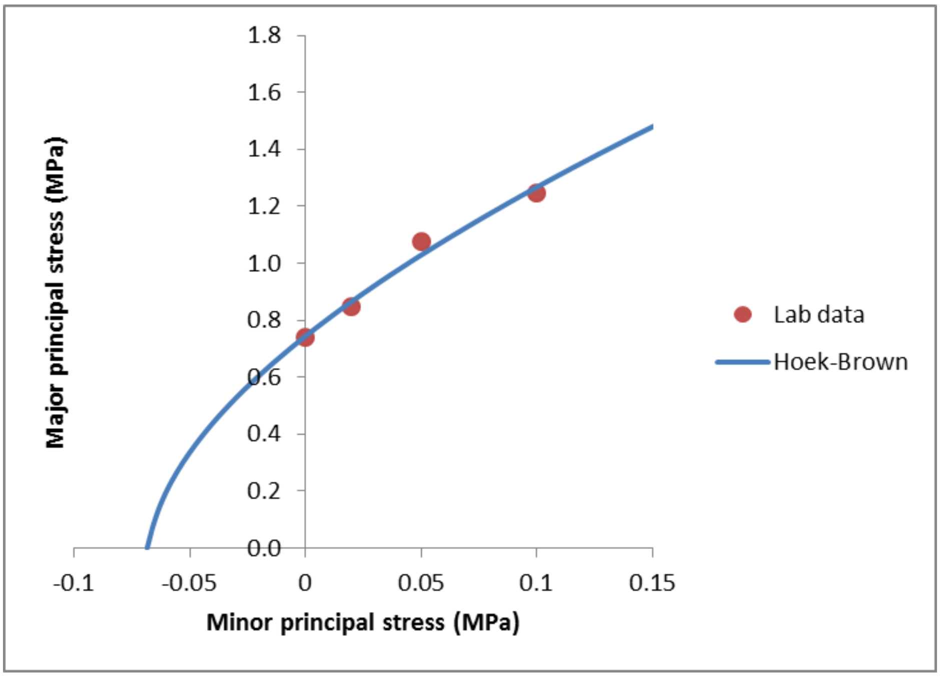


Figure 7: Hoek-Brown failure envelop for LTUFA

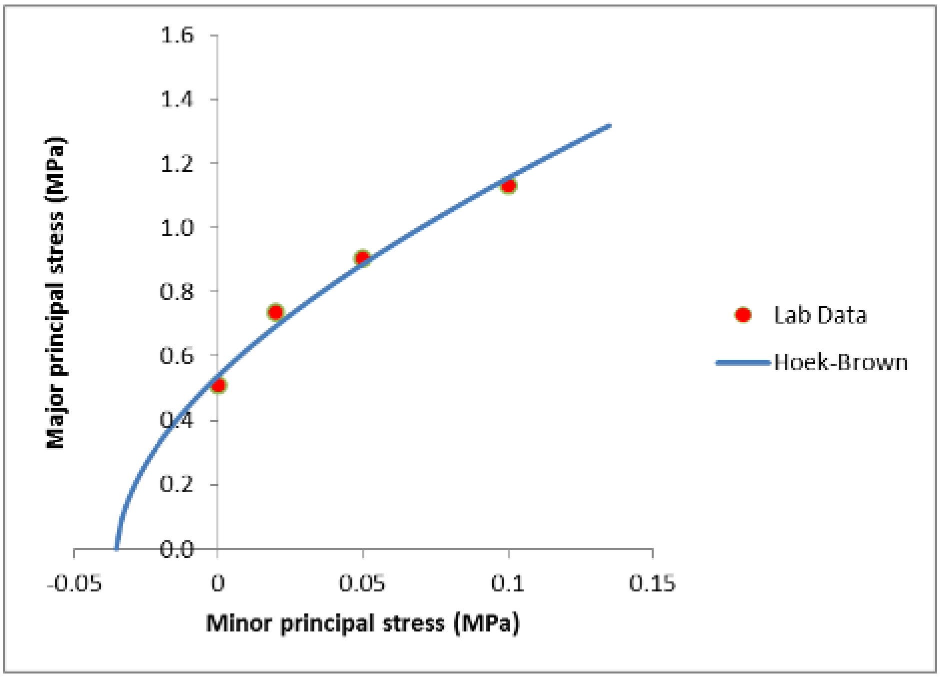


Figure 8: Hoek-Brown failure envelop for ETUFA

The results show that the Hoek-Brown failure envelop covers the measured principal stresses very well. The estimated tensile strength values can be considered as indicators of the characteristics of the materials. Based on the above results, the final estimated tensile strength values to give the best curve fitting results are shown in Figure 9. The results indicate that the lime treated fly ash samples have a slightly higher tensile strength followed by the cement and then the enzyme treated samples. It is to be noted that these values have been obtained by optimizing the curve fitting parameters; further work is needed in this area. However, the magnitude of the tensile strength values seems to be reasonable.

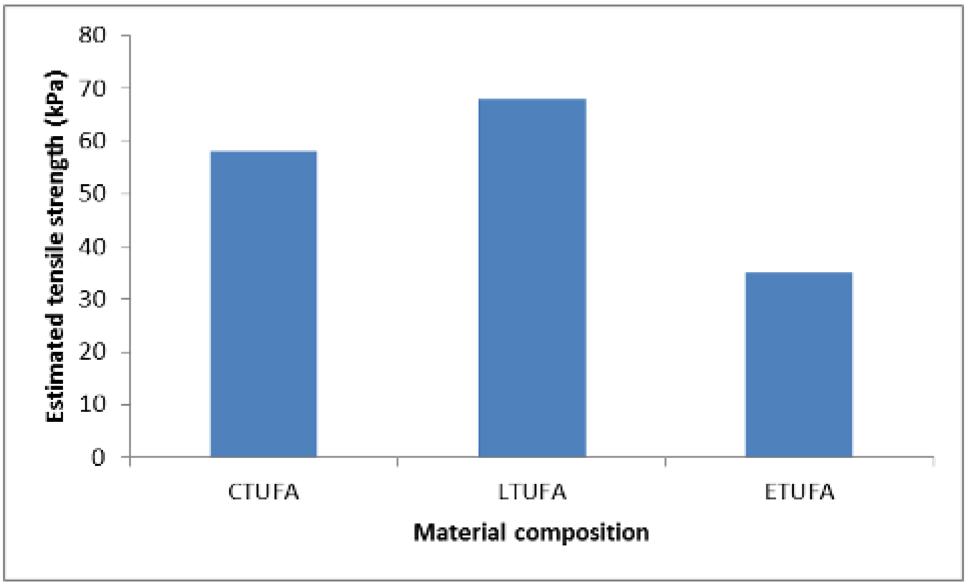


Figure 9: Estimated tensile strength

5. DISCUSSION AND WAY FORWARD

The common practice is to use fly ash in combination with other materials in road construction. Apart from the determination of other properties, such as durability, of interest is whether the achieved strength values of the fly ash compositions are of practical meaning to sustain induced stresses under typical in-service loading conditions. While the application of the stabilised fine-grained fly ash is not necessary for main structural layers in roads, the results showed that the unclassified fly ash stabilised with 2 per cent cement would provide a typical C3 material. On the other hand, with 1 per cent lime stabilisation, the unclassified fly ash would provide a C4 quality material, based on dry UCS test, which can be used as base course for lightly trafficked roads. The content of the stabiliser is one of the most important parameters contributing to the strength of a stabilised material. The influence of varying the proportion of the stabilisers and durability tests are underway as well as the investigation on mixing the fly ash with other alternative materials, with the aim of providing solutions for alternative materials and innovative technologies. The treatment of fly ash with enzyme-based liquid stabiliser shows some potential and the determination of an optimum concentration level is to be explored.

6. CONCLUSION

A study into the stabilisation of two grades of fine-grained fly ash from Lethabo Power Station in Vereeniging was carried out. This included testing the fly ash treated with the minimum required amounts of cement, lime and an enzyme-based liquid stabiliser. Standard test methods were employed to determine the appropriate strengths after treatment and normal curing through the unconfined compression test and the static triaxial test. The paper has presented some of the results of an on-going study which show that moderate to high compressive and shear strength values are achievable with the minimum required amounts of cement and lime to stabilise the unclassified fine grained fly ash. The results should complement existing information on the strength characteristics of fly ash streams.

ACKNOWLEDGEMENT

Funding for the research project is provided through the Parliamentary Grant by the CSIR. The author would like to acknowledge the support provided by Ash Resources (Randburg) in providing the fly ash samples.

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