FIT–FOR-PURPOSE LABORATORY ASSESSMENT OF LIGHTLY STABILISED FLY ASH MATERIAL FOR ROAD CONSTRUCTION

M B Mgangira[1], T George[2] and R Mokoena[3]

CSIR Built Environment, P O Box 395, Pretoria, 0001.
1) Tel.: +27 (12)-841-4499 Email: Mmgangira@csir.co.za
2) Tel.: +27 12 841-2947, Email: Tgeorge@csir.co.za
3) Tel.: +27 12 841-2933, Email: Rmokoena@csir.co.za

ABSTRACT

The increased use of alternative materials, particularly streams of industrial by-products in transportation construction is motivated by the need to optimize construction of sustainable pavements. Fly ash has mostly been used as an additive in various applications in transportation construction. This paper presents a study on the use of a fly ash product as the primary constituent, rather than an additive. A fly ash product was lightly treated with cement in one test series, with lime and an enzyme based liquid stabilizer in the second and third test series respectively producing lightly stabilised fly ash (LSFA) material. Testing was aimed at fit-for-purpose assessment of the LSFA material in terms of mechanical properties. This is work in progress. The results have shown that the LSFA can achieve shear strength and modulus values highly appropriate and fit for design application in low volume roads.

1. INTRODUCTION

The last 20 years has seen significant amount of research on the use of industrial by-products, recycled and waste materials. There is a need for the increased use of alternative materials, particularly streams of industrial by-products such as fly ash. Fly ash is a by-product of the burning of coal at electric power generating stations. The sheer amount of fly ash being generated worldwide has motivated considerable research in its utilisation. Ahmaruzzaman (2010) has provided a general review on fly ash utilization in different fields. One of the areas of fly ash utilisation is in the area of construction of transport infrastructure. Specifically for application in road construction, fly ash is used as filler in asphalt production, structural fill, road base and subbase stabilization and as a soil modifier.

According to FHWA (1997), the use of fly ash in stabilized base and subbase mixtures dates back to the 1950’s and over the years numerous variations of the basic lime-fly ash-aggregate formulations have evolved. In the last 20 years, there has been a significant increase in the number of study initiatives by highway authorities, research institutions worldwide but more particularly state transportation agencies in the United States. A survey conducted by the National Cooperative Highway Research Council (NCHRP, 2013) showed that between 1998 and 2009, Type C and Type F fly ash accounted for 68% of highway applications in the US.

These applications included the use in Portland Cement Concrete, flowable fill, soil stabilization and embankments. Pilot projects in Missouri for using bottom ash in embankments were reported to be successful. The survey also indicates that proper data and documentation is still required for the use of these alternative materials in industry. Kim et al. (2005), amongst others, have shown that fly ash can be used successfully in pavement layers. They demonstrated that high fly ash content mixtures can be used in highway embankments provided proper design and construction procedures are followed; accompanied by appropriate environmental requirements.

Sen and Mishra (2010) found that typical applications for fly ash in road construction include soil stabilization, soil drying and control of shrink-swell. Additives such as lime, cement or enzymes have been used to enhance strength and durability through stabilization of pavement substructure (Ahmed and Khalid 2011). They showed that adding incinerator bottom ash (IBA) to a conventional limestone aggregate improved the performance of road layers compared to traditional materials. They also showed that introducing a plant based enzyme improved the characteristics of the conventional limestone blend but had no effect on the IBA blend. Cyclic triaxial tests were conducted and the IBA blends exhibited higher resilient modulus values compared to conventional mixtures. This also demonstrated that the selection of an enzyme should be based on a case specific approach depending on the soil and industrial by products used (Wright-Fox et al.1993).

Heath et al. (1997) demonstrated that fly ash from a Sasol power plant in South Africa could be used as an aggregate in unstabilized basecourse. In the study different ratios of fly ash and soil samples were tested. Santos et al. (2011) conducted a similar investigation which compared the geotechnical properties of fly ash and soil mixtures for the highway embankment construction. Results showed that as the percentage of fly ash in the mixture increased, maximum dry unit weight decreased and the optimum moisture content increased. The tested samples, 20% fly ash mixture to 100% fly ash achieved unconfined compressive strength values that far exceeded the minimum requirement of 35.9kN/m^2.

Vestin et al. (2012) found that fly ash is suitable to be used in the stabilization of gravel roads sections in Sweden. Results showed that bearing capacity of the fly ash stabilized sections increased over time and with increasing fly ash content.

The primary goal of all of these research initiatives has been to optimise fly ash utilisation for road construction application. In most of these studies, fly ash has been used to stabilise other materials. On the other hand, fly ash as the primary constituent, rather than an additive has been studied in limited investigations. Examples of earlier studies are reported by Kaliski and Yerra (2005) and Lav et al (2006). The study being reported in this paper is on the assessment of fly ash as a primary constituent, but lightly stabilized. In contrast, Heath et al. (1997) investigated influence of varying the proportion of fly ash as an aggregate substitute in unstabilized layers. Samples were not subjected to repeated loading.

In this study the fly ash was lightly treated with cement in one test series, with lime and an enzyme based liquid stabilizer in the second and third test series respectively. The mechanical properties of the LSFA have been investigated in terms of shear strength and response to repeated loading under varying stress levels in the current study.

In the South African Pavement Design Method (SAPDM), the response of unbound and stabilised materials to repeated loading is quantified using the Chord Modulus (Mc). Figure 1 shows the difference in the definition between commonly used resilient modulus and the chord modulus. The calculation of the resilient modulus is based on the ratio of the deviator stress and the recoverable strain, while chord modulus is the ratio of the instantaneous deviator stress and the corresponding strain. Further details are available in Theyse (2012).

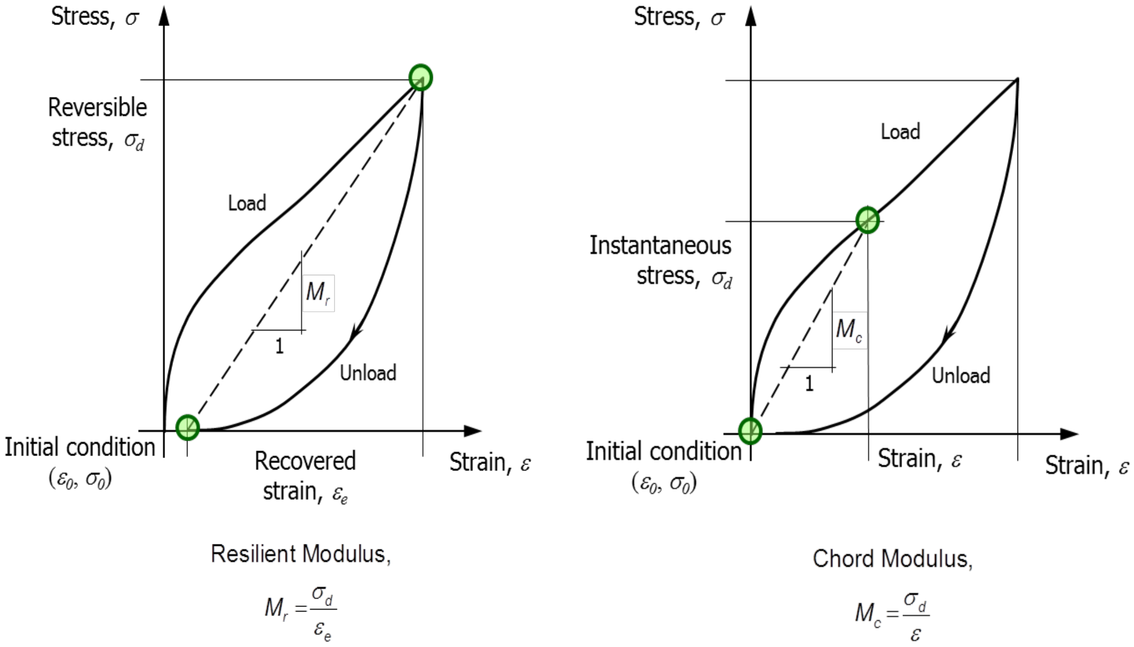

Figure 1: Definition of the Chord Modulus (Theyse 2012)

The study is aimed at building knowledge base and therefore make available further data to previous studies on the mechanical properties of fly ash. This will provide a measure of confidence in establishing the fit-for-purpose referencing threshold for the application of LSFA material in the construction of pavements and to prepare appropriate guidelines.

2. TEST PROGRAM

2.1. Material

A fly ash product from Lethabo Power station in South Africa was used in this study. It is a by-product from pulverised coal-fired power station and predominantly alumina silicate. The extracted data on the properties that are used as indicators of the potential for pozzolanic reaction of a fly ash (Janz and Johansson, 2002) as provided by the supplier are presented in Table 1 below. This fly ash is a Class F with very low cementing potential. This means it will require an activating agent, for example cement or lime, to react with water for proper pozzolanic reactions to take place and provide appropriate strength for road application (Bergeson and Barnes, 1998; Tastan et al.,2011).

Table 1: Selected elemental composition of the fly ash product

Parameter	Range of Composition (%)
SiO_2	51.0 – 65.0
Al_2O_3	25.0 – 35.0
Fe_2O_3	3.0 – 5.0
CaO	1.0 – 6.0
MgO	0.5 – 2.0
Loss On Ignition (LOI)	0.8 – 2.5

The major constituents of the fly ash are SiO_2 and Al_2O_3. According to Tastan et al (2011), the significant characteristics of fly ash that affect the increase in strength include CaO content and CaO/SiO_2 ratio. The $CaO/(SiO_2 + Al_2O_3)$ ratio can also be used as an indicator of potential to form calcium silicate gel (CSH) provided there is relative abundance of CaO pozzolans (Tastan et al., 2011). From the above data, the calcium oxide (CaO) content ranges from 1% to 6%, the silicon dioxide (SiO_2) content ranges from 51% to 65%, thus the CaO/SiO_2 ratio ranges from 0.02 to 0.09 which according to Janz and Johansson (2002) indicates low cementing potential. Loss of ignition, a measure of the amount of unburned coal in the fly ash indicates low carbon content, ranging from 0.8% to 2.5%.

2.2. Preparation of samples

Preparation of the fly ash samples involved the determination of the required mix proportions of the cement, lime to fly ash quantity or concentration of the enzyme-based liquid stabiliser as described in Mgangira (2014). As the focus of the study was the investigation of the performance of LSFA product under loading, the minimum required amounts/concentrations for cement, lime or enzyme-based liquid stabiliser were used. 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 used for the enzyme-based liquid stabiliser was the one normally recommended for use with fine grained materials by the Manufacturer of the product. Based on the initial consumption of stabiliser tests, samples were prepared with 2 per cent cement, 1 per cent lime and 0.033 ml/m^3 enzyme-based liquid stabiliser as per Manufacturer's recommendation.

The specimens were dynamically compacted in a split mould of 150 mm diameter, producing specimens with height of 305 mm. After compaction the specimens were removed from the mould by disassembling the split mould and placed on a porous stone, cured in a plastic bag under room temperature until testing at 28 days. The choice of testing at 28 days is based on previous testing which showed that the treated fly ash samples reached the optimum strength gain at 28 days. For the quasi static triaxial compressive strength determination samples were cast in triplicate.

2.3. Testing of samples

Materials in pavement layers are subjected to different stress levels and as such the most practical tests are those that simulate repeated loading and variation in stress levels. Samples are therefore loaded with multi-loading and unloading cycles configuration. The triaxial repeated load (TRL) test is the most appropriate to achieve this. A series of monotonic tests were first carried out with a combination of these cell pressures: 20 kPa, 50 kPa, 100 kPa, 150 kPa and 200 kPa. The cell pressures were used to produce a set of three Mohr's circles and the resultant failure envelopes.

Following the monotonic tests, the TRL tests for the determination of the resilient modulus were then carried out. This procedure consisted of application of a repeated axial deviator stress of a fixed magnitude to a specimen under constant confining pressure application. The initial stage (conditioning), consists of a total of 300 cycles of loading and unloading applied in three stages of 100 cycles. This stage is aimed at removing the sample irregularities and supress most of the initial stage of permeant deformation and is therefore done at the highest confining pressure of 200 kPa. The conditioning stage was followed by five specified stress regimes in the sequence with confining pressure and deviator stress levels as shown in Table 2.

Table 2: Loading schedule during triaxial repeated load test

Phase	**Confinement Pressure (kPa)**	**Stress Ratio Sequence**	**Phase**	**Confinement Pressure (kPa)**	**Stress Ratio Sequence**
Conditioning	200	20%	3	100	20%
		40%			30%
		60%			40%
					50%
					60%
1	200	20%	4	50	20%
		30%			30%
		40%			40%
		50%			50%
		60%			60%
2	150	20%	5	20	20%
		30%			30%
		40%			40%
		50%			50%
		60%			60%

The repeated axial deviator stress levels are specified as a ratio to the average failure deviator stress obtained from the monotonic triaxial test results. During the repeated load test, a haversine shaped load pulse was applied consisting of 0.1 sec followed by 0.9 sec rest period. The response to repeated loading was quantified using the Chord Modulus (Mc) as defined in Figure 1.

3. RESULTS

3.1. Monotonic load test

The monotonic triaxial tests were carried out to determine the repeated axial deviator stress levels which were specified as a ratio to the average failure deviator stress obtained from the monotonic test results. The results of the maximum mobilised shear strength values were reported by Mgangira (2014). The mobilised shear strength increased with increasing confining pressure and showed dependence on the type of treatment. The cement treated samples showed the greatest strength compared to both the lime treated and enzyme treated samples. In addition to maximum mobilised shear strength, the shear strength parameters that define the response of a material to induced shearing stresses are required. Data on the shear strength parameters at age 28 days is provided in Table 3. The cement treated samples show the highest cohesion and samples treated with the enzyme based stabiliser show the lowest value. The friction angle values of the cement treated and lime treated samples are not significantly different. These values fall within the range of typical pavement materials.

Table 3: Shear strength parameters

Sample description	Friction angle	Cohesion (kPa)
Fly ash + 1% Lime	52.8	171
Fly ash + 2% Cement	53.1	198
Fly ash + Enzyme based stabiliser	54.8	90

3.2. Repeated load test

Figures 2 to 4 show that at stress ratios less than 10%, the influence of confining stress on the chord modulus is less significant in both the cement treated samples and the enzyme treated samples, while in the case of the lime it can be considered to be moderate.

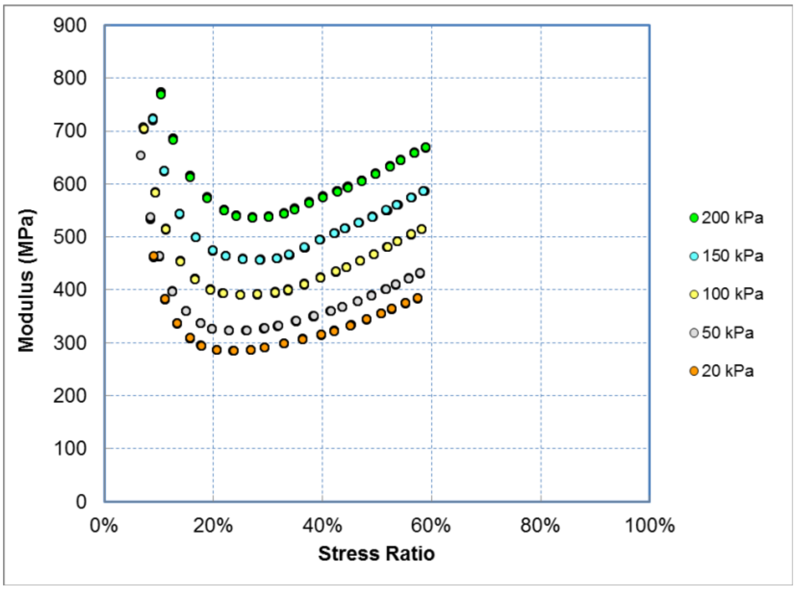

Figure 2: Response of fly ash samples treated with 1% Lime

It can therefore be stated that at the initial state of stress the chord modulus is less dependent on the confining stress. But as the stress ratio increases beyond 10%, the results clearly show the influence of confining pressure on the chord modulus. The higher the confining pressure the higher the chord modulus at a given stress ratio. The results also show a stiffening behaviour with stress ratio increase and confining stress

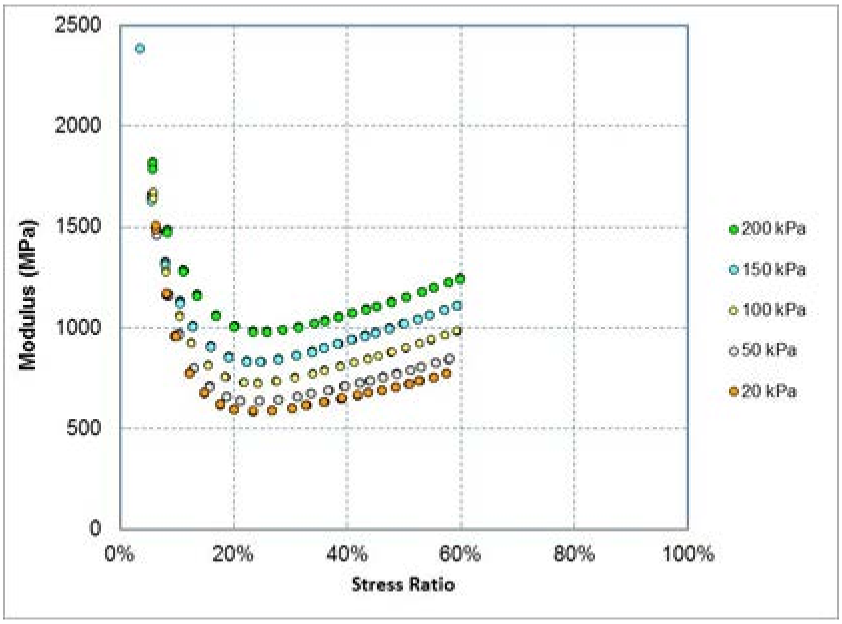

Figure 3: Response of fly ash samples treated with 2% cement

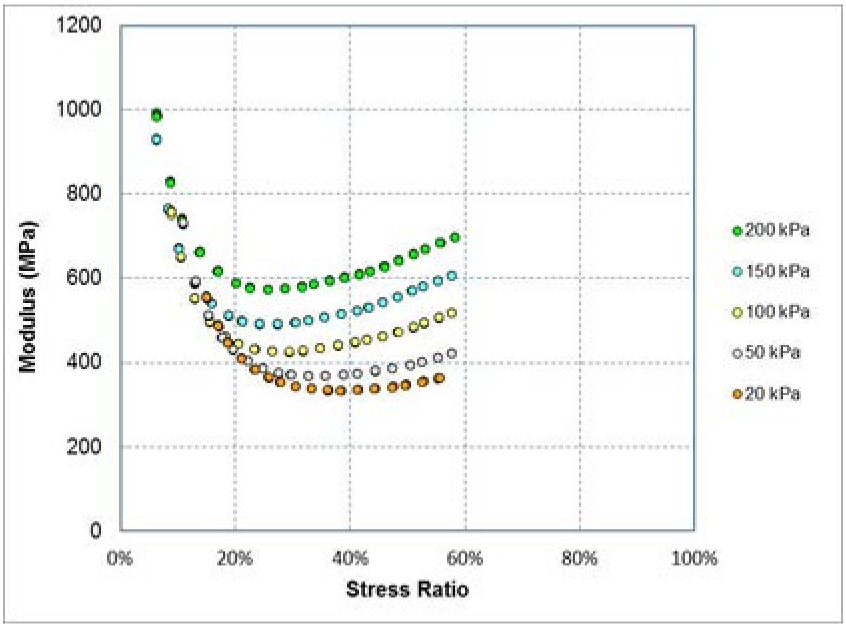

Figure 4: Response of fly ash samples treated with enzyme-based stabiliser liquid

Figure 5 shows the response of the tested samples, quantified through the relationship between chord modulus and stress ratio. The results in Figure 5 are an illustration for two confining stress levels, 20 kPa and 100 kPa in Figure 5a and Figure 5b respectively. It is clear that the addition of 2% cement had a dominant influence on the strength development of the fly ash product. The comparison between material response as characterised by the evolution of the relationship between modulus and stress ratio is also clear in Figure 5. Type of treatment has an influence as well as the influence of the confining stress is evident.

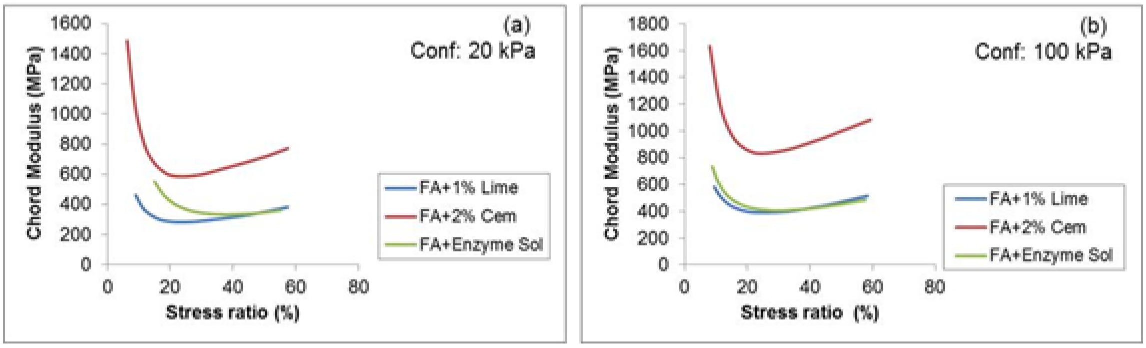

Figure 5: Relationship between modulus and stress ratio with confining pressure

4. DISCUSSION AND WAY FORWARD

In the typical Mechanistic-Empirical design method, stress and modulus are the input and output parameters. Since the modulus is related to the stiffness of materials, comparison between pavement materials can thus be assessed through the modulus-based response that is linked to loading stress levels relative to the strength of the individual material and a reference confining stress. The following is an illustration towards a fit-for-purpose assessment in order to allow for comparisons between conventional materials used for a specific application within the pavement structure and alternative materials.

As an example, a bench marking pavement structure for low volume roads in a moderate climatic region comprising 125 mm G4 basecourse on a G6 quality material underlain by a G7 at least 150 mm thick on a 150 mm G9 quality material is considered. The above granular materials classes are according to the South African guidelines for road construction materials (TRH14,1985) as shown in Table 4 below.

Table 4: Design equivalent material classes

Material Type	**Design Equivalent**
Crushed Stone	G1
	G2
	G3
Natural Gravel	G4
	G5
	G6
Gravel Soil and Cohesive Soils (Silt and Clay)	G7
	G8
	G9
	G10

An assessment which is based on modulus response and plastic strain development under a specified stress regime is used to establish the most appropriate place and function of the LSFA within a pavement structure. To this end, a comparison is made between a G6 quality material and the LSFA materials formed by the lime treatment and by treatment using enzyme-based liquid stabiliser. The LSFA product formed by cement treatment as shown in Figure 5 is far more superior and was therefore not included in the assessment. The specimens of the G6 material were prepared at the optimum moisture content.

Results for two reference confining stresses are used for the assessment, a low of 20 kPa as shown in Figure 6a and a high of 100 kPa in Figure 6b. The results show that both LSFA products have better engineering properties in terms of modulus and its evolution with stress levels, than the G6 quality material, a natural material. However, at a confining stress of 20 kPa and stress ratio less than 15% the G6 material shows higher modulus values than the lime treated fly ash sample. Most striking, is the strength gain of the LSFA using the enzyme-based liquid stabiliser.

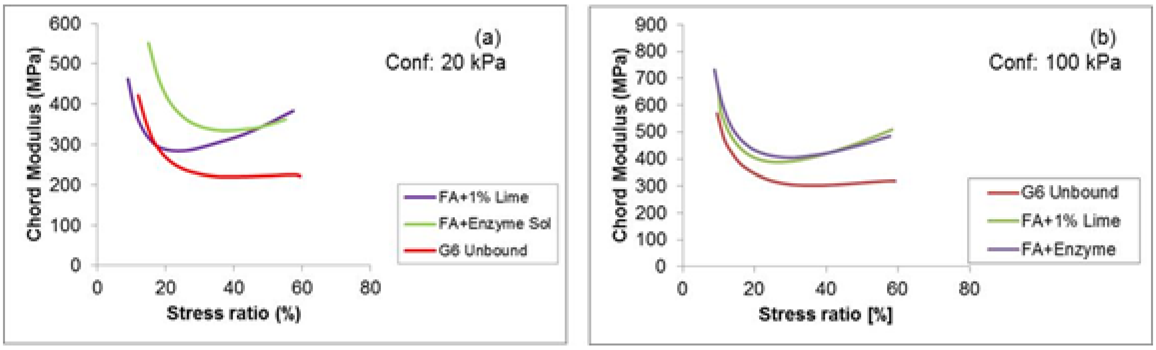

Figure 6: Comparison of modulus-based response

The second assessment is in terms of plastic strain development during the test period as shown in Figure 7. These results describe the plastic strain development history during the resilient modulus test. It is worth noting that each material is subjected to stress levels relative to the maximum strength for a given confining pressure as shown in Table 2. The same stress ratios are used in all the stages of the application of repeated loading.

The increase of the plastic strain over the test period, corresponding to the increase in the number of load cycles is shown in Figure 7. The plastic strain mainly occurred in the first phase of the load application and it can be observed that there is a decrease in the rate at which the plastic strains develop with increasing load cycles. The observed behaviour is due to the decreasing applied stress levels with increasing loading phases as shown in Table 2. As expected, the results indicate that the LSFA sample treated with cement is more effective in constraining the development of plastic strain due to its superior modulus. The response of lime treated and the enzyme treated LSFA samples, in terms of the development of plastic strain is moderate with the enzyme treated sample developing slightly higher plastic strains in the first 1000 load cycles, but the plastic strain profiles are almost similar in subsequent loading cycles. Relative to the G6 material, the behaviour of the LSFA materials indicate an enhanced plastic deformation resistance.

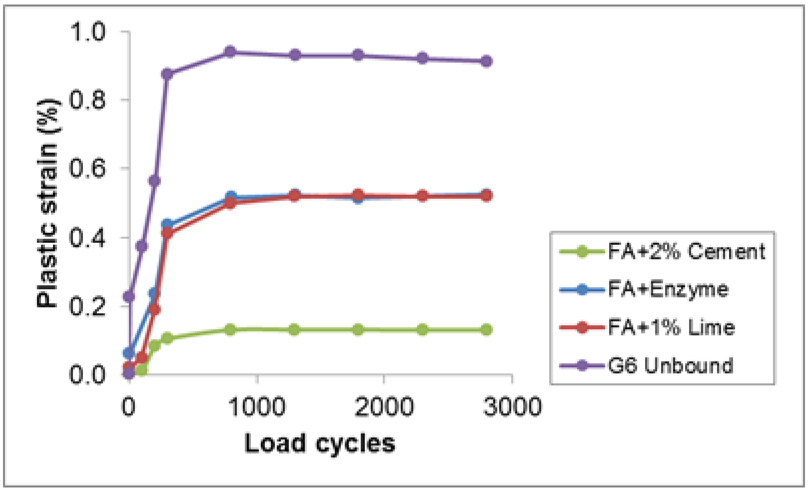

Figure 7: Plastic strain development during the repeated load test

At this stage of the research, the assessment of the LSFA materials remains primarily at the laboratory level in terms of strength through UCS and both monotonic and repeated triaxial test. Analysis based on the mechanistic-empirical design method was carried out and showed that the carrying capacity would increase by at least 3-fold if the LSFA material is used in place of the G6 in the considered pavement structure. The assessment and characterisation of the LSFA materials under field conditions is still lacking.

However, the utilisation of LSFA material ought to be financially viable. The costs for both material transportation and construction should be assessed to determine the competitiveness of the LSFA material utilisation. Transport analysis should be undertaken to determine the cheapest method of transporting the fly ash from the source to the road construction site as proposed by Heath et al. (1996).

5. CONCLUSION

The material and response parameters of LSFA material as described in this study have been established. These material parameters are in terms of strength and resilient properties and the response is in terms of plastic strain development quantified during the multi-stage repeated load testing phase. Based on the outcome of the study, it is reasonable to state that the LSFA material exhibited better response than the G6 quality material used in this investigation. Thus LSFA material is potentially capable to perform as a subbase in a typical pavement structure for low volume roads. It is worth noting that the option to re-use LSFA materials during road construction will reduce consumption of naturally occurring material resources.

The study is work in progress and makes available further data to previous studies on the mechanical properties of fly ash for road application. It provides a measure of confidence in establishing the fit-for-purpose referencing threshold for the application of LSFA material in the construction of pavements and the preparation of appropriate guidelines, which the ultimate goal of the study.

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