CSCE 2013 General Conference - *Congrès général 2013 de la SCGC*

Montréal, Québec
May 29 to June 1, 2013 / *29 mai au 1 juin 2013*

Finite Element Modelling and Laboratory Determination for the Elastic Modulus of Granular Waste Materials

A.T.Ahmed[1], M. H. Elsanabary[2]
[1] Department of Civil Engineering, Faculty of Engineering, Aswan University, Egypt
[2] Postdoctoral Fellow, Department of Civil and Environmental Engineering, University of Alberta, Assistant Professor, Civil Engineering Department, Port Said University, Egypt

Abstract: Many granular waste and recycling materials are being considered for use as substitutes for natural aggregates in construction applications. Incinerator bottom ash Waste (IBAW), a residue from burning household waste, was previously landfilled but now two-thirds of this ash is recycled mostly in road construction. In this study, IBAW was mixed with limestone to produce a blend with acceptable properties for use as a road foundation layer. Cyclic and monotonic triaxial tests were used to determine the resilient and Young's modulus of IBAW blends respectively. A three Dimensional Finite Element (3DFE) models were built to simulate the laboratory triaxial tests. In this paper the effect of the confining pressure and cement treatment on the mechanical behaviour of the samples has been experimentally and numerically investigated. The results showed adequate accuracy to model laboratory tests, making the 3DFE models suitable for addressing the elastic and plastic behaviour of different granular materials through changing the material properties in the models. Experimental and modelling results also showed that IBAW material behaved like a conventional aggregate.

1 INTRODUCTION

Most developed countries nowadays face aggregate supply and waste disposal challenges. In UK, 25 % of household waste production is currently incinerated, which generates an annual output of around one million tonnes of incinerator bottom ash waste (IBAW). In the past, this ash was generally landfilled but in recent years, nearly two-thirds of the ash has been used mostly in road construction (Bouvet et al. 2007) IBAW has physical and chemical properties that make it amenable for use as an aggregate substitute in different construction applications, such as compacted road base material; structural fill in wind barriers, sound barriers and highway ramps; and asphalt applications (Kosson et al. 1996). Waste and recycled materials were generally overlooked in the past because their use in road pavement structures had not been adequately substantiated. To achieve this goal, the behaviour of these materials needs to be examined.

In pavement foundation design, the assumptions are made that granular materials are designed for loading within the elastic range (DMRB 2009). Therefore, elastic modulus is the main input parameters required to design the foundation thickness. The modulus was estimated in the past based on empirical relations, in which the elastic modulus was related to a test value, such as the California Bearing Ratio (CBR). The trend in recent years, however, has been to measure the elastic modulus directly to increase the efficiency of the pavement design. Several laboratory and field test methods have been developed to determine the elastic modulus of granular materials and soils (Hopkins et al. 2004). Among all these laboratory methods, the triaxial test is considered the best one in replicating the field conditions because it provides reasonable representation of the applied stresses and reliable and repeatable test results. The strength of granular materials depends on their triaxial stress state. Thus, a complete characterization of the material behaviour requires conducting experiments where such a condition is reproduced. In the triaxial tests, the specimen undergoes an axial force together with a lateral hydrostatic pressure (Mahabadi et al. 2010). Cyclic triaxial test is commonly used for the determination of resilient modulus of soils. Monotonic triaxial tests have also been used to determine Young's modulus in the elastic phase during specimen loading.

The main role of the finite element simulation is to confirm theoretically the experimental results. The finite element method can be also used as an alternative to the laboratory based approaches. In addition, the FE modelling allows obtaining the complete behaviour of the material, e.g. the stress in the test specimen at or near failure. It also allows the analysis of the stress distribution and the identification of different modes of failure of the material (Hughes et al. 1993 Thabet and Haldane 2001).

In this study, research is being undertaken to simulate the behaviour of IBAW blends under triaxial stresses by using Three Dimensional Finite Element (3DFE) models. The available package LS-DYNA (LSTC 2007) was adopted to build and run the FE models. The model's dimensions and boundary conditions were defined according to the laboratory conditions of the triaxial tests. The models were used to investigate the effects of static and cyclic loading on IBAW material based on linear elastic and non-linear elastic-plastic concepts.

2 Experimental Work

2.1 Materials

Two main materials were used in this study: IBAW and limestone. IBAW was supplied in two sizes: 20-10 mm and 10-0 mm. Limestone was chosen as the control aggregate in the blends. It was supplied in six sizes: 20, 14, 10, 6, 4 mm - dust and filler. IBAW was mixed with limestone in two different combinations, coded as A and D. Group A was the control blend of limestone only. Group D had 80% IBAW and 20% limestone. 6% Portland cement by weight was added as a treatment for the blends.

2.2 Specimen preparation

Cylindrical specimens of 100 mm diameter and 200 mm height were prepared in a split steel mould. Aggregates were placed in the mould in three layers and compacted for 30 seconds each using a 30 kg vibrating hammer with a tamping foot attachment that had a diameter equal to the internal diameter of the compaction mould. The surface of each layer was manually roughened before adding the next layer on top; in this way a good layer interlock and a homogeneous sample was obtained. Specimens were kept in the steel mould for 24 hours within a plastic sheet in order to make them airtight. Meanwhile, a membrane was placed on a stretcher to which vacuum was applied. The membrane was then carefully placed on the specimen. The stretcher was removed from the membrane by switching off the vacuum. After placing the rubber membrane around the specimen, it was kept in a humid environment at 20◦C for seven days to allow for uniform distribution of water within the specimen and for any pozzolanic reactions as well. After seven days, the specimen was attached to the top and bottom platens with rubber O-rings and was then installed in the triaxial cell. Specimens were kept under the same curing conditions and further tests were conducted after 14 and 28 days from time of manufacture.

2.3 Equipment and test procedure

Cyclic triaxial test (CCT)

Cyclic triaxial tests were performed to determine the resilient modulus on the cylindrical specimens, placed in a cell, under a confining pressure, σ_3, and a vertical stress, σ_1 in a servo-pneumatic machine which uses air as a pressure medium. Axial stress was cycled while the confining pressure was maintained constant during the test. The deformation in the samples was recorded using two linear variable differential transformers (LVDTs) mounted outside the testing chamber, as shown in Figure 1-a.

The resilient modulus test was carried out according to TP46, AASHTO procedure (FHWA 1996). in which the sample was subjected to 15 stress sequences. Test results represent the average of three identical samples.

Monotonic triaxial test (MTT)

A monotonic compressive load was applied on the specimen with a constant strain rate of 2% with two different confining pressures, namely 0 and 70 kPa. Axial and radial displacements under the load were recorded until axial displacement exceeded 10 mm (5% strain) or when the sample exhibited excessive buckling. Test set-ups are shown in Figure 1-b.

3 Experimental Results

3.1 Resilient modulus

The resilient modulus of pavement materials is an essential parameter for mechanistically based pavement design procedures, especially for granular material layers and it is generally considered as an appropriate measure of stiffness for unbound pavement materials. The resilient modulus is defined as the ratio of deviator stress to recoverable strain under repeated loading. The Figure 2 shows the results of the resilient modulus of untreated and cement-treated blends A and D at seven days. Results revealed a slight improvement of the resilient modulus with using cement at 6% for both blends. The figure also shows that the resilient modulus of blend D of 80% IBAW is close to the conventional aggregate blend, i.e. blend A with limestone only.

3.2 Young's modulus

Young's modulus represents the stiffness of the material. It describes the linear relationship of the stress-strain behaviour of the material under static and monotonic loads in the elastic stage before the yield stress is attained. This relation is more conspicuous in mild materials than in brittle materials. In the latter, including granular materials, because the stress-stain relationship is initially linear shape then changes to a nonlinear one, there are two types of Young modulus namely the initial and secant modulus. Initial Young's modulus of the material is predominantly determined depending on the first linear part of the stress-strain relationship. The secant modulus, however, is defined as the slope of the line connecting the point of origin and a point on the stress-strain curve. In this study, the initial elastic modulus for untreated and cement-treated blends A and D was evaluated using a stress-strain relationship from a monotonic triaxial test applied to the investigated blends at Optimum Moisture Content (OMC), as shown in Figure 3. The modulus was determined as the slope of the initial part of the stress-strain curve. The cement treatment showed a good improvement in the stiffness of the both blends. it showed a significant cease for the material strain before yielding stress points of the treated blends. This is perhaps due to the robust interlock between materials particles provided by the treatment.

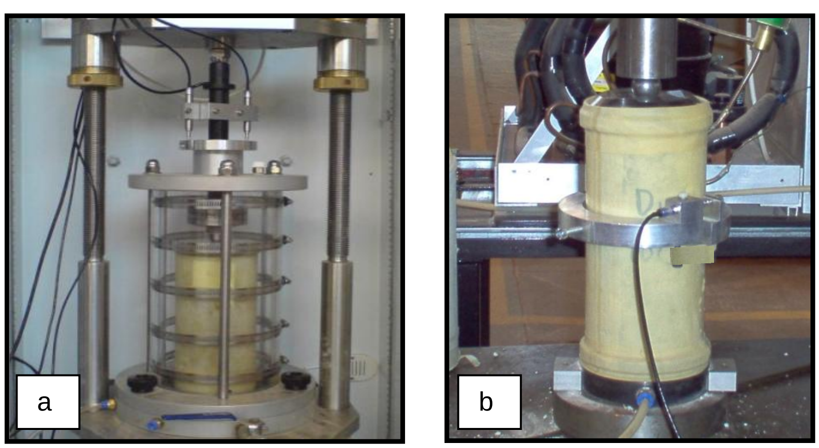

Figure 1: Triaxial Test Assembly: a for Cyclic and b for Monotonic

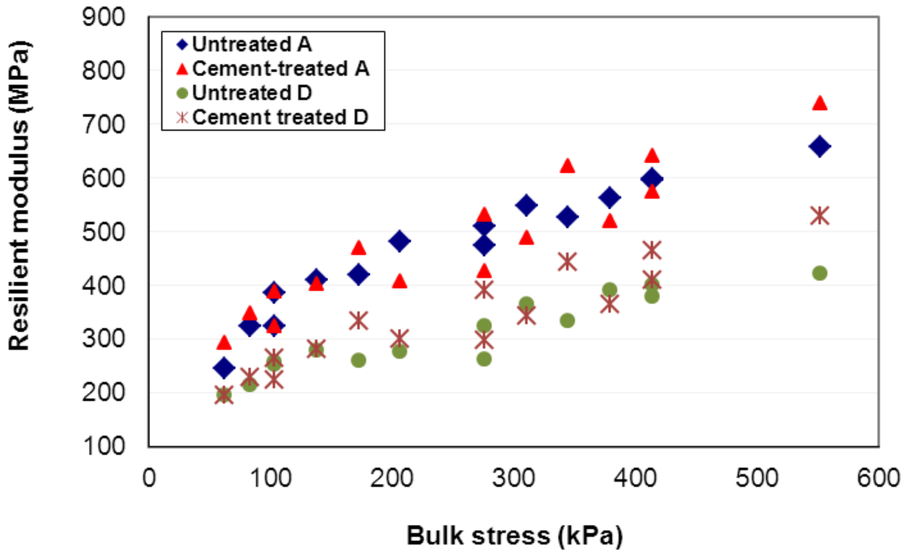

Figure 2: Resilient Modulus of Untreated and Cement-treated Blends A and D

4 Finite Element Simulation

4.1 Monotonic triaxial test simulation

After several trials with model variables, the final stable model was built successfully for monotonic triaxial tests. Figure 4 shows the final model details. The model consisted of 627 nodes and 432 hexahedral brick elements. The realistic data of load-time relationship collected from the experiments was applied as a loading condition on the top of the model cap. The total run times of the model ranged between 70 and 250 minutes to simulate the duration of the monotonic triaxial experiments, which ranged from 120 to 300 seconds.

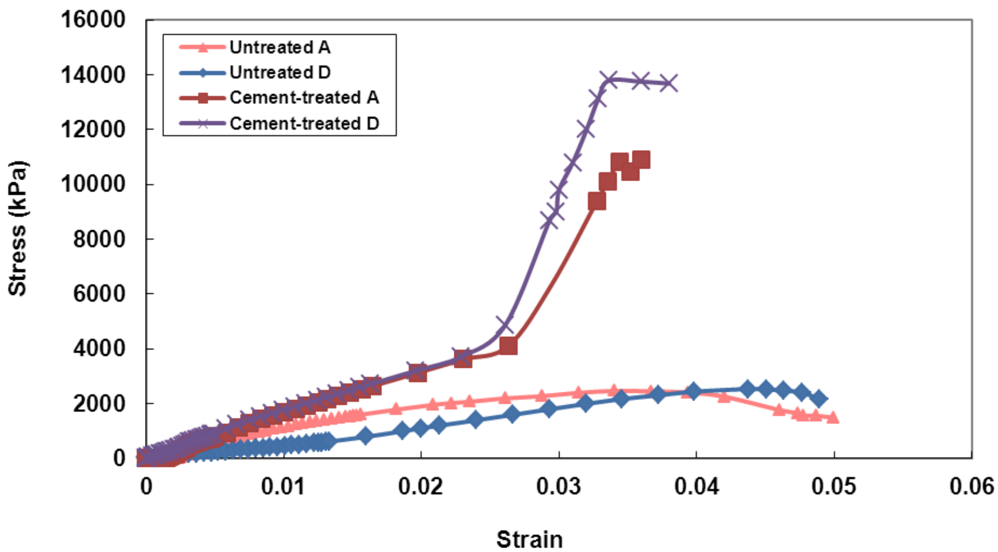

Figure 3: Stress-strain Relationship for Untreated and Cement-treated Blends A and D

The output interval was every 5 seconds of the experiment time. The final vertical displacement of the model was estimated as the average of nine displacements at the top nodes as shown in Figure 8.5. The same set of nodes at the middle of the model was used for lateral displacements and dilation progress monitoring.

The 3DFE model matches the behaviour of the blends in both elastic and plastic stages very well. Figure 5 shows the stress-strain relationship of untreated blends A and D at 70 kPa confining pressure resulting from the experiment and model. In spite of the fact that the model has so many complicated material parameters, it provides a good simulation of the hardening and softening stages of the material loading. The main problem with the modelling generally is after reaching peak strength, as the stress level decreases and the specimen becomes unstable. The unstable part of the stress-strain curve is usually known as material softening, during which the deformation pattern over the specimen becomes inhomogeneous as a result of the formation of one or more local deformation zones, known as shear bands. Specimen failure is strongly determined by particle sliding inside the shear band, while the adjacent bulk material unloads elastically (Suiker 2002). The model presented herein depicted this behaviour very well.

Figure 6 shows an example for these local deformation zones for untreated blend A at 70 kPa confining pressure. The results of the monotonic triaxial experiment of the blend showed that cracks and failure zones initiated from the top of the specimen where the loading was applied. The FE model depicted this behaviour very well as it showed a high plastic strain at the top spots of the model at the peak loading level, as shown in Figure 6.

At the peak loading stage, Von Mises stress contours showed that maximum stresses were located at the middle part of blend D and the top part of blend A as shown in Figure 7. This indicates the different behaviour of the blends in transporting the stress through the specimen body. Blend A provided strength for the whole specimen resulting in stress concentration at the top of the specimen where the loading was applied, while blend D was weaker as the maximum stress effects reached the middle of the specimen. This may also explain why, although the two blends had the same final plastic strain, they had different elastic moduli. This is because blend A underwent less deformation than blend D in the strain hardening stage.

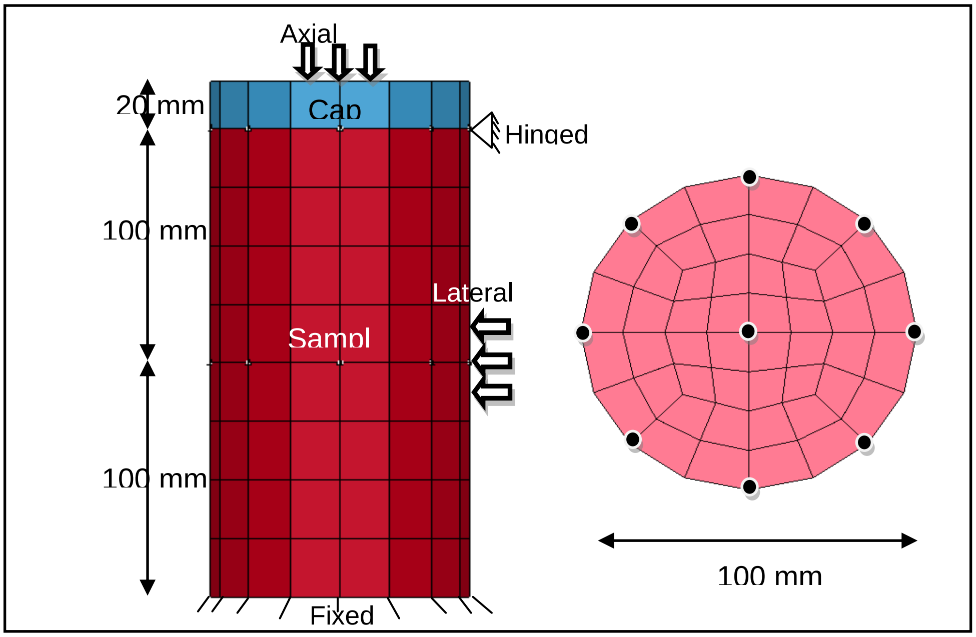

Figure 4: Displacement measurement on the top of the sample

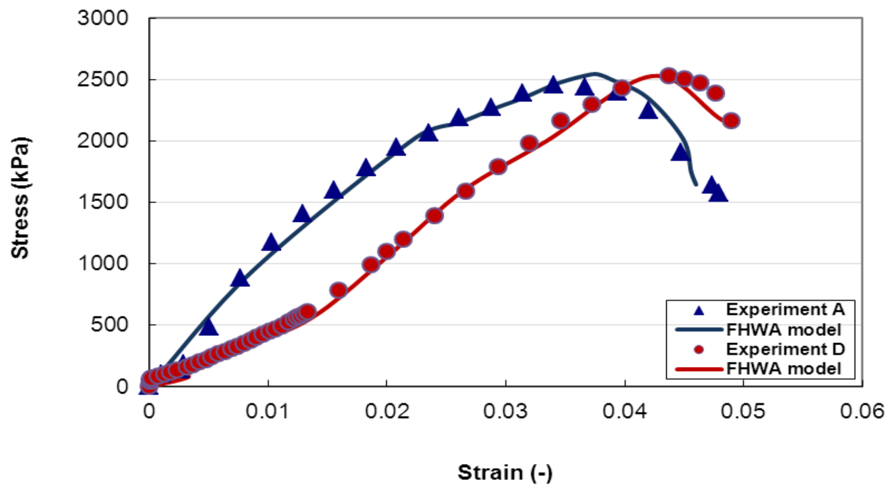

Figure 5: stress strain relationship from the experiments and FE model for untreated blends A and D at 70 kPa of confining pressure.

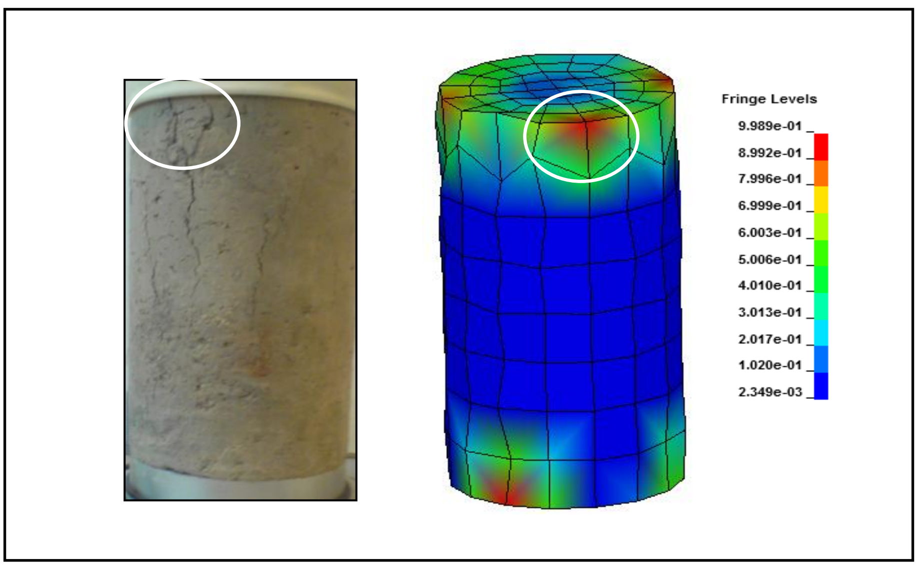

Figure 6: Effective plastic strain at peak loading in the experiment and FE model for untreated blend A at 70 kPa of confining pressure.

Figure 8 shows the numerical and experimental results of volumetric strain at confining pressures of 70 kPa for cement-treated blend D. The results indicate that the FE model's description of the dilation i.e. relations of uniaxial stress to lateral strain, behaviour of the blend agreed well with the experimental results up to 0.01 axial strain and then showed a slight difference. From Figure 8 and previously Figure 5, it seems that, the axial strain prediction is perfect while the lateral strain is greater in the model than in the experiment.

4.2 Cyclic triaxial test simulation

Details of the final model for the cyclic triaxial tests are the same as those of the monotonic triaxial model except for the loading which was applied according to the AASHTO TP46 protocol. The total run time of the programme ranged between 33 to 35 hours to simulate the test duration of 2000 seconds. The output interval was every 100 milliseconds of the experiment time in order to capture sufficient details of each load cycle.

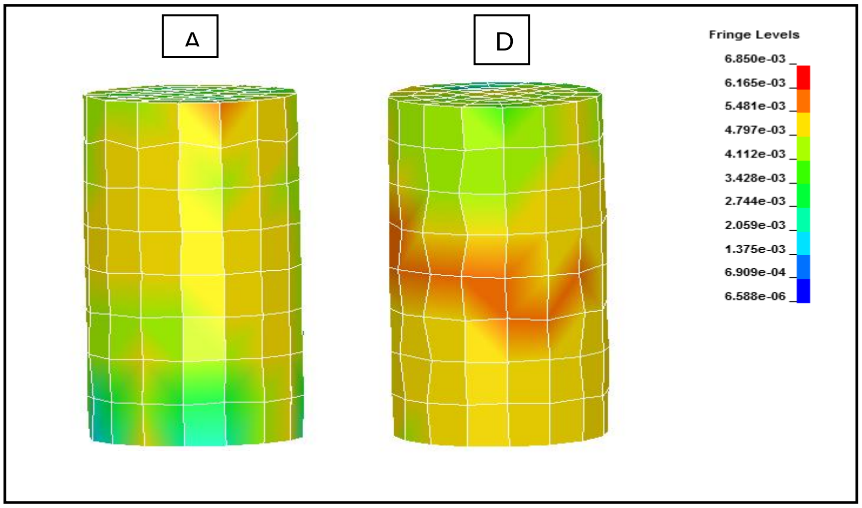

Figure 7: Von Mises stress at peak loading in FE model for untreated blends A and D at 70 kPa of confining pressure.

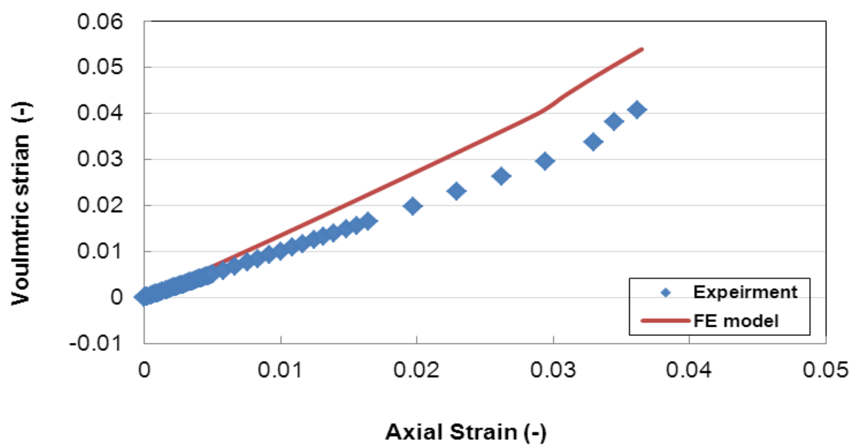

Figure 8: Volumetric strain of cement-treated blend D from FE model and experiment results

In granular materials, a typical relationship between time and strain under cyclic triaxial loading shows elastic and plastic strains varying according to different parameters, such as the compaction, the size and shape of the particles, and stress levels.

Figure 9 shows a schematic diagram of a typical strain-time relationship for granular materials. This relationship was observed clearly during the resilient modulus test in both experiments and simulations. Figures 10 and 11 show screen shots during the test and FE model output for blend A. The FE model results depict the experimental measurements in recoverable and plastic deformations as shown in the figures. The experimental results are presented as strain percentage and the model outputs are presented as deformations in mm as 1 mm deformation corresponds to 0.5% strain. The corresponding plastic strains produced by experiment and FE model are 0.23% and 0.22% respectively and the resilient strains are 0.1% and 0.12%.

The FE model generated relatively high resilient strains and, consequently, model results showed lower resilient moduli than those of the experiments as shown in Figures 12 and 13 for blends A and D respectively. For example, blend A had average resilient modulus of 322 MPa from the experiment while the model gave a value of 301 MPa. The figures show that the FE model was more successful in matching the experimental results in the earlier stages than in the latter stages. It is worth noting that both experimental and modelling results exhibited a high plasticity in the material during the last five sequences of the test due to the high stress levels adopted by the TP46 protocol. In the author's opinion, these sequences of high stresses are not convenient because they may not replicate the field loading conditions and also, in granular material, increasing the stress decreases the resilient strain and, consequently, generates high modulus values. Thus, these high values of modulus do not represent the elastic modulus of the material and are not suitable for design purposes.

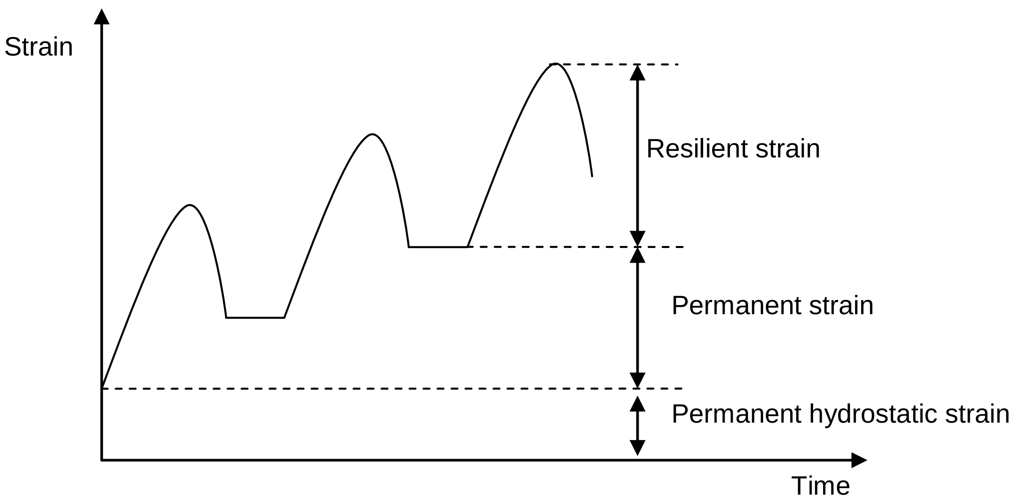

Figure 9: A schematic diagram of a typical strain-time relationship for granular materials under cyclic loading (Werkmeister, 2003).

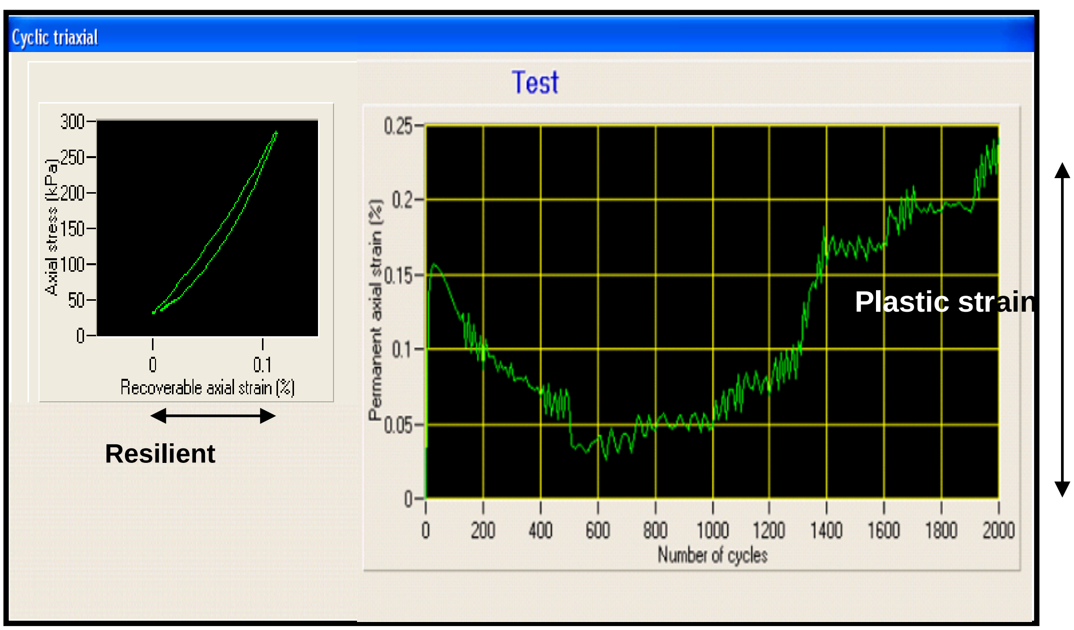

Figure 10: A snapshot of the Pc monitor during the resilient modulus test of blend A

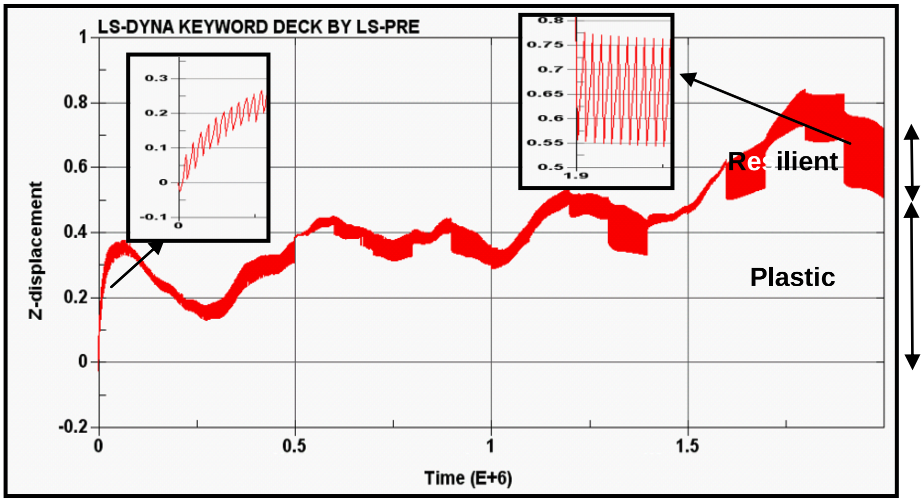

Figure 11: A snapshot of FE model deformation output at the middle nod of the specimen top for blend A

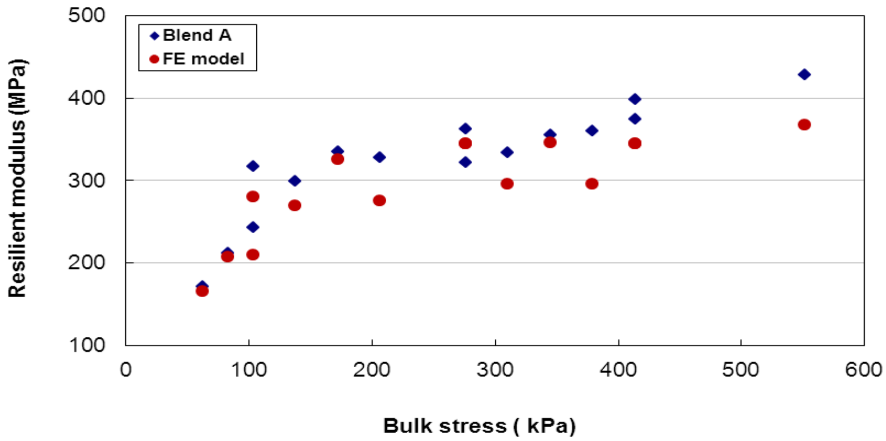

Figure 12: Resilient modulus of blend A experimental results and LS-DYNA model

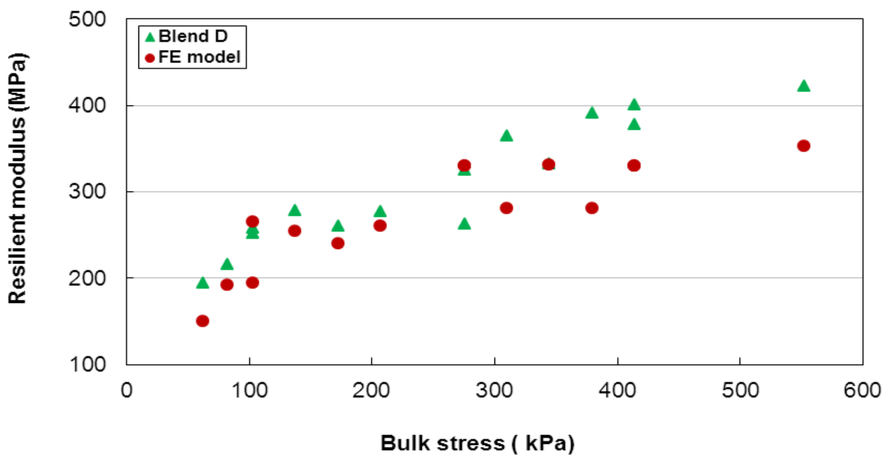

Figure 13: Resilient modulus of blend D experimental results and LS-DYNA model

5 CONCLUSIONS

From the results obtained in this work, the following remarks can be made:

FE model depicted the behaviour of blends A and D under monotonic load very well.
The results showed that the FE model of the dilation behaviour of the blend matches the experimental results.
The FE model of the resilient modulus test was more successful in matching the experiment results in the earlier loading stages than in the latter stages.
Modelling results of the resilient modulus test exhibited a high plasticity in the material during the last five sequences of the test due to the high stress levels adopted by TP46 protocol.
Experimental and modelling results showed that the cement treatment improved the elastic modulus of the IBAW material.
Experimental and modelling results also showed that the IBAW material behaved like a conventional aggregate.

Acknowledgement

Thanks for all academic staff and technicians of the University of Liverpool who support and help in this work.

References

Bouvet, M., François, D. and Schwartz, C. 2007. Road Soil Retention of Pb Leached from MSWI Bottom Ash. *Waste Management,* 27: 840–84.

Design Manual for Roads and Bridges (DMRB). 2009. Design Guidance for Road Pavement Foundations. *Interim Advice Note 73/06,* Volume 7, Section 1, Part 2, Draft HD25*.*

Federal Highway Administration (FHWA). 1996. Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils. *U.S. Department of Transportation, Federal Highway Administration,* Washington, D.C. TP46.

Hopkins, T. C., Beckham, T. L., Sun, C. and Ni, B. 2004. Resilient Modulus of Kentucky Soils. *Kentucky Transportation Centre,* Research report KTC-01-07/SPR-163-95-1F.

Hughes M. L., Tedesco J. W. and Ross C. A. 1993. Numerical Analysis of High Strain Rate Splitting-tensile Tests. *Computers and Structures* 44: 653-71.

Kosson, D. S., Van der Sloot, H. A. and Eighmy, T. T. 1996. An Approach for Estimation of Contaminant Release during Utilization and Disposal of Municipal Waste Combustion Residues. *Journal of Hazardous Materials* 47: 43-75.

Livermore Software Technology Corporation (LSTC). 2007. LS-DYNA Keyword User's Manual. Vol. I and II, version 971. ISBN: 0-9778540-2-7.

Mahabadi, O. K., Grasselli, G. and Munjiza, A. 2010. A Graphical User Interface and Pre-processor for the Combined Finite-discrete Element Code, *Y2D, incorporating material heterogeneity. Computers & Geosciences* 36: 241-252.

Thabet, A. and Haldane, D. 2001. Three-dimensional Numerical Simulation of the Behaviour of Standard Concrete Test Specimens When Subjected to Impact Loading. *Computers and Structures* 79: 21-31.