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Modeling of fly ash stabilized base layers

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ABSTRACT: In South Africa and developing countries, the base or sub-base layer serves as the main structural element or bearing capacity of the pavement. As a result, more focus is placed on the base or sub-base layer for the accurate designing of the pavement structure. However, flexible pavement still experiences failures; these failures are generally caused by various factors such as soil expansion, inadequate soil stabilization, inappropriate use of materials in base courses and inadequacy in design. Consequently, the roads need regular maintenance and rehabilitation, which increases the operational cost of the roads. However, with an appropriate method of soil stabilization and the use of finite element-based software, the design and construction of flexible pavement can be enhanced. This paper attempts to validate the optimization of Cement-enhanced Class-F Fly ash usage, as the base layer stabilizer in the South African flexible pavement, using the ABAQUS model. The validation results are discussed in this paper.

1 INTRODUCTION

South Africa has the 10th longest total road network in the world, after the likes of the first three countries, namely the USA, China and India (Kannemeyer 2013). The road network in South Africa is approximately 746,978 km, of which only 153,791 km is paved (The South Africa National Roads Agency Ltd. (SANRAL) 2010). About 90 percent of the paved roads in South Africa are flexible pavement (De Beer et al. 1999); this can be attributed to the fact that flexible pavements are: cost-effective, generate less tire-pavement noise and are environmentally sustainable (Asphalt Pavement Alliance 2010; Jain et al. 2013). However, despite the fact that only 21 per cent of the road network is paved; approximately 62 per cent is in good conditions, 26 per cent is in fair conditions and the remaining 12 per cent is in poor or very poor conditions (Kannemeyer 2013).

Some of the poor conditions experienced in flexible pavement are as follows: permanent deformation, cracking of surface course and creation of potholes (Jassal 1998; Adlinge & Gupta 2013); these are generally caused by various factors such as soil expansion (Kordi et al. 2010), inappropriate use of materials in base courses, inappropriate soil stabilization (Paige-green 2008) and inadequate design (Kordi et al. 2010; Shafabakhsh et al. 2013, Pavement Failure Identification 2014). As a result, the roads need regular maintenance and rehabilitation, which increases the operational cost of the roads and consequently influences the national annual budget that skyrockets every year (Ndebele 2012).

The aforementioned conditions are the major factors that contribute to inappropriate soil stabilization and inadequate design because soil and pavement materials are part of the design process; therefore, these factors that lead to failure in the pavement structure can be averted if careful consideration is taken. However, with an appropriate method of soil stabilization and the use of Finite Element (FE) model, the possibility of designing and constructing quality and cost-effective flexible pavement can be enhanced. Thus, this paper attempts to close the gap through validation, between the state of practice (stabilization) and the state-of-the-art (FE design) in flexible pavement design.

1.1 *Stabilization of flexible pavement*

Flexible pavements with asphalt on the surface are used worldwide. This structure consists of various layers, with different strength and deformation characteristics, which make the layered system difficult to analyze in pavement engineering (Kim 2007). In flexible pavement, the material quality gradually and smoothly increases from the *in situ* subgrade up to the structural layers and surfacing (SANRAL 2013). Basically, the layers above the subgrade are selected to ensure that the transmitted stresses due to the loading are sufficiently reduced, so that the stress will not exceed the subgrade bearing capacity (Adu-Osei 2001).

Nevertheless, in South Africa and other developing countries, the main structural element or bearing capacity of the pavement is obtained from the deep and well-balanced unbounded granular base or sub-base layer (Araya 2011; SANRAL 2013); using only thin asphalt (≤50 mm) on the surface to mainly provide protection against water ingress (De Beer et al. 1999; Araya 2011; SANRAL 2013). However, due to various factors such as inter-particle friction, particle distribution, particle hardness, cohesion, elasticity, durability and porosity (SANRAL 2013), which influence the behavior of the unbounded granular and other materials, the material characteristics of the entire pavement change continuously over time with environmental changes and later result in pavement failure.

The effects of these aforementioned factors are mostly significant for materials in its natural state. In order to stabilize the material behavior to a bearable or improved state, the concept of soil stabilization is introduced. However, stabilization concept is not new but the materials and the methods of stabilization are set to be evolving year after year. Stabilization primarily aims at improving the strength of soil or pavement materials and increasing the resistance to softening by water through bonding the soil particles together, water proofing the particles or combination of the two (Sherwood 1993; Takhelmayum 2013). This can be done by inducing vibration or compaction, and introducing a coarse or fine material and geosynthetic material (Hejazi et al. 2012); this process is known as mechanical stabilization. Also, chemical stabilization involves the addition of cementitious materials or soil minerals that produce the chemical reaction, thereby increasing the host material strength. Results have indicated that chemical stabilization is more advantageous (Makusa 2012; Heynes & Hassan 2013; Yadu & Tripathi 2013) but with few limitations such as the presence of organic matters, sulfate, sulfide and carbon dioxide in the stabilized soils, which may inhibit the stabilization process (Makusa 2012).

However, with the global increase in the production of by-products and waste materials such as blast furnace and steel slag, spent oil shale, china clay waste, slate waste, rice husk ash, millet husk ash, corn cob ash, coconut shell ash, waste foundry sand, cement kiln dust, fly ash, bottom ash, mining wastes, and demolition and construction waste (Hassan & Khalid 2010; Amin 2012; Bindu & Vysakh 2012; Heynes & Hassan 2013; Yadu & Tripathi 2013), also coupled with the challenge of disposal and environmental pollution, these factors have stimulated greater interest in their use in road construction (Nunes et al. 1996; Brennan & O'Flaherty 2002). Furthermore, in South Africa, mining wastes and fly ash tend to be common, which result from the fact that mining activities and coal play an important role in its economy, and also coal is a primary energy source for electricity generation (Furter 2011). Given the fly ash production of 30 mega ton per year in South Africa with only 6% utilized, the government is at the stage where it is strategically finding ways to reduce it through treatment, reuse and beneficiation (Furter 2011, Heyne & Hassan 2013).

Overall, fly ash has been found to be useful in pavement application purposes such as sub-grade, granular base or sub-base, asphalt surface and structural fill (United State Environmental Protection Agency 2009). However, unlike Class C, which is self-cementitious, Class F fly ash is often used alongside with other stabilizers (e.g. cement, lime or other industrial wastes) as a component of base or sub-base mixtures (Fhwa.dot.gov 2012), since pavements with a stabilized base or sub-base layer have proven to deliver better performance during their service life (Brennan & O'Flaherty 2002). According to Aydilek and Arora (2004), using fly ash as a stabilizer with cement increases the California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS) and resilient modulus of the base layer, similarly Lav et al. (2006), using Class F fly ash with 2, 4, 8, and 10% of cement by total weight, discovered that the maximum dry density increases and optimum moisture content decreases upon addition of cement to fly ash to form an aggregate-free stabilized mixture for the pavement base. Recently, Heyns and Hassan (2013) in South Africa, utilizing three different types of fly ash (Kendal Dump Ash, Durapozz and Pozzfill) enhanced with cement on the G5 sub-base material classified according to the Committee of Land Transport Officials (COLTO) (1998), discovered that when the G5 sub-base material is stabilized, it can meet the C3 stabilized standard for the base layer as classified by the COLTO. Despite all the successes recorded in the empirical procedure of fly ash as a stabilizer, it has not yet been fully incorporated in the new pavement design method, which consequently may result in the failure of pavements (Paige-green 2008).

1.2 *Design innovations*

Pavement design has been transitioning from empirical methods to mechanistic approaches (Kim 2007). Empirical methods rely on more experience or observation of past pavement performance for the development of models, while mechanical approaches (layered elastic and FE method) involve the use of fundamental engineering mechanics to evaluate the state of stress in a pavement and thereby predict the response, behavior and performance of pavement (Seeds 2000). However, empirical methods tend to be simple and easy to use, yet these methods are limited and mostly confine to the location of development, and are probably not valid outside the location; as a result, mechanistic methods are preferred (Wang 2001; Huang 2012).

The South African Mechanistic-Empirical Design Method (SAMDM) (Van Vuuren et al. 1974), developed in South Africa, works on the principle of layered elastic to determine pavement responses to the load; however, in recent years, the SAMDM has been scrutinized and criticized based on over sensitiveness to the change in the input variables and outdated damage models, a result that is presently under review (Jooste 2004; Theyse et al. 2011). However, mechanistic methods based on the FE model provide better material characterization options (Tilioune & Sandjak 2014) and can be used to obtain stresses and strains at the bottom of the surface layer, compressive stress/strain within the base layer and at the top of the subgrade (Darwish 2014). Considering the increasing application of 3D models as the best compared with 2D models in the FE model (Rahman et al. 2011; Shafabakhsh et al. 2013), a 3D FE model was used in this study. Furthermore, Abaqus® 3D FE base software has been used extensively in pavement design (Kim 2007; Rahman, et al. 2011; Shafabakhsh et al. 2013). In addition, Abaqus® has a wide library of different element types and material models, and it also has the capability of analyzing a variety of problems (Rahman et al. 2011; Britto 2014). As a result of the extent of Abaqus® usage with its advantages and capability, it is considered in this study. Overall, the success of any FE model depends greatly on accurate material characterization.

2 NUMERICAL DESIGN

The Abaqus® (6.13) 3D FE model was used to represent the conventional three-layered flexible pavement structure in South Africa with both unbounded granular material (G5) and Cement-enhanced Class-F Fly ash as the base layer stabilizer. The following two scenarios were developed in this present study: in the first scenario, G5 material was used as the base layer; in the second scenario, G5 stabilized with cement (1%) and fly ash (20%) was used as the base layer (which is classified as C3) (Heynes and Hassan 2013). The description of the flexible pavement model used in this study is presented below.

2.1 *Description of pavement geometry and material characterization*

The model geometry is basically 3000 mm length by 3000 mm breath and the total depth varies based on the thickness of the base layer that changes over a range of 100 mm–300 mm (Fig. 1). This geometry is similar to that used by Ahmed (2006), with the aim of avoiding edge error when loaded. However, with respect to material characterization, there exist three levels of material characterization inputs in the mechanistic empirical design, but level 2 that relies on basic laboratory testing (CBR, UCS etc.) and correlations is commonly used based on the fact that level 1 depends on difficult laboratory testing such as triaxial test (Mallela 2004). Using the correlation proposed by Barenberg (1977), Equation (1) that was validated by Little et al. (2002) and Al-Jhayyish (2014), the material properties of the Cement-enhanced Class-F Fly ash as the base (C3) (Heynes & Hassan 2013) are obtained and other material properties are obtained from SANRAL (2013). All material characterizations used in this study are linear elastic for simplicity as nonlinear characterization requires a lot of input parameters and computational time (Al-Jhayyish 2014). Details of each layer of the pavement in terms of elastic modulus and Poisson's ratio with their thickness are presented in Table 1.

$$R_{(psi)} = 1200\ \mathrm{UCS}_{psi}. \tag{1}$$

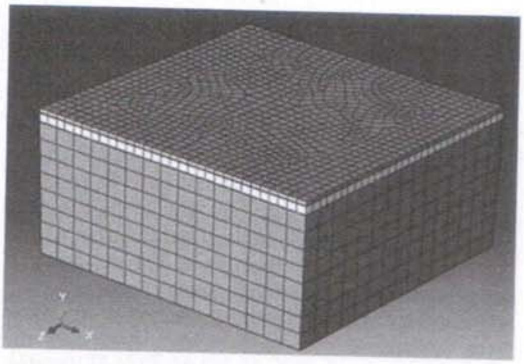

Figure 1. General geometry of pavement layers.

Table 1. Material properties of pavement layers.

Layer	Material code*	Thickness (mm)	Modulus of elasticity (Mpa)	Poisson's ratio
Surface	AG	50	3000	0.44
Granular base	G5	100–300	200	0.35
Stabilized base	C3	100–300	4596	0.35
Subgrade	G20	1500	45	0.35

*Classification according to the COLTO.

where M_R is the elastic modulus in psi; UCS is the unconfined compressive strength results in psi.

2.2 *Description of element type and meshing*

In this study, 8-node solid continuum elements (C3D8R) with reduction integration were used, as they had the capability of representing large deformation and material nonlinearity (Rahman et al. 2011; Ahmed 2006). Meshing of the geometry was done independently so that the thinnest layer (Surface) was finer (Fig. 1) (Tilioui ne & Sandjak 2014).

2.3 *Description of boundary conditions and loadings*

The pavement layers were assumed to perfectly bond together and the model was fixed at the bottom of the element (subgrade) and roller constraints on the vertical boundaries. On loading, a standard equivalent single axel load with dual tires was used in this model. The load was applied and uniformly distributed over an equivalent circular area of dual tires (72557 mm²) (Al-Jhayyish 2014) with a pressure of 0.65 Mpa (Theyse et al. 2011). Overall, all analyses were run as a static linear perturbation analysis procedure type.

3 ANALYSIS OF RESULTS AND DISCUSSION

In this study, the structural importance of the base layer was evaluated by considering Cement-enhanced Class-F Fly ash as the base layer stabilizer (C3); as a result, a critical area such as surface deflection, compressive vertical strain/stress within the base layer and at the top of the subgrade is used for the pavement verification analysis.

First, the increase in the thickness of the base layer (stabilized and unstabilized) decreases the deflection in the surface layer, thus it implies that the base layer is of structural importance in the pavement. However, the stabilized base layers show better results because the layer tends to act like a rigid surface (Table 2).

Table 2. The results of deflection in the surface layer.

Unstabilized base thickness (mm)	Deflection (×10⁻⁵ m)	Stabilized base thickness (mm)	Deflection (×10⁻⁵ m)
100	168.9	100	72.7
200	129.1	200	34.1
300	110.5	300	22.7

Second, the strain in the base and subgrade layers of the pavement is high in the y-direction (vertical); however, with the increase in the thickness of the stabilized base layer, it decreases. However, the stress in the base layer tends to be high in the x-direction (horizontal) (Table 3) and the stress in the stabilized layer against the unstabilized layer increases. This is due to the fact that the stabilized layer acts as a rigid surface and tends to absorb more stress as in the rigid pavement. The stress in the subgrade layer is high in the xy-direction (Table 4) and tends to decrease more in the stabilized layer because of the stress already absorbed by the stabilized base layer.

Finally, the stabilized base layer in the flexible pavement structure acts as a rigid layer, which uniformly distributes the stress generated by the traffic load, and it thus reduces the stress transferred

Table 3. The results of stress in the base layer.

Unstabilized base thickness (mm)	Stress (Mpa)	Stabilized base thickness (mm)	Stress (Mpa)
100	0.203	100	0.582
200	0.145	200	0.493
300	0.097	300	0.295

Table 4. The results of stress in the subgrade layer.

Unstabilized base thickness (mm)	Stress (Mpa)	Stabilized base thickness (mm)	Stress (Mpa)
100	0.028	100	0.001
200	0.017	200	0.003
300	0.011	300	0.002

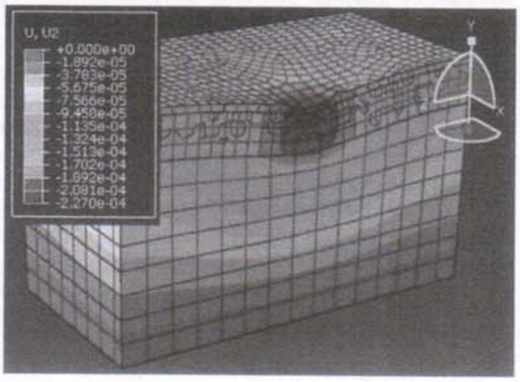

Figure 2. Stabilized base layer displacement distribution.

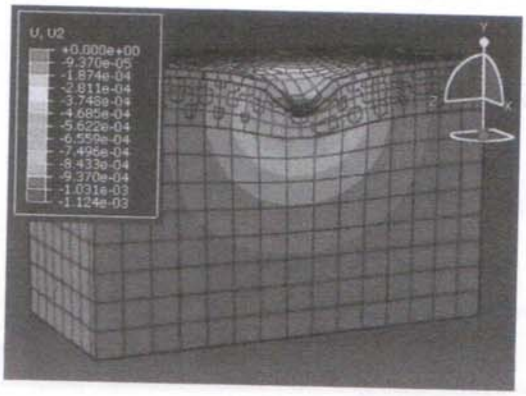

Figure 3. Unstabilized base layer displacement distribution.

to the subgrade when compared with the unstabilized base layer (Figs. 2 and 3).

4 CONCLUSION

Through the present study, the following conclusion can be drawn:

- The base layer in flexible pavement is the main structural element or bearing capacity of the pavement, and when stabilized, it can reduce the stress transferred to the subgrade; as a result, more attention should be paid to the design mix and laboratory testing of the base and other layers.
- The results of this study validate the use of Cement-enhanced Class-F Fly ash as an alternative stabilizer for the base layer in flexible pavement in place of the conventional use of cement only.
- Compared with the laboratory results, G5 stabilized with Cement-enhanced Class-F Fly ash at 20% can be used as the C3 material for base work.
- This work confirms that the use of Abaqus software has a great potential in the design and analysis of flexible and rigid pavements.

REFERENCES

Adlinge, S.S. & Gupta, A.K. 2013. Pavement deterioration and its causes. *International Journal of Innovative Research and Development* 2(4): 437–450.

Adu-Osei, A. 2001. *Characterization of Unbound Granular Layers in Flexible Pavements*. Technical Reported. Texas: Texas A&M University Texas Transportation Institute College Station.

Ahmed, H.Y. 2006. Effect of surface cracking on responses of flexible pavements structure. *Journal of Engineering Sciences* 34(3): 699–717.

Al-Jhayyish, A.K. 2014. *Incorporating Chemical Stabilization of the Subgrade in Pavement Design and Construction Practices*. Athens OH: Ohio University.

Amin, E.R. 2012. A review on the soil stabilization using low-cost methods. *Journal of Applied Sciences Research* 8(4): 2193–2196.

Araya, A.A. 2011. *Characterization of Unbound Granular Materials for Pavements*. Faculty of Civil Engineering and Geosciences. Delft, Netherlands: Delft University of Technology.

Asphalt Pavement Alliance. 2010. *Perpetual Asphalt Pavements: A Synthesis*. Maryland: APA 101, Lanham.

Aydilek, A.H. & Arora, S. 2004. Fly ash amended soils as highway base materials. *Journal of Materials in Civil Engineering* 17(6): 640–649.

Barenberg, E.J. 1977. *Evaluating Stabilized Materials*. National Cooperative Highway Research Program, Contract No. HR 63-4-1, Unpublished Report.

Bindu, J. & Vysakh, P. 2012. *Stabilisation of Lateritic Soil Using Coconut Shell, Leaf and Husk Ash*. Institution of Electrical and Electronics Engineers.

Brennan, M.J. & O'Flaherty, C.A. 2002. Materials used in road pavements. *Highways: The Location, Design, Construction & Maintenance of Road Pavement*. O'Flaherty, C.A. Oxford: Butterworth-Heinemann.

Britto, A. 2014. Running ABAQUS 6.9. *http://www-h.eng.cam.ac.uk/help/programs/fe/abaqus/doc/aba69f-double.pdf*.

Committee of Land Transport Officials (COLTO), 1998.

Darwish, S.G. 2012. Stress and Strain in Flexible Pavement. http://www.unimasr.net/ums/upload/files/2012/Dec/UniMasr.com_892f9fb48f1aa1918a5cfbb7ad4d6f08.pdf.

De Beer, M., Kannemeyer, L. & Fisher, C. 1999. Towards improved mechanistic design of thin asphalt layer surfacing based on actual tyre/pavement contact Stress-In-Motion (SIM) data in South Africa. *Proceedings of 7th Conf. Asphalt Pavements Southern Africa, Sun City, South Africa, 12–16 September 2004*.

Fhwa.dot.gov. 2012. Coal Fly Ash—User Guideline—Stabilized Base—User Guidelines for Waste and Byproduct Materials in Pavement Construction—FHWA-RD-97-148. *http://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/cfa55.cfm*.

Furter, E. 2011. Coal Fly Ash holds African Opportunities. *www.sheqafrica.com/fly-ash-conference/*.

Hassan, M.M. & Khalid, H. 2010. Mechanical and environmental characteristics of bituminous mixtures with incinerator bottom ash aggregates. *International Journal of Pavement Engineering* 11(2): 83–94.

Hejazi, S.M., Sheikhzadeh, M., Abtahi, S.M. & Zadhoush. A. 2012. A simple review of soil reinforcement by using natural and synthetic fibers. *Construction and Building Materials* 30(1): 100–116.

Heyns, M.W. & Hassan, M.M. 2013. South Africa class F fly ash for roads: Physical and chemical analysis. *Interim: Interdisciplinary Journal* 12(3): 28–41.

Huang, Y.H. 2012. *Pavement Analysis and Design*. 2nd edi. NJ: Pearson Education Inc.

Ibrahim, S.F., Gandhi, G.S. & Zaman, T.T. 2014. An approach in evaluating of flexible pavement in permanent deformation of paved and unpaved roads over sand dunes subgrade under repeated loads. *Journal of Environment and Earth Science* 4(14): 78–89.

Jain, S., Joshi, Y.P. & Golia, S.S. 2013. Design of rigid and flexible pavements by various methods and their cost analysis of each method. *International Journal of Engineering Research and Applications* 3(5): 119–123.

Jassal, K.S. 1998. *Development of Potholes from Cracks in Flexible Pavements*. Canada: Concordia University.

Jooste, F. 2004. Re-Evaluation of Some Aspects of the Mechanistic-Empirical Design Approach. *Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa, Sun City, South Africa, 12–16 September 2004*.

Kannemeyer, L. 2013. Asset Management: General Status Overview. 25th Road Pavements Forum Meeting, Western Cape, 7–8 May, 2013.

Kim, M. 2007. *Three-Dimensional Finite Element Analysis of Flexible Pavements Considering Nonlinear Pavement Foundation Behavior*. Urbana-Champaign: Department of Civil Engineering, Graduate College of the University of Illinois at Urbana-Champaign.

Kordi, N.E., Endut, I.R. & Baharom, B. 2010. Types of Damages on Flexible Pavement for Malaysian Federal Road. *Proceeding of Malaysian Universities Transportation Research Forum and Conferences, Universiti Tenaga Nasional, 21 December 2010*.

Lav, A., Hilmi, M., Lav, A. & Goktepe, A.B. 2006. Analysis and design of a stabilized fly ash as pavement base material. *Fuel*. 85(16): 2359–2370.

Little, D., Snead, B., Godiwalla, A., Oshiro, P. & Tang. P. 2002. Characterization of Design Properties (Compressive Strength and Resilient Modulus) of Lime, Cement, Fly Ash Stabilized Structural Recycled Concrete Base As A Function of Curing Time. *Presentada en The 2002 Federal Aviation Administration Airport Technology Transfer Conference, Atlantic City, NJ, May 2002*.

Makusa, G.P. 2012. *Soil Stabilization Methods and Materials*. Luleå, Sweden: Department of Civil, Environmental and Natural resources, Luleå University of Technology.

Mallela, J., Harold Von Quintus, P.E., Smith, K.L. & Consultants, E.R.E.S. 2004. *Consideration of Lime-stabilized Layers in Mechanistic-empirical Pavement Design*. Arlington, Virginia: The National Lime Association.

Ndebele, S.J. 2012. *Keynote Address by the Minister of Transport*. Presented at the occasion of department's budget vote.

Nunes, N.C., Bridges, M.G. & Dawson, A.R. 1996. Assessment of secondary materials for pavement construction: Technical and environment aspects. *Waste Management* 16(1–3): 87–96.

Paige-green, P. 2008. A reassessment of some road material stabilization problems. *Proceedings of the 27th Southern African Transport Conference, Pretoria South Africa, July 7–11, 2008*.

PFI. 2010. Pavement Failure Identification. *http://www.apai.net/cmdocs/apai/designguide/Appendix_A-B.pdf*.

Rahman, M.T., Mahmud, K. & Ahsan, S. 2011 Stress-strain characteristics of flexible pavement using finite element analysis. *International Journal of Civil and Structural Engineering* 2(1): 233–240.

Seeds, S.B. 2000. *Flexible Pavement Design: Summary of the State of the Art*. Transportation in the New Millennium.

Shafabakhsh, G.A., Motamedi, M. & Family, A. 2013. Influence of asphalt concrete thickness on settlement of flexible pavements. *Electronic Journal of Geotechnical Engineering* 18(Bund. C): 473–483.

Sherwood, P. 1993. *Soil Stabilization with Cement and Lime. State of the Art Review*. London: Transport Research Laboratory, HMSO.

Takhelmayum, G. 2013. Laboratory study on soil stabilization using fly ash mixtures. *International Journal of Engineering Science and Innovative Technology* 2(1): 477–482.

The South Africa Natinal Roads Agency Ltd. 2010. Annal report 2010. *http://www.nra.co.za/content/Sanral_A Rep_10_Web.pdf*.

The South African National Road Agency Ltd. 2013. *Materials Testing: South African Pavement Engineering Manual*. South Africa: An Initiative of the South African National Roads Agency Ltd.

Theyse, H.L., de Beer, M., Maina, J.M. & Kannemeyer. L. 2011. Interim Revision of the South African Mechanistic-Empirical Pavement Design Method for Flexible Pavements. *Presented at 10th Conference on Asphalt Pavements for Southern Africa, Champagne Sports Resorts, KwaZulu-Natal, South Africa, 11–14 September 2011*.

Tiliouine, B. & Sandjak, K. 2014. Numerical simulation of granular materials behavior for unbound base layers used in Algerian pavement structures. *International Journal of Civil and Structural Engineering* 4(3): 419–429.

United State Environmental Protection Agency. 2009. Using Recycled Industrial Materials in Roadways. *http://www.epa.gov/epawaste/conserve/imr/pdfs/roadways.pdf*.

Van Vuuren, D.J., Otte, E. & Paterson. W.D. 1974. The Structural Design of Flexible Pavements in South Africa. *Proceedings of the 2nd Conference on Asphalt Pavements in South Africa, Durban, South Africa, 1974*.

Wang, J. 2001. *Three-Dimensional Finite Element Analysis of Flexible Pavements*. United States: Department of Civil Engineering, University of Maine.

Yadu, L.K. & Tripathi. R.K. 2013. Stabilization of soft soil with granulated blast furnace slag and fly ash. *International Journal of Research in Engineering and Technology* 2(2): 115–119.