Asphalt concrete modeling using discrete element method

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Abstract: Pavement is a complex multi phase system which consists of aggregates, binder, filler material and sufficient air voids content. Primary function of a pavement is to transfer loads to the sub base and underlying soil. Pavement failure is one of the major problems associated with asphalt concrete performance. In present the continuous and increasing traffic volume causes pavement failure in asphalt concrete. The main causes of pavement failure are related to material properties, construction techniques, and different traffic loading pattern in term of mode, volume, moisture, and different environmental conditions. To recognize pavement distress or failure phenomena of asphalt concrete like fatigue, rutting, and cracking some advanced modeling techniques are used. These models offered an opportunity for more realistic pavement design procedure with mathematical and computational mechanics improved ability to predict pavement response to traffic load and environment effect. In this paper we discussed about an advanced and valuable modeling approach discrete element modeling (DEM) for asphalt concrete and provide a realistic behavior of pavement performance in term of materials characteristics, methods of testing, temperature, loading rate on specimen, loading time and different environmental conditions.

Keywords: Asphalt concrete, Pavement failure, Fatigue, Rutting, Asphalt modeling, Realistic Design, Discrete element method.

INTRODUCTION:

Pavement is an important transportation infrastructure which has dominant position amongst the various modes of transportation infrastructures due to its flexibility, door-to-door service, reliability and speed. Pavement is highly desirable transportation mode which contributes to movement of people, goods and development of industrial and social activities. Pavement is a complex system which consists of various layers. Asphalt concrete is composite multi phase material consists of aggregates, binder, filler and air voids then laid down in layers and compacted [1] Asphalt concrete used in road construction, parking lot and airport pavement. In present traffic volume is increasing very fast day by day, which is responsible for pavement deterioration. It is a major task for a pavement engineer to construct a long life pavement performance under economic aspect. A realistic prediction of pavement behavior and long term service life is difficult and not an easy task for pavement engineers [2]. Asphalt concrete has various performance parameters in terms of surface durability, workability, tire wear, temperature variation and drainage. Asphalt concrete pavement performance is depend on the behavior of asphalt concrete in field conditions under high traffic intensity, over loading of vehicles, material characteristics and significant variation in daily and seasonal temperature.

For achieving long lasting and good performance pavement better mix design of asphalt concrete is needed. The life of a pavement can be increased through good mix design, construction and maintenance practices. During design process measure the traffic on a road, types of loading, material properties, temperature variation, moisture and different environmental conditions. Lack of these factors resulted in deterioration of pavement and various distress symptoms were observed in pavement surface. Pavement distress is a result of gradual deterioration that may take place throughout the pavement life. Pavement deterioration or distress symptoms can include fatigue, rutting, thermal cracking, pothole, raveling, stripping, and grade depressions. These distress conditions have affected the mechanical, physical, and rheological properties of pavement. Rutting, fatigue, and cracking are the serious distress symptoms in asphalt concrete pavement. The serviceability of asphalt concrete is reduced by these distresses [3]. Asphalt concrete is consider viscoelastic behavior in nature and these complex behavior of asphalt concrete requires determined their micro structural and stress-strain behavior of the binder [4].

The prediction of asphalt concrete behavior is based on pavement response model and pavement performance model. Pavement response model is based on stress and strain distribution and performance model such as permanent deformation model (rutting), fatigue cracking, and fracture under different laboratory and field loading condition in pavement. To understanding these pavement distress behaviors some modeling techniques are required. The model should be able to predict major distresses associated with asphalt failure such as rutting, fatigue cracking, thermal Cracking, and reflection cracking from basic pavement responses. The considerable cost and resource consumption in construction and rehabilitation can be reduced by distress modeling. Asphalt modeling for asphalt concrete is an advanced approach to recognize the actual long term pavement performance with help of numerical and computational method.

ASPHALT MODELING:

In the asphalt modeling approach behavior of asphalt mixture is modeled numerically. Different models are used to predict the mechanical behavior of the asphalt concrete and long term pavement performance for road distress symptoms like rutting, fatigue, raveling, and cracking. Asphalt concrete is a complex composition of many layers of different materials. In layer system layers receives loads from the above layer and passes to the next layer. As discussed earlier asphalt concrete is behave like viscoelastic material and determined through different modeling techniques. The performance of asphalt concrete pavement is related to performance of asphalt concrete and models developed to capture the effects of different factors such as rate of loading, loading time, mode of loading, aging, stress-strain behavior and moisture on asphalt concrete pavements [5].

In asphalt concrete pavement main design factors are stress due to different loading condition and temperature variations. The stress strain behavior of asphalt concrete is understood by two approaches: macro mechanical approach, and second is micro mechanical approach [6]. Model is a numerical device which is to enable to predict the effect of change and behavior of system and modeling is the process of producing a model. Mathematical models can classified into two category first is deterministic (variables are fixed) or stochastic (one variable is probabilistic) and second is static or dynamic. Most of the models are stochastic and dynamic in nature. Models are typically conceptual, existing as an idea, a computer program or a set of mathematical formulas [7]. A numerical model should be a close prediction of the real system. Asphalt modeling is most important to evaluate the complex behavior of asphalt concrete and comparison between realistic and experimental data's. These models are based on the micro-structural behavior of materials and asphalt concrete. The modeling of asphalt concrete is more realistic mathematical tool to predict the performance of materials and pavement behavior. Modeling of asphalt concrete for design consist some modeling approaches which are use widely: empirical design, mechanistic design and mechanistic empirical design. Empirical method is based on the results of experience or experiment and it requires number of observation to obtain the relationship between input and outcome variables. In empirical method of asphalt concrete pavement, characteristics relates to actual pavement performance and more reliable performance prediction of asphalt concrete is done. The major disadvantage of these empirical methods is that mixture performance in the field in not directly related to properties measured in the laboratory. Mechanistic empirical models are based on an understanding of the behavior of a system through mathematical and computational analysis. Mechanistic-Empirical method of modeling is based on the mechanics of materials that relates input wheel load to an output pavement response and distress modeling using vertical strain. The models are based on simplification of reality and used the value of the calculated stresses, strain, and deflections, are reasonably close to stresses and strain in real pavement results in pavement failure for realistic pavement performance [8]. Mechanistic-empirical methods are an intermediate step between empirical and mechanistic methods. To predict the micro structural and viscoelastic behavior of asphalt concrete different modeling approach like finite element modeling, discrete element modeling, continuum damage approach, multi scale modeling, artificial neural network, and finite difference modeling and so on are introduced by various researchers. With the help of these modeling approaches a realistic pavement performance prediction has done in an accurate and simple manner. In this paper only discrete element modeling approach are discussed in next section.

LITERATURE REVIEW:

In this section discussion about discrete element modeling and implementation of discrete element modeling in asphalt concrete pavement to predict micro structural behavior and realistic pavement performance is done.

Discrete element method:

The discrete element method is first proposed by cudnall in 1971 to problems in rock mechanics and it is also known as distinct element method. The discrete element method (DEM) is a mathematical method which is used to compute the stress and displacement in a volume containing a large number of small particles and based on Newton's second law and finite differences method concept. The granular material is modeled as an assembly of rigid particles and the interaction between each particle is considered. The basic assumption of the method is that the material consists of separate and discrete particles and these particles have different shape and properties. The discrete element method utilizes the breakage of individual structure units or bonds to directly represent damage. With the help of this discrete element model many researchers observed the complex behavior of asphalt concrete in simple and realistic manner in long term pavement performance [9] investigated the complex mechanical interaction of a discontinuous system to detect and categorize contacts between three dimensional particles. This method detects the contact between blocks of any arbitrary shape and represents the geometrical and physical characteristics for the contact [10] presented micro fabric two dimensional discrete element modeling approach to predict asphalt concrete complex modulus, particle and interface properties, such as normal and shear stiffness and strength in extension and compression with different range of test temperature and load frequencies. This modeling approach determined better complex modulus across a range of test temperature and load frequencies compare to more traditional calibration method [11]. Determined dynamic mechanical behavior of asphalt mastic for different binder and filler material and discussed on the effect of binder stiffness and filler volume fraction on the overall mastic stiffness by discrete element modeling method. [11] proposed a advanced discrete element modeling method called particle flow code in two dimensions (PFC2D) for modeling the micromechanical behavior of asphalt mastic and hot mix asphalt concrete under various loading condition. The main objective of this study to analyze the effect of fillers in stiffening mastics and the effect of binder type on the viscoelastic and tensile properties of hot mix asphalt. It was observed that cracking due to high concentration of stresses has occurred at the interface between the aggregate and binder and depends on binder film thickness. [6] proposed a micromechanical approach for viscoelastic response of asphalt mixture.

This methodology has the advantage of accounting for the aggregate shape, and distribution with asphalt mixture and provided the connection between the performance of asphalt mixtures and material properties of their constituents. It was observed discrete element model gave mix phase angel higher than the experimental results. [12] proposed modified discrete element model like contact force prediction method that make a larger time step possible for complex mechanical interaction between particles. This method determined the predicted values of contact force at every contact point which are actual solution of differential equations that represent two particle contacts and accelerate discrete element modeling calculation three to eight time. [13] presented a methodology to predict and simulate the permanent deformation resistance behavior of asphalt concrete under uniaxial loading by discrete element method. This report introduced new automated digital image processing (DIP) algorithm, called volumetric based global minima (VGM) algorithm. This algorithm identified boundary thresholds between air, mastic, and aggregate phases with reference to volumetric information. Investigated fractures mechanisms in asphalt concrete at low temperature by discrete element method. The modeling approach provide details of the fracture test process, heterogeneity on crack path, and the effects of local material strength and fracture energy on fracture test response. [14] developed three dimensional microstructure based discrete element model of asphalt mixture to study the dynamic modulus from the stress- strain response under compressive loads.[15] presented a viscoelastic model of asphalt mixtures with the discrete element method, where the viscoelastic behaviors of asphalt mastics, fine aggregates, fines, and asphalt binder, are represented by a Burger's model. A series of equations are developed to express the Correlation between the micro scale discrete element model parameters and the Macro scale material properties of asphalt mastics and aggregates Measured in the laboratory. [16] proposed the discrete element model to predict the asphalt mixture dynamic modulus in the hollow cylindrical specimen with different range of test temperature and load frequencies.[17] introduced an approach to analyze the combined effects of aggregate gradation, shape, stiffness, and strength on asphalt concrete resistance to fracture. The model was used to measured the internal forces in asphalt mixture and determine their relationship to aggregate fracture. [18] proposed a discrete element model to investigate the isolated effects of the aggregate spehericity index, fractured faces, and orientation angles on the creep stiffness of hot mix asphalt mixture. [19] developed a user defined micromechanical model using discrete element method to investigate the cracking behavior of asphalt concrete. The effects of air void content and aggregate volumetric fraction on the cracking behavior of asphalt concrete were evaluated.

CONCLUSION:

In the above section some literature review on asphalt modeling using discrete element modeling method are presented and gives a clear indication that asphalt concrete modeling is an important tool for realistic observation of pavement performance. In present discrete element method is becoming widely accepted as an effective mathematical tool of addressing engineering problem related to prediction of asphalt concrete pavement performance. This model advances in computing power and numerical algorithms which numerically simulate millions of particles on a single processor. Discrete element modeling simulation is advantageous in describing the effect of aggregate shape and distribution on the susceptibility of asphalt mixtures to permanent deformations especially at high strain levels. Discrete element method is discontinuum analysis method, which can model the deformation process of joint systems and dynamic condition and provide a more detailed study of the microstructure dynamics of asphalt concrete and other granular materials. Limitation in discrete element method is the maximum number of particles; duration of a simulation is limited by computational power.

REFERENCES:

[1] Collop, Andrew C., Glenn R. McDowell, and York W. Lee.(2006). "Modelling dilation in an idealised asphalt mixture using discrete element modelling." Granular Matter 8.3 (2006): 175-184.(2006)

[2] Dai,Qingli,and Sadd,Martin.(2004)."Parametric model study of microstructure effects on damage behavior of asphalt samples." The International Journal of Pavement Engineering, vol. 5 (1), pp. 19–30.(2004)

[3] Monismith, C. L.(1992). "Analytically based asphalt pavement design and rehabilitation: theory to practice." Transportation Research Board, 500 Fifth Street, NW, Washington, DC,20001, USA, ISSN: 0361-1981,ISBN: 0309052181.(1992)

[4] Abbas, A, Masad, E., Papagiannakis, T., and Shenoy, A. (2005). "Modelling asphalt mastic stiffness using discrete element analysis and micromechanics-based models." International Journal of Pavement Engineering, 6(2), 137-146.(2005)

[5] Kim, Y. R.(2007). "Modeling of asphalt concrete." Mcgraw-Hill, United State of America: ASCE Press.
Kim, H., Wagoner, M. P., & Buttlar, W. G. (2008). "Simulation of fracture behavior in asphalt concrete using a heterogeneous cohesive zone discrete element model." Journal of materials in civil engineering, 20(8), 552-563. (2007)

[6] Abbas,A.,Masad,E.,Papagiannakis,T.,and Harman,T. "Micromechanical modeling of the viscoelastic behavior of asphalt mixtures using the discrete-element method." Int. J. Geomech., 7:131-139. (2007)

[7] Masad, E., Tashman, L., Little, D., and, Zbib, H. "Viscoplastic modeling of asphalt mixes with the effects of anisotropy, damage and aggregate characteristics." Mechanics of materials, 37(12), 1242-1256.(2005)

[8] Oscarsson,E. "Mechanistic-empirical modeling of permanent deformation in asphalt concrete layers." Traffic and Roads Department of Technology and Society, Faculty of Engineering, LTH Lund University,Box 118, SE-221 00 Lund, Sweden. (2011)

[9] Cundall, P. A. "Formulation of a three-dimensional distinct element model—Part I. A scheme to detect and represent contacts in a system composed of many polyhedral blocks." International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. Vol. 25. No. 3. Pergamon. (1988)

[10] You,Z.,and Buttlar,G.W. "Discrete element modeling to predict the modulus of asphalt concrete mixtures." J. Mater. Civ., 16:140-146. (2004)

[11] Abbas,R.A.,and Papagiannakis,T.A. "Micromechanical simulation of asphaltic materials using the discrete element method."Asphalt Concrete,pp.1-11. (2006)

[12]Tokoro, C., K. Okaya, and J. Sadaki."A fast algorithm for the discrete element method by contact force prediction." Kona 23: 182-193.(2005)

[13] Zelelew, H. M., & Papagiannakis, A. T. "Micromechanical modeling of asphalt concrete uniaxial creep using the discrete element method." Road Materials and Pavement Design, 11(3), 613-632.(2010)

[14] You, Z.,Adhikari,S.,and Dai,Q. "Three-dimensional discrete element models for asphalt mixtures." Journal of engineering mechanics.,1053-1063.(2008)

[15]Liu,Yu,Dai,Qingli,and You,Z. "Viscoelastic Model for Discrete Element Simulation of Asphalt Mixtures." J. Eng. Mech.,135:324-333.(2009)

[16] Adhikari,S.,and You,Z."3D discrete element models of the hollow cylindrical asphalt concrete specimens subject to the internal pressure." International Journal of Pavement Engineering Vol. 11, No. 5, 429–439.(2010)

[17] Mahmoud, E., Masad, E., and, Nazarian, S. "Discrete element analysis of the influences of aggregate properties and internal structure on fracture in asphalt mixtures." Journal of Materials in Civil Engineering, 22(1), 10-20.(2010)

[18] Liu,Yu, and You,Z. "Discrete-element modeling: impacts of aggregate sphericity, orientation, and angularity on creep stiffness of idealized asphalt mixtures." J. Eng. Mech., 137:294-303.(2011)

[19] Chen,J. "Discrete element method (DEM) analyses for hot-mix asphalt (HMA) Mixture Compaction."Ph.D.thesis, University of Tennessee, Knoxville.(2011)