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Modelling the Viscoelastic Behavior of asphalt Concrete at the Nanoscale

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ABSTRACT

The main purpose of this paper is to investigate the mechanical properties “hardness H and elastic modulus E ” of asphalt concrete AC at the nanoscale to get its mechanical behavior comparing to the distinct behaviors of its different phases got from experimental works. AC is generally composed of coarse aggregates that have an elastic mechanical behavior, a viscoelastic or viscoplastic binder and interface transition zone ITZ. For this; as bituminous material we have used an asphalt concrete sample which is subjected to a nanoindentation simulation test using a Berkovich indenter tip with a load of 2500 μN for 10 s of loading and 10 s of unloading. AC is supposed to be a viscoelastic material; so the Prony series are introduced and different coefficients of prony are obtained from an experimental relaxation's master curve of AC. Finite element software ABAQUS 6.13 is used to simulate this mechanical behavior where our study is carried out at a temperature of 25°C. The results showed that hardness and young's modulus values are closer to the aggregates phase than to the fine matrix results, in other words it seems that our asphalt concretes responds of an elastic behavior at the nanoscale.

1 Introduction

A bitumen mixture is a heterogeneous complex material composed mainly of a viscoelastic binder combined with a granular elastic skeleton and containing a certain percentage of air voids.

The study of mechanical behavior of this heterogeneous material is very complex so the geometry of the microstructure and mechanical behavior of the different phases must be taken into account.

Known in its different forms and therefore in several uses, asphalt concrete has dominated the field of pavement construction since the earliest times and the knowledge of its constitutive makes the foundation in predicting its mechanical

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behavior; this can only be validated after an identification at the microstructural scale, thing that strongly induces the determination of Young's modulus and hardness.

These last two parameters are derived from experimentation or simulation tests based on research techniques; we note in our case the simulation of nanoindentation test with finite element method which will be compared to the experimental work.

Indentation is a test where measurements are in micrometers (10^{-6} m) or meters scale, while nanoindentation, the measurements are in nanometers (10^{-9} m) scale where, an indenter tip with known geometry (pyramidal, spherical, conical) is penetrated in a material with known history loading (rate, time, depth, load) [1-5] to get an X-Y data giving different values of mechanical properties: hardness, young's modulus, creep...etc

It has been used to determine material properties [6-8] but the studies on bituminous materials such as asphalt concrete are limited [1, 9, 10] because of the heterogeneity of its composition and due to its complex mechanical behavior [11]. Researchers have supposed that asphalt concrete is a multiphase material (aggregates, interfacial transition zone and binder) and only few studies have been done on the compression and hardness of the binder [2, 4, 11-13].

Young's modulus E and hardness H are observed to be influenced negatively by indentation depth and loading rate, by evaluating the mechanical properties and creep behavior of solid bitumen via nanoindentation test [14].

Loading curve and unloading curve were used [15] to get hardness and Young's modulus; and it has been assumed that while unloading the contact surface is constant.

Tarefder et al. [16] have made an indentation on asphalt binder using spherical and Berkovich indenter tips; they concluded that Berkovich indenter is better than spherical one for testing, and a nanoindentation for determining hardness and young's modulus of an aging asphalt has been used [15].

A nanoindentation test on mastic materials were conducted and investigated the effect of moisture in [10].

Studies have distinguished three different phases of asphalt concrete visually; on which nanoindentation tests were explored [17, 18].

Tarefder et al [3] investigated the effect of aging of asphalt mixtures on the two phases: aggregate and mastic.

Khorasani et al. [19] have studied the local mechanical properties at nano-scale of fine aggregate mixture FAM phase and interface.

Also, for a nanoindentation using a Berkovich indenter, it was found that the Young's modulus and hardness for samples with hydrated lime are higher than the samples without them [20].

A statistical model was proposed to identify different phases of AC from nanoindentation test results [21].

In terms of elastic modulus, interface transition zone seems not the softest part in the asphalt mixture. The modulus value of ITZ was found between that of aggregate and that of mastic [22].

1.1 Mechanical behavior

Dynamic modulus is one of the fundamental technical properties used to describe mechanical behavior of bituminous materials.

For the viscoelastic behavior, there are many methods to obtain the dynamic modulus of asphalt concrete.

The most reliable is by direct laboratory testing on asphalt samples at different temperatures and different loading frequencies. However, it is difficult to measure dynamic modulus in laboratory tests under extreme conditions of high temperature and loading frequencies (viscosity) and it is more expensive and time-consuming than any other method.

Nevertheless, empirical models such as the Hirsch model [23] and the Witczak model [24] used in the Guide to Mechanistic-Empirical Design of Pavements (MEPDG) were developed to estimate the dynamic modulus of mixtures of asphalt as a function of binder properties and volume fill rates.

Empirical regression modeling work has been developed by Witczak and his collaborators over nearly 30 years.

For the viscoelastic behavior of bituminous materials, it was the work of many researchers; recently, Aljarrah et al. [25] found that asphalt binders using a nanoindentation test; exhibit an elastic behavior at the nanoscale.

For the viscoelastic mechanical behavior of asphalt; Jager et al. [26] used the nanoindentation test on two asphalt samples trying to get the effect of loading rate and maximum load on asphalt behavior; they concluded that maximum load has a significant effect that loading rate hasn't.

Veytskin et al. explored the viscoelasticity behavior of asphalt binder [27].

Wang et al. [28] explored the nanoindentation data to identify the mechanical properties of viscoelastic/plastic materials.

The structure (arrangement) of the molecules in the material and its chemical composition can determine the viscoelastic characteristics of bitumen [29].

Pichler et al. [30] used a nanoindentation test to study the viscoelastic behavior and microstructure of bitumen; they concluded that bitumen behavior is strongly related to its microstructure and studied the relation between viscosity and nanomechanical properties of bitumen.

Fadil et al. [31] used a spherical instrumented indentation test for a characterization of linear isotropic viscoelastic bitumen. They found that the measured shear relaxation modulus of viscoelastic materials is strongly related to the indentation scale [32].

In general, bituminous materials exhibit nonlinear stress /strain behavior with only nonlinearity and become negligible at small strains, as the viscoelastic parameters of the complex modulus, phase angle, storage modulus and loss modulus are all defined under linear viscoelastic conditions LVE, it is essential that rheological measurements are conducted in the LVE region of response where, the relationship between stress and strain is only influenced by temperature and loading time (frequency).

The viscoelastic materials such as asphalt concrete that exhibit time dependent strain and instantaneous deformation can be modelled by spring “solid component” and dashpot” fluid components”

For the spring, the stress-strain relation is linear but for the dashpot the stress is linearly proportional to time derivative of strain.

The common models for viscoelastic behavior are:

- Maxwell model *spring and dashpot are in series*
- Kelvin Voigt model *spring and dashpot are in parallel*
- SLS model *combination of the two previous models*

For Maxwell model: the total stress: $\sigma_T = \sigma_s = \sigma_d$ and the total strain: $\epsilon_T = \epsilon_s + \epsilon_d$

In ABAQUS, we can only use Prony series to simulate a viscoelastic material and so, from Maxwell model we can define them; first by the calculation of strains: ϵ_s , ϵ_d , *instantaneous strain (spring) and time dependent strain(dashpot)* and simultaneously, we use the Laplace transformation to go from time domain to frequency domain and vice versa.

1.2 Prony Series

The constants of shear relaxation modulus can be derived from a Prony series for the nanoindentation results. This relaxation function can be constructed using the model of generalized Maxwell [33] as follow:

$$\epsilon_M = \epsilon_s^{(t)} + \epsilon_d^{(t)} \quad (1)$$

We have: $\sigma = \sigma_s = \sigma_d$

$$\sigma = E_1 \epsilon ; \sigma = \eta_1 \dot{\epsilon}$$

where: η_1 : the viscosity of the material

$$\hat{\sigma}_{(s)} = E_1 \hat{\epsilon}_s(s)$$

$$\hat{\sigma}_{(s)} = \eta_1 \hat{\epsilon}_d(s)$$

So:

$$\hat{\varepsilon}_M(s) = \hat{\varepsilon}_s(s) + \hat{\varepsilon}_d(s) \quad (2)$$

$$\hat{\varepsilon}_M(s) = \frac{\hat{\sigma}(s)}{E_1} + \frac{\hat{\sigma}(s)}{s\eta_1} \quad (3)$$

(3) times E_1s :

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E_1} + \frac{\sigma}{\eta_1} \quad (4)$$

We have stress relaxation response:

$$\varepsilon(t) = \varepsilon_0 \mu_0(t) \quad (5)$$

we know that:

$$\mu_0(t) \text{ is the Heaviside function } \begin{cases} \text{If: } t < 0 & \mu_0(t) = 0 \\ \text{If: } t \geq 0 & \mu_0(t) = 1 \end{cases}$$

$$\varepsilon(t) = \varepsilon_0 \mu_0(t) \text{ using Laplace transformation: } \hat{\varepsilon}_M(s) = \frac{\varepsilon_0}{s}$$

If we apply Laplace transform, equation (4) can be written as follow:

$$s\hat{\varepsilon}_M(s) = \frac{s\hat{\sigma}(s)}{E_1} + \frac{\hat{\sigma}(s)}{\eta_1} \quad (6)$$

$$s \frac{\varepsilon_0}{s} = \frac{\hat{\sigma}(s)}{E_1} s + \frac{\hat{\sigma}(s)}{\eta_1} \quad (7)$$

$$\varepsilon_0 = \left(\frac{s}{E_1} + \frac{1}{\eta_1} \right) \hat{\sigma}(s) \quad (8)$$

$$\varepsilon_0 = \left(\frac{\eta_1 s + E_1}{E_1 \eta_1} \right) \hat{\sigma}(s) \quad (9)$$

$$\hat{\sigma}(s) = \left(\frac{E_1 \eta_1}{\eta_1 s + E_1} \right) \varepsilon_0 \quad (10)$$

$$\hat{\sigma}(s) = \left(\frac{1}{s + \frac{E_1}{\eta_1}} \right) \varepsilon_0 E_1 \quad (11)$$

where $\tau_1 = \frac{E_1}{\eta_1}$ is the relaxation time. Apply Laplace transformation for equation (11):

$$\sigma(t) = \left(e^{-\frac{t}{\tau_1}} \right) \varepsilon_0 E_1 \quad (12)$$

$\sigma(t)$ is the stress relaxation response in Maxwell model.

Now a generalized Maxwell is a model that is just a set of Maxwell elements connected in parallel.

From equation (4) and (12), total stress is given by:

$$\sigma(t) = \varepsilon_0 E_\infty + \sum_{i=1}^n \left(e^{-\frac{t}{\tau_i}} \right) \varepsilon_0 E_i \quad (13)$$

$$\sigma(t) = \varepsilon_0 \left[E_\infty + \sum_{i=1}^n \left(e^{-\frac{t}{\tau_i}} \right) E_i \right] \quad (14)$$

Where:

$$E(t) = \left[E_\infty + \sum_{i=1}^n \left(e^{-\frac{t}{\tau_i}} \right) E_i \right] \quad (15)$$

At $t=0$, $E(0) = [E_\infty + \sum E_i]$

(15) Can be written:

$$E(t) = \left[E_\infty + \sum_{i=1}^n \left(e^{-\frac{t}{\tau_i}} \right) m_i E_0 \right] \quad (16)$$

We define: $m_i = \frac{E_i}{E_0}$

For isotropic material:

$$\begin{cases} G = \frac{E}{2(1-\nu)} \\ K = \frac{E}{3(1-2\nu)} \end{cases} \Rightarrow \begin{cases} G(t) = \frac{E(t)}{2(1-\nu)} \\ K(t) = \frac{E(t)}{3(1-2\nu)} \end{cases} \quad \begin{array}{l} \text{Shear modulus} \\ \text{Bulk modulus} \end{array}$$

$$G(t) = \left[G_\infty + \sum_{i=1}^n \left(e^{-\frac{t}{\tau_i}} \right) g_i G_0 \right] \quad (17)$$

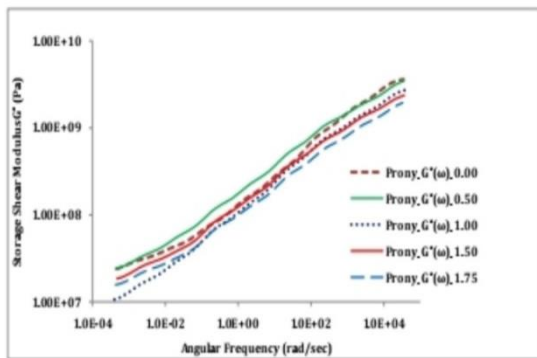
$$K(t) = \left[K_\infty + \sum_{i=1}^n \left(e^{-\frac{t}{\tau_i}} \right) k_i K_0 \right] \quad (18)$$

$$g_i = \frac{G_i}{G_0}, \quad k_i = \frac{K_i}{K_0}$$

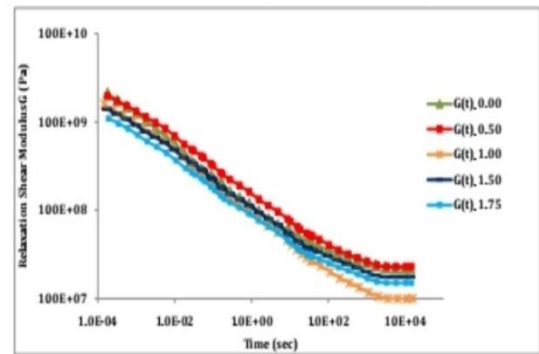
These three parameters will be asked for the modeling in ABAQUS: g_i , k_i , τ_i . The constants g_i and τ_i are the intrinsic properties of the material. The relaxation function or the storage function of a material makes possible to determine all of its viscoelastic properties.

1.3 Master Curves of Relaxation and Storage Shear Modulus.

To get viscoelastic behavior for our model, we used the storage and relaxation shear modulus master curves from the oscillatory sweep test of fine aggregates matrix as shown in Fig. 1. at different frequencies to obtain the Prony coefficients g_i and τ_i



(a)



(b)

Fig. 1 – Master curve of fine aggregate matrix (a) storage shear modulus (b) relaxation shear modulus [34]

2 Materials and Methods

In nanoindentation test, a load is placed on the indenter with a known loading rate that penetrates the surface of asphalt concrete using a Berkovich indenter tip (Fig. 2.) and the displacement is recorded to plot load-displacement curve.

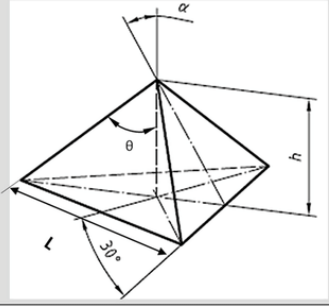
Feature	Size	Berkovich indenter
Semi-angle (α)	65.3 (Degree)	
Apex half angle (θ)	76.9 (Degree)	
Tip radius	200 (nm)	
Height (h)	1 (μm)	
Base length (L)	7.52 (μm)	

Fig. 2 – The geometry of the Berkovich indenter tip.

Berkovich tip is suitable for concrete and spherical tip for binder [2]. This is a reason why a Berkovich indenter tip is used in our study and the indentation load versus displacement data was analyzed using the Oliver-Pharr method [35] for the determination of Young's modulus E and hardness H using nanoindentation test [1-5] as shown in Fig. 3.

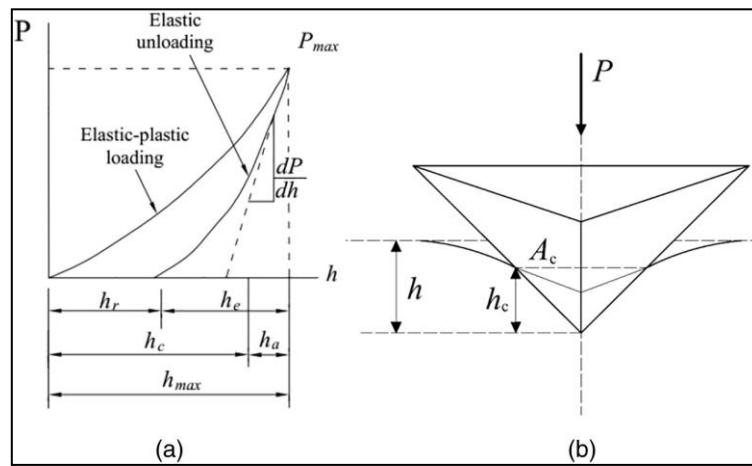


Fig. 3 – Nanoindentation parameters according to the Oliver-Pharr method.

Where:

h_c : vertical depth along which contact is made; h_e : elastic depth recovery during unloading; h_p : final depth after unloading. h_{max} : depth at maximum load and h_s : displacement of the surface at the perimeter of the contact.

The Oliver-Pharr method begins by mounting the data unloading part of the load-displacement curve:

$$P = \alpha(h - h_f)^m \quad (19)$$

where α and m are adjustment parameters; $M=1$ cylinder indenter; $M=1,5$ sphere and parabola of revolution indenter; $M=2$ cone indenter and E_r is the effective elastic modulus defined by:

$$\frac{1}{E_r} = (1 - \nu^2) \frac{1}{E} + (1 - \nu_i^2) \frac{1}{E_i} \quad (20)$$

ν : Poisson's ratio of the indented material; E : Young's modulus of the indented material; ν_i : Poisson's ratio of the indenter (0.07) and E_i : Young's modulus of the indenter (1141 GPa).

E_r can be defined as:

$$E_r = \frac{\pi}{2} \frac{1}{\beta} + \left(\frac{S}{\sqrt{24.56 h_c^2}} \right) \quad (21)$$

β : correction factor (1.034 for Berkovich indenter)

The hardness of the material is defined as:

$$H = \frac{P_{\max}}{A_c} \quad (22)$$

Where:

$P_{\max}$: the maximum load of the indentation.

A_c : the projected contact area of the indentation.

For a Berkovich Indenter:

$$A_c = 24.56 h_c^2 \quad (23)$$

The contact depth can be derived from the initial slope:

$$S = \frac{dP}{dh} \quad (24)$$

The stiffness S , gives information about the elastic modulus of the material, as follows:

$$S = \frac{dP}{dh} = 2E_r \sqrt{\frac{A_c}{\pi}} \quad (25)$$

The main intention of nanoindentation (NI) is to identify the mechanical properties of indented material. During NI measurements, a Berkovich indenter tip penetrates the asphalt concrete sample surface with an indentation load P and the depth h is recorded as a function of time. Commonly, each dash consists of: loading, unloading and holding phase Fig. 4.

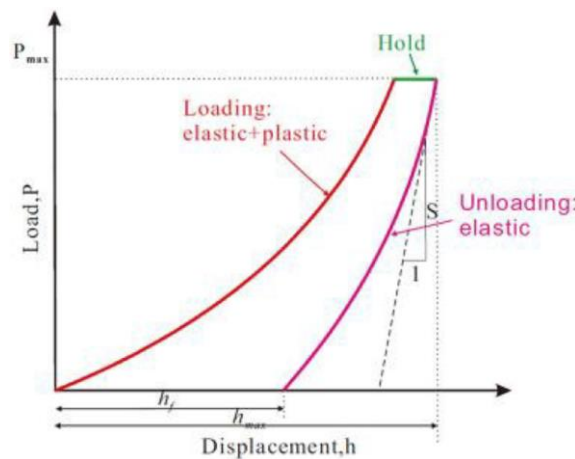


Fig. 4 – Schematic illustration of nanoindentation loading-displacement curve “with holding time” [36]

It can also consist only of two steps: loading and unloading, in this case no time is needed for holding the load on the specimen, as shown in Fig. 5.

The loading time may vary as long as unloading or holding time.

The holding time allow the accurate calculation of creep in each step or phase.

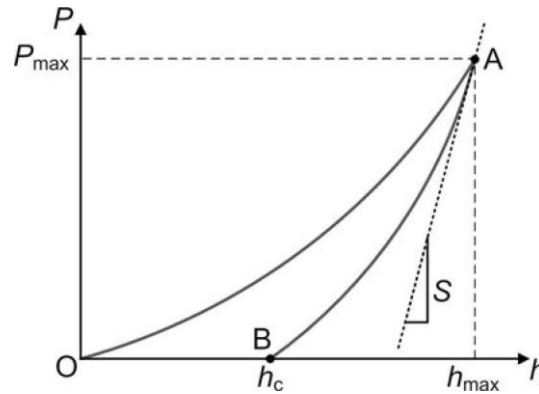


Fig. 5 – Schematic illustration of nanoindentation loading-displacement curve “without holding time”.

2.1 Finite Element Modelling.

Software can be used for a wide analyses range of solid mechanic problems, creep, fluids. Heat transfer. ...etc

The prediction of the response of asphalt concrete in long term is difficult in laboratories so the use of calculations codes is highly recommended.

For the simulation of nanoindentation test with a Berkovich indenter on linear viscoelastic bitumen, a finite element *FE* model has been developed using ABAQUS 6.13 software [37].

This model is linearly viscoelastic composed of two domains: elastic one which needs the value of Young's modulus E and Poisson ratio ν and the second one is viscoelastic and can be identified from relaxation modulus master's curve, which is transformed internally into generalized Maxwell model, basically; the formulation of this law is based on a discretization in Prony series and so they characterized the constitutive equation as a function of time which gives a link between the stress and the strain of a linear viscoelastic material [38].

To summarize, the simulation test consists of pushing a Berkovich indenter tip for 10s into the asphalt concrete sample and unloading phase of 10s according to the experimental procedure.

Loads applied in this study are in the range of micronewton (μN), dimensions in micrometer (μm) and elastic modulus in Giga Pascal (GPa).

For the FE software modeling, the required properties of asphalt concrete are:

- A consideration of an instantaneous Young's modulus E as an elastic part (spring), Poisson's ratio ν , and volumetric mass density ρ .

Since AC behaves like isotropic material at intermediate temperatures, the Poisson's ratio was assumed to be 0.35

- a viscoelastic Prony series in Time domain, g_i , k_i , τ_i

The sample of asphalt concrete is a piece of $(10 \times 10 \times 5) \text{ mm}^3$ considered as a 3D deformable part.

The selected geometry for the indenter was Berkovich, in that indentations, the contact area increases with time.

The Berkovich indenter tip shape is three sided pyramid, made of diamond and considered as a 3D discrete rigid part with a reference point.

For the history of loading, the indenter tip penetrates the AC sample for 10 s of loading gradually by a loading rate of $250 \mu\text{N/s}$ till a maximum of $F = 2500 \mu\text{N}$, then an unloading of 10 s by the same loading rate as illustrated in Fig. 6 without recording any time of holding.

Since our model is a contact problem between the sample of asphalt concrete and the surface of Berkovich tip, and to maintain geometric self similitaty to very small depths. we presume that the surface of the sample is smooth and flat However, a coefficient of friction equal to 0.1 is set between the surface of the asphalt concrete sample and the indenter tip surface, this

with a boundary conditions supposing that the base of the asphalt concrete is fixed and the indenter is moving only in vertical axis.

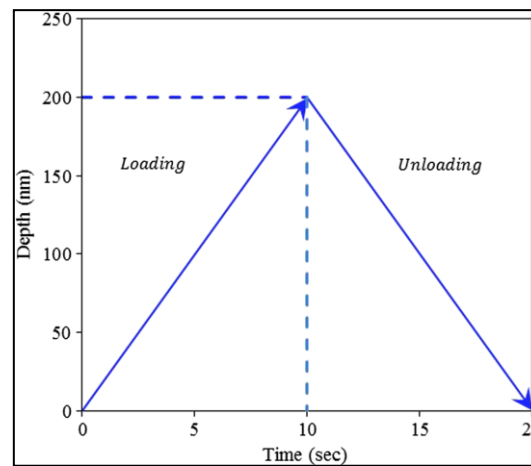


Fig. 6 – Time-depth controlled loading-unloading history.

The two parts asphalt concrete and Berkovich indenter were defined as materials with specific properties and the Prony series parameters have been inserted in the software to take into account the viscoelasticity of the asphalt concrete, then The two parts were associated and meshed to get refined results as illustrated in Fig. 7.

The total time of the test is 20 s, considered as one step including time loading of 10s and time unloading of 10s.

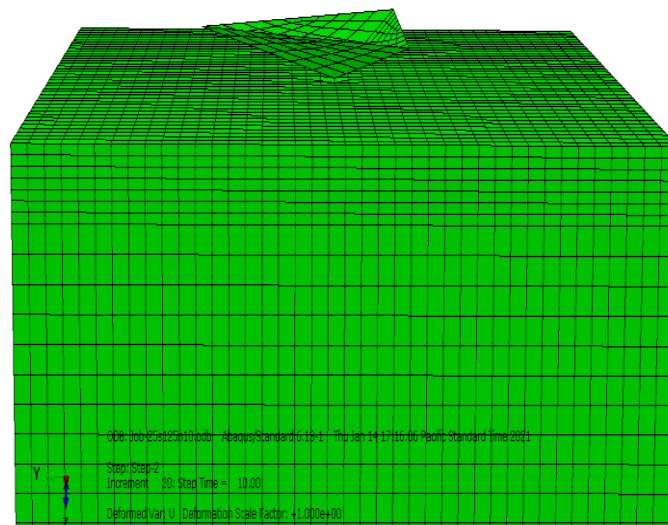


Fig. 7 – Finite element meshing of the assembly.

3 Results and Discussions

Aggregates make the mostly component in asphalt concrete; the fact that asphalt concrete is a multi-phase material; then the aggregates should be rounded by a ductile thin film of binder to fill as much as possible the air voids and avoid primarily cracking especially under repetitive loadings.

The Young's modulus E and the Poisson ratio ν of the elastic part and the Prony series parameters of the viscoelastic part are listed in table 1.

The number of elements of the Prony series is adopted to define the corresponding relaxation time interval τ_i from the relaxation modulus master's curve in the frequency domain to finally determine the prony coefficients: g_i , τ_i before their introduction in ABAQUS software to finally be able to simulate the viscoelastic behavior of the asphalt concrete.

Table 1 – Elastic properties and Prony coefficients.

Elastic properties			Prony coefficients		
E(GPa)	ν	t (s)	G_0 (GPa)	g_i	τ_i (s)
60.9	0.35	0,01	9,9	0,075	0,01
		1		0,01	0,1
		100		0,035	0,1
		1000		0,31	0,001
				0,051	0,01
				0,01	0,05
				0,507	0,001

The curves loading-displacement got from the experimental work [39] of an elastic aggregates and viscoelastic matrix are presented in Fig 8 to compare them with the load-displacement curve of our model.

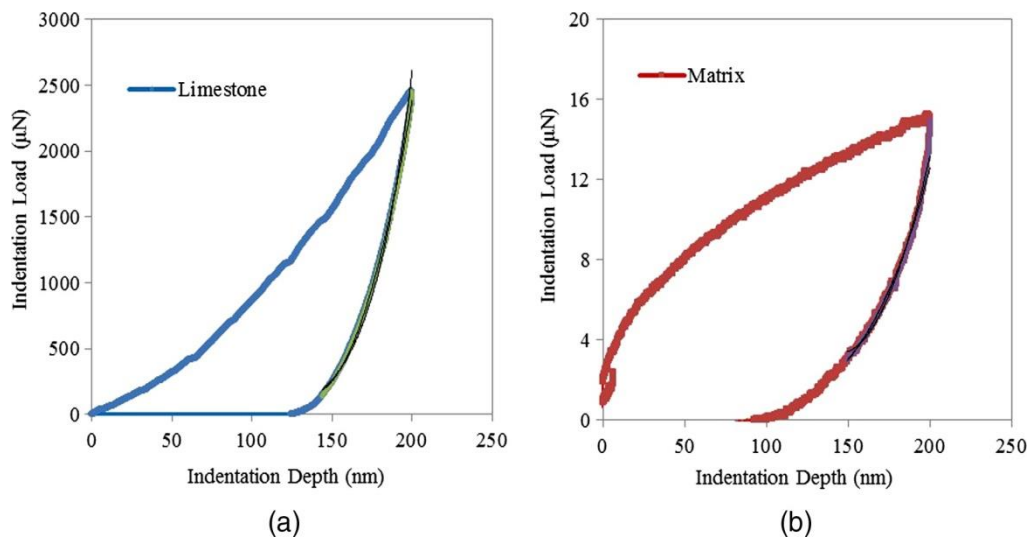
**Fig. 8 – Load-displacement curves obtained from (a) the aggregate phase; (b) the matrix phase [39]**

Table 2 lists for comparison the elastic modulus E and hardness H values of the different phases of an asphalt concrete from experimentation nanoindentation test Fig. 8 separately and the micromechanical model of AC using finite elements FE modeling respectively in nanoindentation test.

After a simulation of a nanoindentation on asphalt concrete AC using a Berkovich indenter tip with the software ABAQUS 6.13 (Fig.9) it can be seen from Fig. 10. That in the loading step; the depth of indentation in asphalt concrete increases to reach the value of 200 nm against a maximum force value of 2500 μN however, during unloading time; the indentation depth decreases to finally reach the value of 46 nm (a recovery depth).

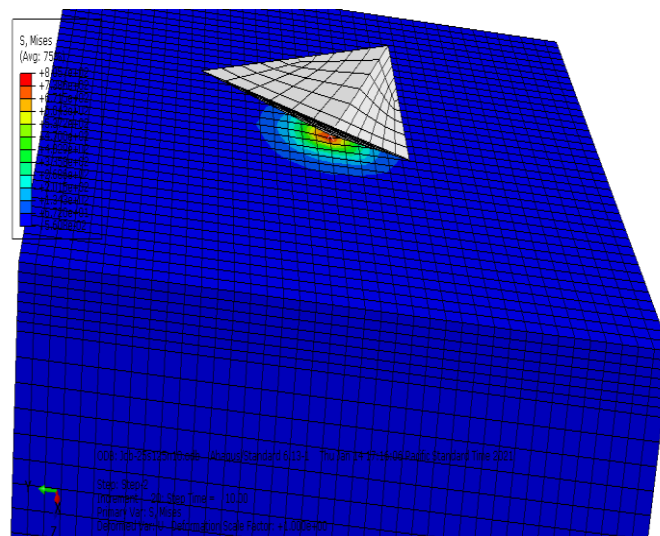
The much of the depth has been recovered (200nm-46nm) so the material is more elastic for this depth of recovery, in unloading, The force displacement curve probe the mechanical behavior, by loading and unloading many times we will get the same result : it is reversible elastic deformation

Table 2- Nanoindentation test results as average values of each material phase indents comparing to micromechanical model

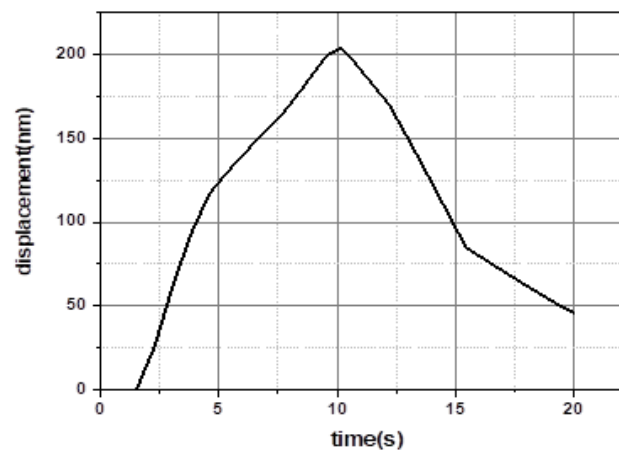
Material phase	Young's modulus (GPa)	Hardness (GPa)
Aggregates	67.9*	2.7*
Interface transition zone	22*	1.3*
Matrix	0.5*	0.03*
Current study	31,5	1,4

*: [31]

While for the area below the unloading curve starting from the final depth to point zero presents the plastic domain or the plastic energy where the depth in asphalt concrete will not recover to its original shape and the deformation is permanent and takes closely the indenter tip shape “three sided pyramid with a depth of ($h=46\text{nm}$)

**Fig. 9 – Vizualisation of model response in nanoindentation test in ABAQUS 6.13**

Comparing the curve form obtained from the simulation, a reasonable agreement is observed with limestone indentation curve got from experimentation in the loading phase however, in the unloading phase the curve form of AC is closer to the matrix curve form with a residual displacement ($h>0$).

**Fig. 10 – Time-displacement curve of asphalt concrete under a nanoindentation**

This is due to the viscoelastic behavior of fine matrix and the elastic behavior of aggregates which is shown in Fig. 11. Explaining that the final displacement after unloading in an elastic material can be a zero ($h=0$).

The same for the result's values obtained of young's modulus and hardness, giving that the young 's modulus is about 31.5 GPa, close to between interphase 22 GPa and aggregates young modulus 67.9 GPa.

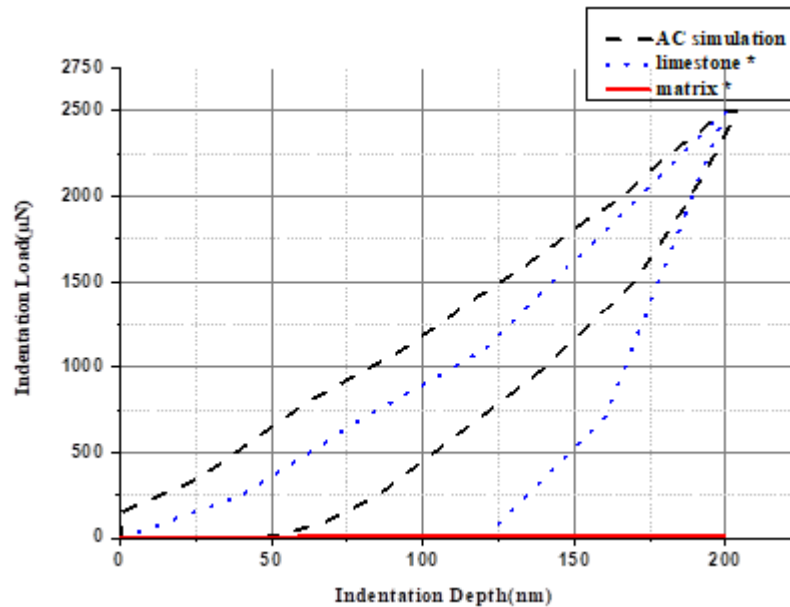


Fig. 11. Comparison of load-displacement curves of AC obtained from experimentation and simulation. * [39]

Clearly the hardness obtained from nanoindentation simulation of AC as a viscoelastic material $H=1,4$ is between that of interface transition zone $H=1,3$ GPa and aggregates value $H=2,7$ GPa.

So Asphalt concrete has low modular properties. we have an elastic return thanks to the return of the Young's modulus however, for the plastic part; the dislocation allows the plasticity, In the plastic behavior we have dislocations which are movement of the axes of the atoms that will generate internal shear where the orientation of the crystal planes in asphalt, are not perfectly perpendicular to the sections on which the load is applied.

Finally, the model identified can allowed us to predict the behavior of asphalt concrete regarding its elastic modulus representing the aggregates phase and the viscoelastic paste under medium temperatures and a loading rate.

4 Conclusion

This paper presented the simulation FEM of asphalt concrete mechanical response using a Berkovich nanoindentation on ABAQUS 6.13 by considering its viscoelastic properties including basically the Prony series, and measured the elastic modulus and hardness of AC and compared them to those of different phases obtained from experimentation nanoindentation test.

From the results of the current study, the following conclusions can be made:

- This study determines the Young modulus “E” and the hardness “H” values which are 31, 5 GPa; 1,4 GPa respectively, they are closer to experimental Interface transition zone ITZ phase properties. The value of Young's modulus found is between that of the aggregates and that of the interface. In consequence; considering asphalt concrete as a viscoelastic material shows that it is a soft material especially under high temperatures and frequencies; it is complex to predict its response because of the weaker interatomic bonds. it could be viscous or plastic presenting a huge plastic deformation caused by atoms bonds breaking at dislocations. deformation is permanent and remains after load is removed and this must be taken in account while calculations of bituminous structures. For viscoelasticity there will be time delayed displacements, this is why the higher is Young's modulus taken in calculation of the elastic part, the stiffer is asphalt concrete.

- The asphalt concrete nanoindentation simulation curve and aggregates experimental nanoindentation curve forms are closer; it seems that AC exhibits an elastic response at nanoscale and medium temperatures more than a viscoelastic behavior, as we should select a stiff material that will ensure that elastic deformation remains small for large loads.
- This study also introduces the Prony series in a finite element modeling, so they contribute to better represent a viscoelastic material that dissipates energy while elastic ones store it.
- Berkovich nanoindentation simulation is practical and is an economical way to predict and study the different properties and responses of materials but in condition to suppose that we use sharp Berkovich tips, something not applied always in experimental nanoindentation because the tip geometry start to change when the tip start to get rounded then the contact mechanism at small depths are changing from perfectly sharp elastic plastic contact. and there is a change in basic contact mechanism as we go from large depths to small depths.

Therefore, this study should be taken in account for further researches of nanoindentation test on the different phases of bitumen materials separately and using different indenter tips conducted in laboratory or on micromechanical models to best evaluate their mechanical behavior and properties.

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