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Stiffness Modulus Value Estimated by Ultrasonic Testing on asphalt concrete

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Dedication

This study is dedicated to my beloved parents, who have been my source of inspiration and gave me strength when i thought of giving up, who continually provide their moral, spiritual, emotional, and financial support.

To our brothers, and sisters, relatives, mentor, friends, and classmates who shared their words of advice and encouragement to finish this study.

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d	*Aggregate Lower Diameter, in mm*
D	*Aggregate Upper Diameter, in mm*
AC	*Asphalt Concretes*
HMA	*Hot Mix Asphalt*
TL_{ext}	*External Binder Content*
$\sum$	*The Specific Surface Area, in* m^2/kg
G	*the proportion of aggregate particles greater than 6.3 mm*
S	*the proportion of aggregate particles included between 6.3 mm and 0,135 mm*
s	*the proportion of aggregate particles between 0,135 mm and 0.063 mm*
f	*the proportion of aggregate particles less than 0,063 mm*
α	*Correction coefficient relative to the density of aggregates*
ρ_g	*The real density of aggregates in (g/cc)*
ρ	*bulk density of asphalt cocnrete in (g/cc)*
φ	*phase angle, in degrees (°)*
σ	*The stress*
σ_0	*the peak stress amplitude*
ω	*angular frequency of the harmonic excitation in hertz (Hz);*
t	*time, in seconds (s);*
δ_σ	*stress phase shift*
ε	*The strain*
ε_0	*peak strain amplitude*
δ_ε	*strain phase shift*
NDT	*Non-Destructive Testing*
E*	*The complex modulus,*
E_1	*the storage or elastic modulus*
E_2	*the loss or viscous modulus*
γ	*is the form factor as a function of specimen size and form*
μ	*is the mass factor which is a function of the mass of the specimen*
Ø	*the diameter of a cylindrical specimen, in (mm)*
v	*the Poisson's ratio;*
z	*the displacement, in (mm);*
h	*the mean thickness of the specimen, in (mm);*
l_0	*the length of the measurement area l0, in (mm);*
L	*the span length between outer supports in bending tests, in (mm);*
Sm	*the stiffness value, in (MPa);*
Θ	*the test temperature, in degrees (°C);*
UT	*The Ultrasonic testing*
V_p	*The velocity of p-wave in (us)*

M	*Constrained modulus*
V_s	*Velocity of shear waves.in (us)*
G	*Shear modulus in (MPa)*
V_r	*Velocity of Rayleigh waves in (us)*
$\boldsymbol{\lambda}$	*Wavelength*
f	*Frequency in Hz*
M_{DE}	*the Micro-Deval coefficient*
L_A	*Los Angeles coefficient*
SE	*Sand Equivalent value*
M.V.A	*Bulk density, in (g/cc)*
M.V.R	*Reel density, in (g/cc)*
K	*the richness modulus*
S	*Stability, in (kN)*
P	*Plastic flow in (mm)*
Q	*Marshall Quotient in (kN/mm)*
Eu	*the elastic modulus by ultrasonic test in (MPa)*
FFT	*the Fast Fourier Transform*
α_p	*wave attenuation factor*

Summary

GENERAL INTRODUCTION

Thanks to the development and recent discoveries in civil engineering and geo-building materials, we have managed to achieve new tests and technologies that has and still help us in our needs to understand the behaviour of construction materials in order to develop better buildings and roads.

New tests have been discovered to deal with one of these construction materials known as the Asphalt Concrete (AC), especially since it is one of the heaviest materials used in pavement, thanks to the many features it has, such as flexibility, and being easily built, there's also parameters which gives us a good average road life. At some point the researches put three categories for the test which are empiric's test, simulations test and determination for this type of materials, beside it's still developing until this day, both the new tests and the technics used. in the case of asphalt concrete including various characterisations ,one to be highlighted regarding the viscoelastic behaviour and stiffness and with taking in mind the expensive tests in large scales and very time consuming especially when it comes to using it in the field and times and repeatability.

And since the stiffness value remains one of the biggest parameters to evaluate this material, and because there are a lot of tests that used to evaluate and measure its value, new direction came up which is based on the ultrasound as a tools, even if it's not effective yet to measure the value, it could at least evaluate and give us an approach value of the stiffness. This is one of direction where several researches started looking on it since it is new, quick, repeatable and less expensive methods to determine the stiffness.

The ultrasonic (US) is based on the acoustic system, this system relies on the generation of ultrasonic acoustic pulses at a certain point using a transmitter device, after which they are subsequently received by a sensor that is placed at a different position. The system is called ultrasonic when the frequency of the acoustically generated pulse is above 20 kHz. Which could be realised using two methods.

First method is called "Impact Resonance Test" or IR, which rely on applying compression waves and the phenomenon of resonance, and the second method which is the one used in this research is called "direct measurement of flying time". We prefer this method because it is easy to apply in terms of principle and apparatus, and the one most commonly used to control the concrete quality in field.

This study came as a research to continue in this direction to attempt an estimated value of the stiffness modulus using an ultrasonic wave propagation in asphalt concrete, by measuring the flying time of ultrasonic wave in the cylindrical bituminous specimens, and using some formula's we could calculate an ultrasound elastic modulus, and this results are compared to the stiffness measured mechanical technics which is IT-CY.

And from this we could answer two questions, first is could the ultrasound be used to determine the stiffness directly? And the second one is the case considering the ultrasound as a non-determination test, and could we make a correlation between mechanical and ultrasonic properties?

And to answer that we present this research project in form of seven chapters, which are:

First chapter is Generality on Asphalt Concrete and Formulation Study: and it talk about the definition of the materials that used in our research (AC) asphalt concrete and the formula in general.

Second chapter is Viscoelastic Behaviour Characterization: which talk about the characteristics and the viscoelasticity of the material and the dynamic behaviour and the mechanicals test methods used in general.

Third chapter is Ultrasonic Testing: the basics of the test and the physics laws of wave propagation acoustics, test methods, and the researches in general.

Fourth chapter is Material Characteristics: the different testing results on the materials gravel sand and hydrocarbons binders.

Fifth chapter is Formula & Performance; talk about the results tests of formulation study and the mixture Marshall Method which we used to find the best mix.

Sixth chapter Characterization of the Viscoelastic Behaviour Using NDT Test: the results of the stiffness modulus in both mechanicals and ultrasound tests.

And the seven chapter Results and Correlation**:** the methods of determine the Eu ultrasonic modulus and the correlation between it and the Sm stiffness modulus by dynamic tests.

I. GENERALITIES ON ASPHALT CONCRETE AND FORMULATION STUDY

I. GENERALITIES ON ASPHALT CONCRETE AND FORMULATION STUDY

I.1.INTRODUCTION

In this chapter, we will define the asphalt concrete. First, we briefly present some generalities about asphalt and its components (hydrocarbon binder & aggregates) with the appropriate characteristics of each one. Then, we study the asphalt formulation by considering the following parameters: binder content, binder hardness and aggregate size... etc.

Each one has an influence on the compactness, the implementation, stiffness and the durability ...etc., as well as the main characterization tests according to the standards to obtain a mix according to the desired choice.

I.2.DEFINITION OF ASPHALT CONCRETE

Asphalt concrete is a composite material consisting of a mixture of granular (gravel, sand, fines) and a hydrocarbon binder (bitumen, possibly additives); the aggregates ensure the rigid structure of the asphalt and the bitumen provides cohesion and is responsible for the viscous character (1).

Each of these two components are defined by their rheological and mechanical characteristics. Knowing these characteristics makes it possible to obtain a good performance of the bituminous mixture (1).

I.2.1. Hydrocarbon binders

Hydrocarbon binders play an important role in modern road technology; it have been known and used for a long time, the adhesion and impermeability properties of natural bitumen and asphalt have been known since the emergence of civilization (1). The word "binder" can be define as a substance that serves to bring together in a sustainable manner, generally solid particles; the adjective "hydrocarbon" refers to the assembly of carbon atoms and hydrogen (1).

The substance added to the solid particles develops adhesion and cohesion forces within a mixture, ensuring a certain rigidity and resistance to tensile deformation, compressive resistance and shear strength (1). The hydrocarbon binders can be divided into three types: natural binders, tars and bitumen.

a) Natural binders

They can find in the natural state like natural bitumen or asphalt rock, often in combination with mineral materials. And they have been known and used since very ancient times. (1)

Continuous: this is porous rock, usually calcareous, which is deeply impregnated with hydrocarbon binder. It is known as asphaltic rock and, once crushed.

Dispersed: this is natural bitumen in which the minerals take the form of a powder dispersed in the binder. The mineral content is highly variable (2).

b) Tars

Tars are produced by the pyrogenic of vegetable materials such as lignite, peat or wood in an air-free environment. Coal is the main source; in which case the correct term to apply is "coal tar" (2).

c) Bitumen

Petroleum Bitumen, normally called “Bitumen” or “Asphalt” is produced by refining crude oil. Used as a binder in road-building products, it is a very viscous, black or dark brown material. The crude oil is pumped from storage tanks, where it is kept at about 60°C, through a heat exchanger system where its temperature is increased (3).

When applying heat on bitumen it is viscous, but it turns solid once it cools down. Therefore, Bitumen operates as the binder/glue for pieces of the aggregate (3).

I.2.2. Aggregates

Aggregate is a collective term for the mineral materials such as sand, gravel and crushed stone that are used with a binding medium (such as water, bitumen, Portland cement, lime, etc.) to form compound materials (such as asphalt concrete and Portland cement concrete) (4).

I.2.3.The roles of aggregates in asphalt

An aggregate’s mineral composition largely determines the physical characteristics, and how it behaves as a pavement material. Therefore, when selecting an aggregate source, knowledge of the quarry rock’s mineral properties can provide an excellent clue as to the suitability of the resulting aggregate (4).

Aggregate surface chemistry can determine how well an asphalt binder will adhere to an aggregate surface. Poor adherence, commonly referred to as stripping, this can affect the workability and the performance of bituminous mixtures (4).

Depending on the traffic number, the pavement can become slippery. This aspect is the subject of laboratory and road research to determine the surface textures and mineralogical compositions of granular materials in order to obtain rough bituminous mixtures that meet the required conditions. The aggregates used in the production of bituminous asphalt mixes must therefore meet quality criteria and characteristics specific to each use (1).

I.2.4. Aggregate classification

Aggregates are classified into different aggregate classes according to the size of the elements.

Designation of aggregate in terms of lower diameter “d” and upper diameter “D” sieve sizes expressed as “d/D”, the size is expressed in millimeters. It is accepted that an Aggregates fraction may contain up to 15% higher excess materials (5). The following granular classes can be distinguished:

Fines 0/D	with	$D \leq 0{,}080$ mm
Sands 0/D	with	$D \leq 6{,}3$mm
Coarse d/D	with	$d \geq 2$ mm et $D \leq 31{,}5$ mm
Gravel 0/D	with	$6{,}3$mm< $D \leq 80$ mm
Pebbles d/D	with	$d \geq 20$ mm et $D \leq 80$ mm

Fillers is the particle size fraction of an aggregate which passes the 0,063 mm sieve. (5)

The mixture of the filler with the binder is the parameter that gives the asphalt its stability, and the thickness of the mixture film is characterized by a criterion called the richness modulus.
The cleanliness of the filler, in particular its low clay content, is essential to ensure good mechanical performance.

I.3.CLASSIFICATION OF ASPHALT MIXES

Asphalt mixes are materials resulting from a mixture of aggregates and a hydrocarbon binder. The binder-aggregate mixture obtained consists of three phases (4):

- The solid phase: represented by the granular skeleton;
- The viscous phase: represented by the contribution of the binder that ensures cohesion;
- The gas phase: represented by the percentage of air voids contained in the mixture.

Changing techniques in both civil engineering and industry have led to the development of the types of Asphalt mixes, each of which must meet precise specifications. Types of mixtures for asphalt concretes AC according to EN 13108-1 (6):

- AC-BBSG (Asphalt concrete for surface and binder course)
- AC-BBME (High modulus Asphalt concrete for surface and binder course)
- AC-BBM (Thin layer Asphalt concrete)
- AC-BBA (Asphalt concrete for surface and binder course for airfield)
- AC-GB (Graves-Bitume),
- AC-EME (High modulus Asphalt concrete for base course).

And in the same way, for the other types of materials:

- BBTM (very thin layer asphalt concrete)
- PA-BBDr (Porous Asphalt – Béton Bitumineux Drainant)

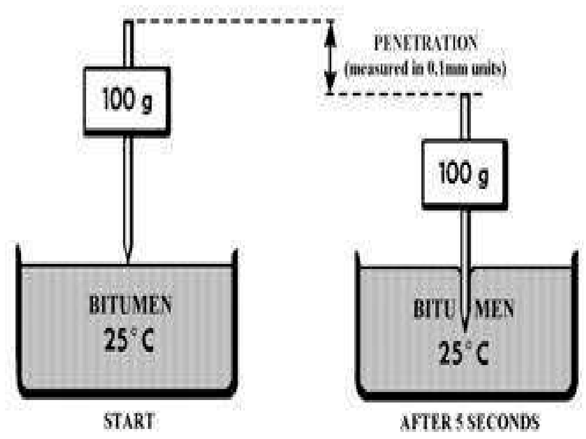
I.4.PRINCIPAL CHARACTERISTICS OF BITUMEN

I.4.1. Penetration Test

Test method for determining the consistency of bitumen and bituminous binders, the word penetration is expressed as the distance in tenths of a millimeter that a standard needle will penetrate vertically into a sample of the material under specified conditions of temperature, load and loading duration.

The penetration of a standard needle into a conditioned test sample shall be measured. For penetrations up to approximately 330 × 0.1 mm the operating parameters shall be a test temperature of 25 °C, an applied load of 100 g, and a loading duration of 5 seconds (7).

Penetration is one of the two fundamental characteristics that define a bitumen, where is defined by their penetration class (penetrability expressed in 1/10th of a millimeter) whose name corresponds to its lower and upper limits, for example a bitumen of class 40/50. The harder a bitumen is, the lower its penetration value (7).



a) Principe of Penetration test. **b) Penetration equipment**

Figure.1. *Penetration test (8) (9).*

I.4.2. Softening point (Ring and ball method)

This test using ring – ball method to determine the softening point of bitumen and bituminous binders. (10)

We have two horizontal discs of bituminous binder, cast in shouldered brass rings shall be heated at a controlled rate in a liquid bath while each supports a steel ball. The softening point shall be reported as the mean of the temperatures at which the two discs soften enough to allow each ball, enveloped in bituminous binder, to fall a distance of (25,0 ± 0,4) mm (10).

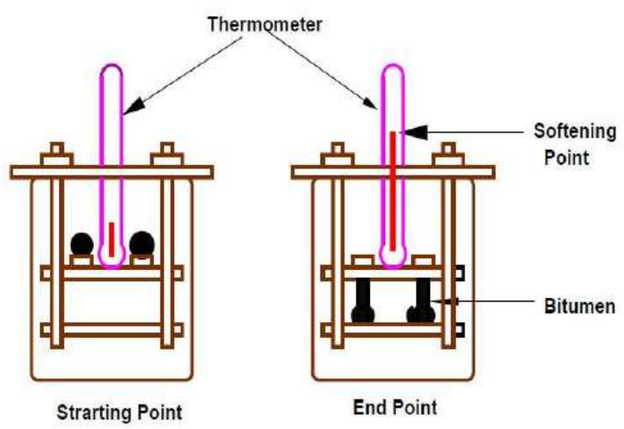


Figure.I.2. Test illustrations Ring and Ball.

Figure.I.3. Equipment Ring and Ball.

Softening points between 28 °C and 80 °C: use freshly boiled distilled or deionized water. Use a thermometer with subdivisions of 0.2 °C. The initial bath temperature shall be (5±1) °C.

Characteristics and Bitumen Grades according to the standards:

Table.I.1. Paving Grade Bitumen Specification as BS EN 12591

CARACTERISTIQUES		METHODE	AZALT®					
			20/30	35/50	40/50	50/70	70/100	100/150
Pénétrabilité à 25 °C	dmm	EN 1426	20 - 30	35 - 50	40 - 50	50 - 70	70 - 100	100 - 150
Point de ramollissement bille et anneau	°C	EN 1427	55 - 63	50 - 58	50 - 58	46 - 54	43 - 51	39 - 47
Point d'éclair (Cleveland)	°C	EN ISO2592	≥ 240	≥ 240	≥ 240	≥ 230	≥ 230	≥ 230
Solubilité	%	EN 12592	≥ 99,0	≥ 99,0	≥ 99,0	≥ 99,0	≥ 99,0	≥ 99,0
Teneur en paraffine	%	EN 12606-2	≤ 4,5	≤ 4,5	≤ 4,5	≤ 4,5	≤ 4,5	≤ 4,5
APRES VIEILLISSEMENT RTFOT		EN 12607-1						
Variation de masse	%	-	≤ 0,5	≤ 0,5	≤ 0,5	≤ 0,5	≤ 0,8	≤ 0,8
Pénétrabilité restante	%	EN 1426	≥ 55	≥ 53	≥ 53	≥ 50	≥ 46	≥ 43
Point de ramollissement bille et anneau	°C	EN 1427	≥ 57	≥ 52	≥ 52	≥ 48	≥ 45	≥ 41
Augmentation du point de ramollissement	°C	EN 1427	≤ 8	≤ 8	≤ 8	≤ 9	≤ 9	≤ 10

I.5.CHARACTERISTICS OF AGGREGATE

The properties of aggregates used in Hot Mixture Asphalt (HMA) are very important to the performance of HMA in pavements. Many of the current aggregate test methods were developed to empirically characterize aggregates (11).

I.5.1. Tests for Geometrical Properties of Aggregates (NF EN 933)

- Sieve analysis
- Flakiness index

I.5.2. Tests for Mechanical and Physical Properties of Aggregates (NF EN 1097)

- Resistance to attrition (micro-Deval)
- Resistance to fragmentation (Los Angeles)
- Bleu Methylene test
- Sand equivalent test.

I.6. DETERMINATION OF THE MINERAL MIXTURE

From the average curves of the granular classes, the mineral mixture curve will be calculated, the percentage of passers-by at a sieve for the mixture curve is the sum of the percentages of passers-by at the same sieve of the component curves weighted by the corresponding proportions (4).

The grain size curve of the calculated mineral mixture should then be drawn in a graph and compared to the specification range.

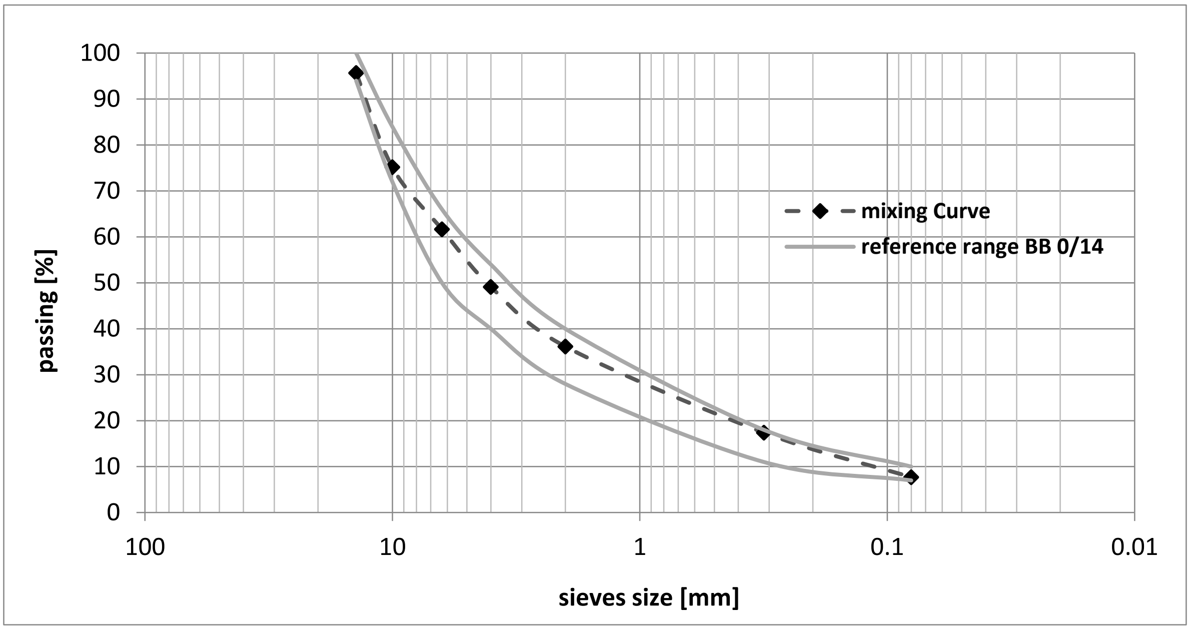


Figure.I.4. An example of Granulometric curve of the mixture 0/14.

The granulometric composition of the mixture must be, according to the type of asphalt, within the ranges given in the following table:

Table.I.2. An example Value of a BBME 0/14

		LIMITS	
SIEVES	PASSING	MIN	MAX
14	96	94	100
10	75	72	84
6.3	62	50	66
4	49	40	54
2	36	28	40
0.315	17	11	18
0.08	8	7	10

I.6.1. Binder content

Binder content is TL_{ext}, which represents the ratio of the binder mass to the dry aggregate mass, expressed as an external percentage. For this reason, the binder's contents of the examples given in the present guide are usually expressed in terms of, TL_{ext} (6).

$$TL_{ext}. = 100 \times \frac{Bitumen\ mass}{Dry\ aggregate\ mass}$$

I.6.2. Richness modulus K

The richness modulus K described by Duriez in 1950, is a value proportional to the conventional thickness of the hydrocarbon binder film coating the aggregate. K is independent of the density of the granular mix; it is correlated with external binder content via the following equation (6):

$$TL_{ext} = K \times \alpha \sqrt[5]{\Sigma}$$

Where Σ is the specific surface area, expressed in square meters per kilogram, determined by the relation:

$$100.\Sigma = 0{,}25\,G + 2{,}3\,S + 12\,s + 150\,f$$

With :

- G the proportion of aggregate particles greater than 6.3 mm
- S the proportion of aggregate particles included between 6.3 mm and 0,250 mm
- s the proportion of aggregate particles between 0,250 mm and 0.063 mm
- f the proportion of aggregate particles less than 0,063 mm

And α is a correction coefficient relative to the density of aggregates given by the formula:

$$\alpha = 2.65\ /\rho_G,$$

Where ρ_G being the reel density of aggregates in grams per cubic centimeter.

II.VISCOELASTIC BEHAVIOR CHARACTERIZATION

II.VISCOELASTIC BEHAVIOR CHARACTERIZATION

II.1. INTRODUCTION

This chapter discusses the complex modulus approach to the viscoelastic behavior characterization of asphalt concrete, which is capable of producing mechanical properties that can be used as input in analytical models. Also including a survey of experimental and theoretical concepts that support the complex modulus approach.

II.2. VISCOELASTICITY

Viscoelasticity is a property of materials that exhibit time-dependent strain. Perfectly viscous materials exhibit stress proportional to strain rate, while perfectly elastic materials feature stress proportional to strain, the proportionality constant being the elastic (or Young’s) modulus (12).

Viscoelastic materials feature intermediate characteristics between purely elastic and purely viscous behavior, they show both behaviors when undergoing deformation (12).

Whether the behavior of a material is closer to purely elastic or purely viscous depends mainly on temperature and the excitation frequency (strain rate), but it may also depend significantly on test and environmental conditions such as the pre-load, dynamic load, environmental humidity, …etc. (12).

II.3. RELATIONSHIP BETWEEN STRESS AND STRAIN

For a linear viscoelastic material submitted to a sinusoidal load wave form at time, t, where applying a stress results in a Strain that has a phase angle $\boldsymbol{\varphi}$, with respect to the stress. (13).

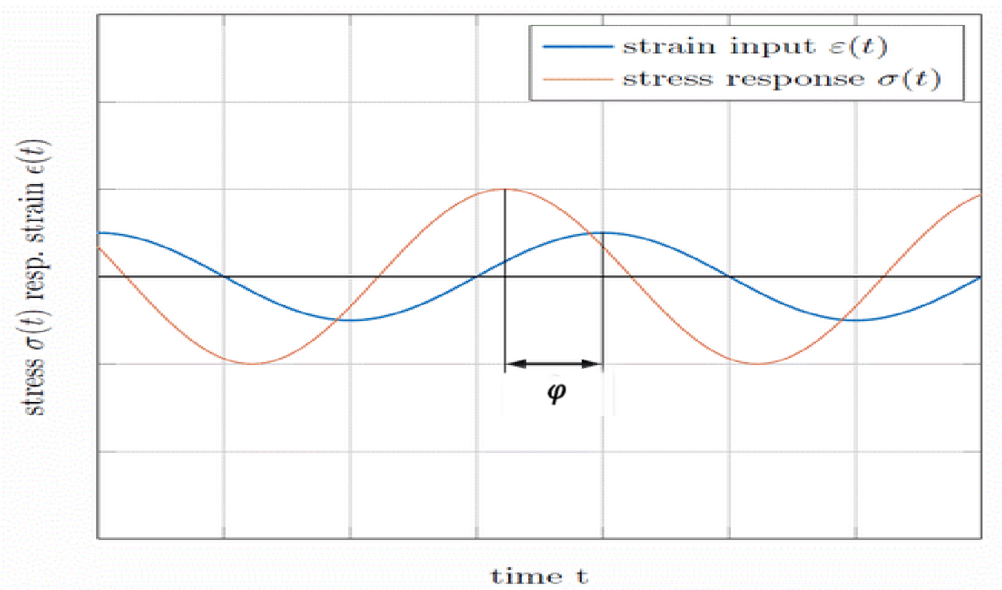


Figure II.1. Viscoelastic response of a material with phase angle φ between Stress and Strain (14).

a. Stress (Contrainte)

The stress applied to a material is the force per unit area applied to the material. The maximum stress a material can stand before it breaks is called the breaking stress or ultimate tensile stress (15).

Resulting stress response will be sinusoidal if the applied strain is small enough so that the tissue can be approximated as linearly viscoelastic (Ferry, 1980; Fung, 1993). (16).

The sinusoidal stress output may differ in phase from the applied strain depending on the viscoelastic properties of the tissue. (16) :

$$\sigma = \sigma_\circ sin(\omega t + \delta_\sigma) \text{ …. Equation II.1}$$

b. Strain (deformation)

The ratio of extension to original length is called strain it has no units as it is a ratio of two lengths measured in meters. (15).

Cyclic strain and observing the cyclic stress response. For a given sinusoidal strain input with the form. (16):

$$\varepsilon = \varepsilon_0 sin(\omega t + \delta_\varepsilon), \text{ …. Equation II.2}$$

Where $\sigma_\circ$ is the stress amplitude, $\varepsilon_\circ$ is strain amplitude and ω is the angular velocity related to the frequency.

II.4.THE DYNAMIC BEHAVIOR

The dynamic behavior of linear viscoelastic materials can be described by the complex modulus approach In particular, the parameters commonly utilized for the characterization of the viscoelastic properties are the two components of the complex (or dynamic) tensile modulus.(12)

II.4.1 dynamic modulus tests

Dynamic modulus tests are type of Non-Destructive Testing **(**NDT), by apply a repeated axial cyclic load of fixed magnitude and cycle duration to a test specimen, Test specimens can be tested at different temperatures and different loading frequencies, to measures a specimen's stress-strain relationship viscoelastic materials this relationship is defined by a complex number called the "complex modulus (17), The tests are performed on compacted bituminous material under a sinusoidal loading or other controlled loading, using different types of specimens and supports (13).

II.4.2.the complex modulus E*

The complex modulus test is one of the several laboratory procedures that have been examined above. There is general agreement among researchers about its effectiveness in evaluating the fundamental stress-strain response of asphalt concrete mixes. The modulus is a complex number, which defines the relationship between the stress and strain for a linear viscoelastic material subjected to sinusoidal loading. The real part of the complex modulus is a measure of the material elasticity and the imaginary part is a measure of the viscosity (18).

The dynamic modulus test in asphalt concrete can be advantageous because it can measure also a specimen's phase angle ($\boldsymbol{\varphi}$). The complex modulus, $\boldsymbol{E*}$, is actually the summation of two components: 1st is the storage or elastic modulus $\boldsymbol{E_1}$ component and 2nd the loss or viscous modulus $\boldsymbol{E_2}$. It is an indicator of the viscous properties of the material being evaluated (17).

The complex modulus **E***is characterised by a pair of two. This pair can be expressed in two ways: the real component E_1 and the imaginary component E_2 (13).

$$E_1 = |E^*| \times cos\ (\varphi) \text{ ... . Equation II.3.}$$

$$E_2 = |E^*| \times sin\ (\varphi) \text{ ... . Equation II.4.}$$

$$\mathrm{E}^* = |\mathrm{E}^*| \times (\cos(\varphi) + \mathrm{i} \times \sin(\varphi)) \text{ ... . Equation II.5.}$$

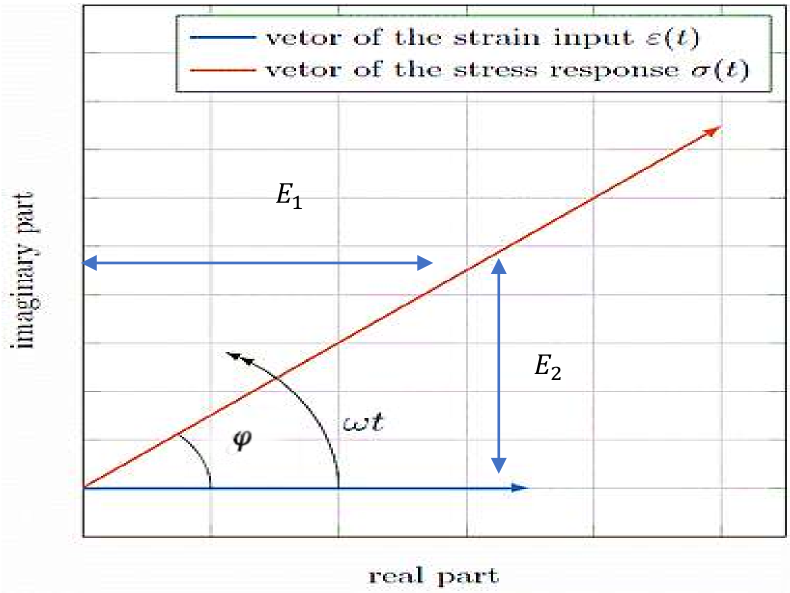


Figure II.2. Relationship between the dynamic tensile modulus E, the real component, E_1, imaginary component, E_2, the phase angle, φ (14).

II.4.3. Stiffness modulus (|E*| or Sm)

Stiffness of hot mix asphalt (HMA) is a fundamental material property, which can be measured using various test equipment and test methods. Traditionally, empirical mix design methods have strongly relied on the belief that the stiffer/stronger the mix, the better the performance against permanent deformation (19).

It can be determined from the absolute value of the complex modulus **|E*|** or the value of the secant modulus and the phase angle φ (13).

$$|\mathrm{E}^*| = \sqrt{{E_1}^2 + {E_2}^2} \text{ ... . Equation II.6.}$$

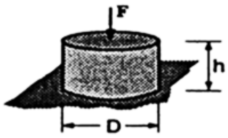
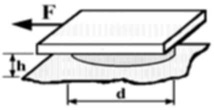
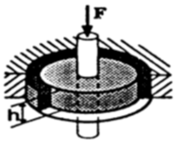
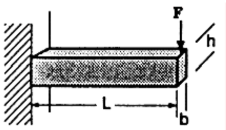
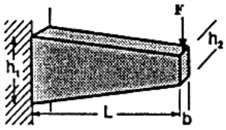
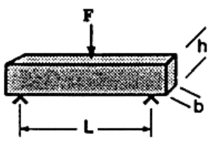
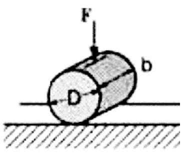
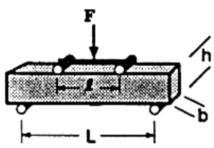
$$\mathrm{E}_1 = \gamma \times \left(\frac{F}{z} \times \cos(\varphi) + \frac{\mu}{10^3} \times \omega^2\right) \text{ ... . Equation II.7.}$$

$$\mathrm{E}_2 = \gamma \times \left(\frac{F}{z} \times \sin(\varphi)\right) \text{ ... . Equation II.8.}$$

γ is the form factor as a function of specimen size and form;

μ is the mass factor which is a function of the mass of the specimen, M, in grams (g) and the mass of the movable parts, m, in grams (g) that influence the resultant force by their inertial effects.

Table II.1. Form and mass factors for different specimens and loading conditions (13).

		Type of loading	Test Geometry	form Factor γ	mass Factor μ	References
Homogeneous tests	CO-CY	Tension compression		$\frac{h}{\pi D^2}$	$\frac{M}{2}+m$	[Charif, 1991] [Doubbaneh, 1995]
	SH-CR	Constant height shearing		$\frac{h}{\pi D^2}$	–	[Kennedy et al, 1994]
	SH-BE	Shear bending Load applied by an axial rod		$\frac{\ln\left(\frac{d}{D}\right)}{2\pi h}$	–	[Gübler, 1990]
Non Homogeneous tests	2PB-PR	2 Point bending		$\frac{4L^3}{bh^3}$	$\frac{M}{4}+m$	[Francken et all.1994]
	2PB-TR	2 Point bending		$\frac{12L^3}{b(h_1-h_2)^3}\Big[\left(2-\frac{h_2}{2h_1}\right)\frac{h_2}{h_1}-\frac{3}{2} - ln\frac{h_2}{h_1}$	$0.135M+m^3$	[Huet.1992 Chauvin.1990]
	3PB-PR	3 Point bending		$\frac{24L^3}{\pi^3 bh^3}$	$\frac{M+m}{2}$	[Myre.1996]
	IT-CY	Inndirect tensile diamteric compresion		$\frac{1}{b}(\nu+0.27)$	–	[Brown .1993 Kennedy et al.1994]
	4PB-PR	4 Point bending		$\frac{2L^3-3LI^2+I^3}{8bh^3}$	$R(x)\left(\frac{M}{4}+\frac{m}{R(A)}\right)$	[Pronk.1996]

II.4.4. Phase angle (φ)

It's the lag between peak stress and peak recoverable strain. The complex modulus, E*, for purely elastic materials, the phase angle is zero and then the complex modulus reduces to the Young's modulus. This happens when bituminous materials are at very low temperatures and the energy lost as heat per cycle is null. For an ideal viscous material, stress and strain are 90º out of phase, Where 0° (purely elastic) < φ < 90° (purely viscous) (20).

$$\varphi = arctan\left(\frac{E_1}{E_2}\right) \text{ … …. Equation II.9.}$$

φ the phase angle, in degrees (°);

E_1 the real component of the complex modulus;

E_2 the imaginary component of the complex modulus

II.4.5. Secant modulus

Relationship between stress and strain at the loading time, t, for a material subjected to controlled strain rate loading (13).

$$E(t) = \frac{\sigma(t)}{\varepsilon(t)} \dots \dots \text{ Equation II.10}$$

Where: σ (t): stress

ε (t): strain

t: time

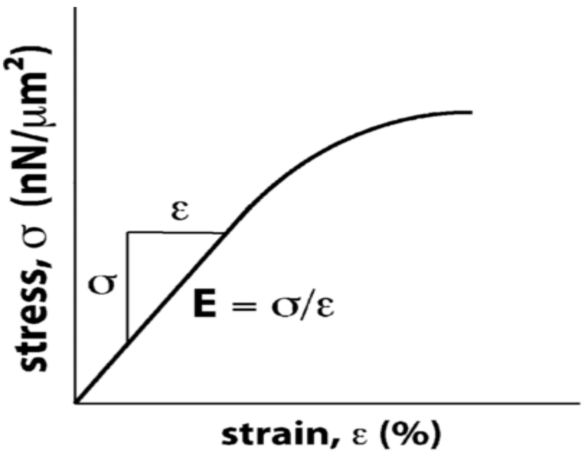


Figure II.3. Secant modulus (21).

II.4.6. Poisson's ratio (ν)

When a material is compressed in one direction, it usually tends to expand in the other two directions perpendicular to the direction of compression. (22)

The Poisson ratio is the ratio of the fraction (or percent) of expansion divided by the fraction (or percent) of compression, for small values of these changes. (22)

Ratio of the strain in the direction perpendicular to the applied force to the strain in the direction of the applied force. (22)

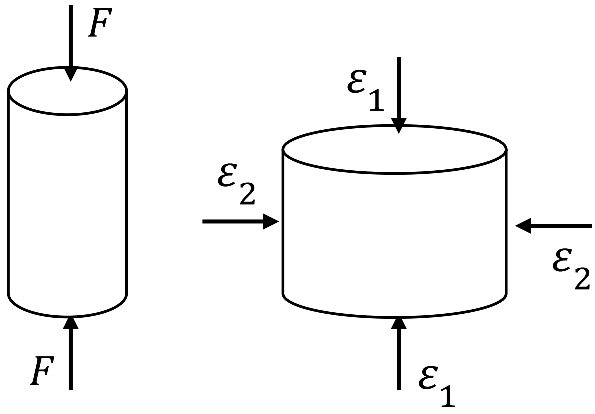


Figure II.4. Poisson's Ratio in an elastic material (22).

II.4.7. Test methods

There is many methods for characterizing the stiffness of bituminous mixtures as it show in down here (13):

a. Bending tests:

2PB-TR: test applying two-point bending to trapezoidal specimens.

2PB-PR: test applying two-point bending to prismatic specimens.

3PB-PR: test applying three-point bending to prismatic specimens.

4PB-PR: test applying four-point bending to prismatic specimens.

b. Indirect tensile test:

IT-CY: test applying indirect tension to cylindrical specimens.

c. Direct uniaxial tests:

DTC-CY: test applying direct tension-compression to cylindrical specimens.

DT-CY: test applying direct tension to cylindrical specimens.

DT-PR: test applying direct tension to prismatic specimens.

In our research we used: IT-CY: test methods applying indirect tension to cylindrical specimens to measure the stiffness modulus for the mechanicals tests

II.5. PERFORMED TESTS

II.5.1. IT-CY TEST (EN 12697-26: Annex C)

Test applying indirect tension to cylindrical specimens of various diameters and thickness, manufactured in the laboratory or cored from a road layer, this similarity was stressed by Brown et al. (Brown and Cooper in 1993), who were among the first researchers to work on the test protocol of cyclic indirect tension, with controlled strain rate, on which the EN 12697-26 Annex C, These authors preferred to use the concept of the Elastic Stiffness Modulus (13).

A- Equipment

Thermometer and/or thermocouples and/or platinum resistance sensors, of appropriate range, which shall be capable of measuring to ± 0,1 °C for determining the temperature of the specimen and the storage and test environment (13).

1- Pneumatic load actuator

2- Steel load frame

3- Load cell

4- Upper loading platen

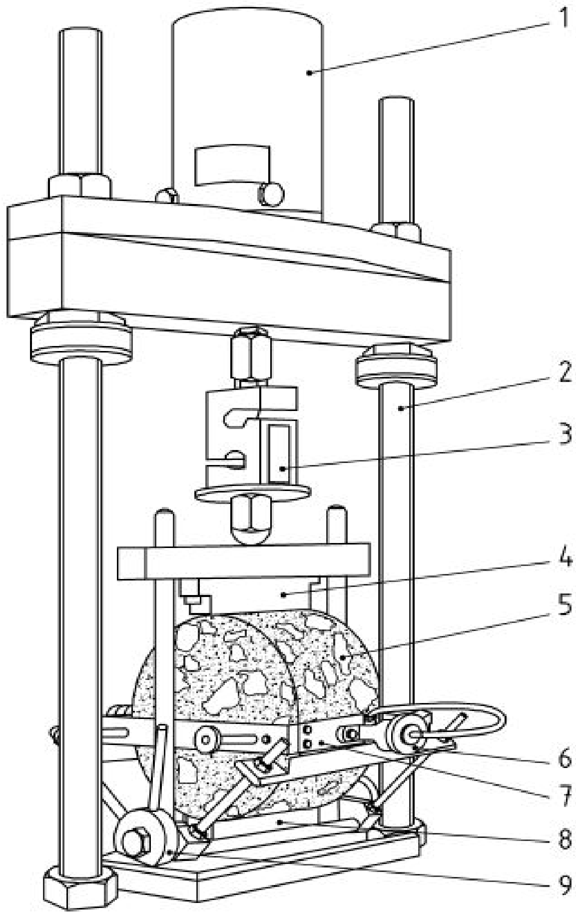
5- Test specimen

6- LVDT adjuster

7- LVDT mounting frame

8- Lower loading platen

9- LVDT alignment jig



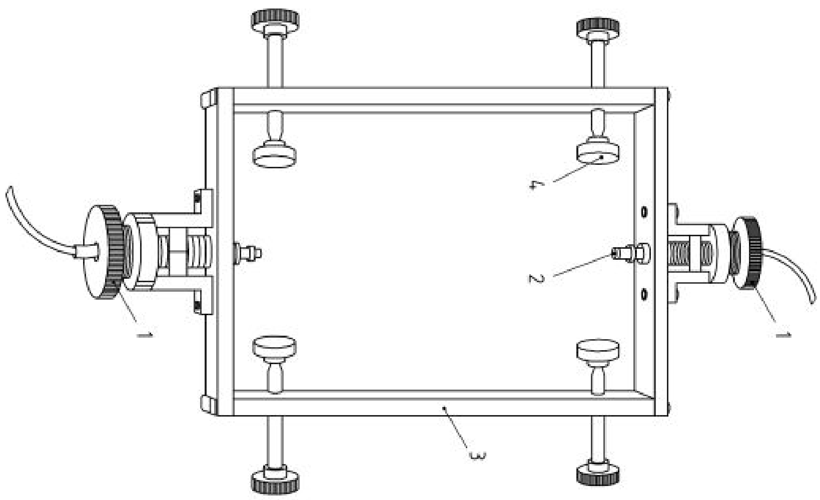


Figure II.5. Example of the test equipment [EN 12697-26].

B- Specimen preparation

Cylindrical specimens shall have a thickness between 30 mm and 75 mm and a nominal diameter of 80 mm, 100 mm, 120 mm, 150 mm or 200 mm. Both dimensions shall be chosen relative to the nominal maximum aggregate size of the mixture.

In our case the specimens are 100 mm diameter and various thickness between 40 to 60 mm.

Test samples can be cored from a compacted pavement layer, or from laboratory compacted slabs, or may be prepared in suitable laboratory molds.

In our case the specimens are prepared by gyratory compactor.

Using a suitable marker, a diameter shall be drawn on one flat face of the specimen. A second diameter shall be drawn at (90 ± 10) ° to the first. Both diameters shall be labelled appropriately.

Figure II.6. One of the specimens tested.

C- Storage conditions

If the storage period is less than 4 days, the storage temperature shall not exceed 25 °C. For storage over 4 days, the temperature shall not exceed 5 °C. The storage temperatures and time shall be recorded. Specimens shall be stored on a flat face on a horizontal surface and shall not be stacked.

In our case the test realized after 1 days, the specimen demoulded and conserved at ambient temperature.

D- Conditioning and test temperature

The specimen shall be placed in a controlled temperature environment and monitored until it has attained the test temperature

The temperature of the specimen shall be determined by resistance sensors attached to the curved surface and the center of the dummy specimen.

The mean of these temperatures shall be recorded as the actual temperature of the specimen, Θ_1. The specimen shall then be moved to the point of test and the test performed.

E- Conditioning load pulses

At least 10 conditioning pulses shall be applied in order to enable the equipment to adjust the load magnitude and duration to give the specified horizontal diametral deformation and time.

F- Calculation of the measured stiffness modulus

Using the measurements from the 5 load pulses, the measured stiffness modulus shall be determined for each load pulse using following formula.

$$S_m = \frac{F\times(\nu+0.27)}{(z\times h)} \text{.... Equation II.11.}$$

S_m is the measured stiffness modulus, expressed in megapascals (MPa);

F is the peak value of the applied vertical load, expressed in Newton (N);

z is the amplitude of the horizontal deformation obtained during the load cycle, expressed in millimeters (mm);

h is the mean thickness of the specimen, expressed in millimeters (mm)

ν is the Poisson's ratio.

If the Poisson’s ratio is not determined, a value of [0.35] shall be assumed for all temperatures.

The measured stiffness modulus shall be adjusted to a load area factor of [0.60] using following formula.

S'_m is the stiffness modulus, expressed in megapascals (MPa), adjusted to a load area factor of 0,60;

$$S'_m = S_m \times (1 - 0.322 \times (\log S_m)\neg 1.82)(0.60 \times k) \text{.... Equation II.12.}$$

k is the measured load area factor;

- If the mean value of the stiffness modulus from this test shall be within +10 % or –20 % of the mean value recorded for the first test, the mean for the two tests shall be calculated and recorded as the stiffness modulus of the specimen.
- If the difference between the two values is greater than that specified above, the results shall be rejected.

III. ULTRASONIC TESTING

III. ULTRASONIC TESTING

III.1. INTRODUCTION

This chapter present the basics of the ultrasonic testing and the different methods that used in the testing with the different types of waves propagation.

The Ultrasonic testing (UT) has been practiced for many decades. Initial rapid developments in instrumentation spurred by the technological advances from the 1950's continue today. Through the 1980's and continuing through the present, computers have provided technicians with smaller and more rugged instruments with greater capabilities (23).

III.2. BASIC PRINCIPLES

Ultrasonic Testing uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more. To illustrate the general inspection principle, a typical pulse/echo inspection configuration as illustrated below will be used (24).

A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. In the applet below, the reflected signal strength is displayed versus the time from signal generation to when an echo was received. Signal travel time can be directly related to the distance that the signal traveled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained (24).

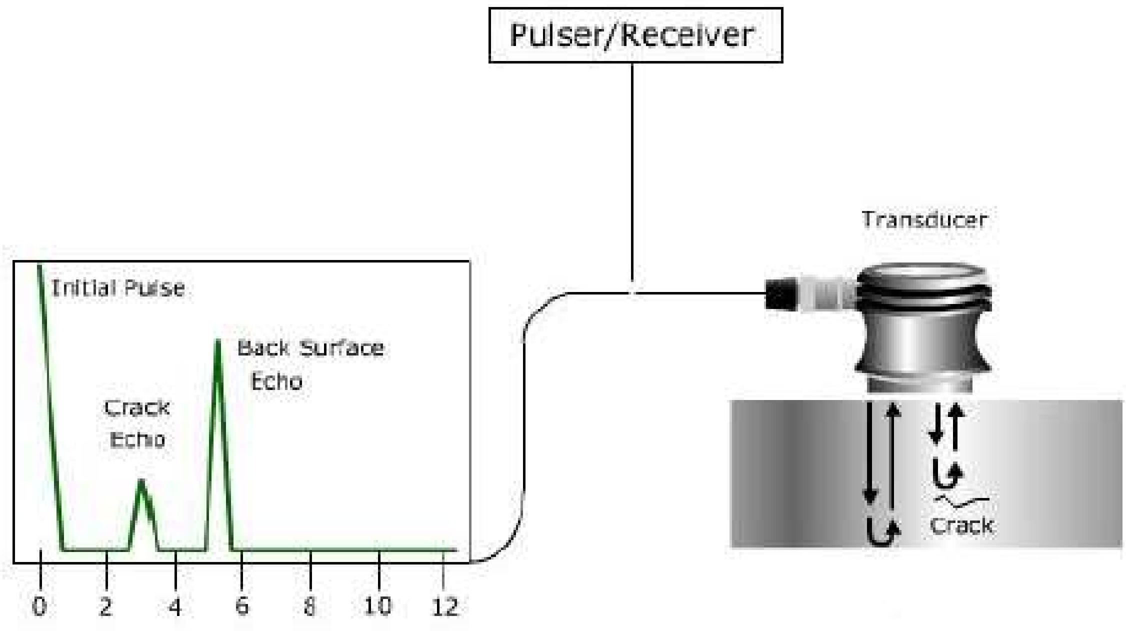


Figure III.1. Basic of ultrasonic transmission in material

III.3. PHYSICS OF ULTRASOUND

III.3.1. Wave propagation

Ultrasonic testing is based on time-varying deformations or vibrations in materials, which is generally referred to as acoustics. (25). Acoustics is the branch of physics that deals with the study of all mechanical waves in gases, liquids, and solids including topics such as vibration, sound, ultrasound and infrasound.

In solids, sound waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing. The particle movement responsible for the propagation of longitudinal and shear waves is illustrated below (25).

The table below summarizes many, but not all, of the wave modes possible in solids (26):

Table III.1. Wave modes used in ultrasonic

Wave Types in Solids	Particle Vibrations
Longitudinal	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface – Rayleigh	Elliptical orbit - symmetrical mode
Plate Wave – Lamb	Component perpendicular to surface (extensional wave)
Plate Wave – Love	Parallel to plane layer, perpendicular to wave direction

III.3.2. Modes of sound wave propagation

Though there are many different modes of wave propagation, these are the four types of waves that are used in NDT:

A) Longitudinal waves (P-waves)

Primary waves are compressional waves that are longitudinal in nature. P waves are pressure waves that travel faster than other waves, hence the name "Primary". These waves can travel through any type of material, including fluids (27).

$V_p = \frac{M}{\rho}$ …. Equation III.1. $\quad$ $M = \frac{(1-v)\times E}{(1+v)-(1-2v)}$ …..Equation III.2

- V_p The velocity of p-wave
- M Constrained modulus
- ρ Mass density
- v Poisson's ratio
- E Young's modulus

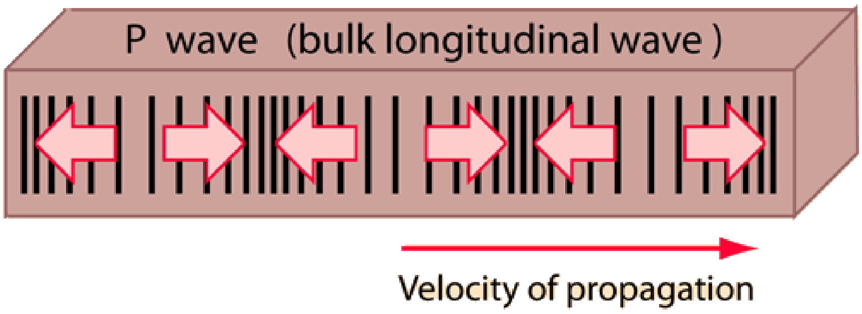


Figure III.2. Propagation of P-waves through material (28).

B) Transverse (S-waves)

Secondary waves are shear waves that are transverse in nature. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves (27).

$$V_s = \sqrt{\frac{G}{\rho}} \ldots\ldots Equation\ III.3.$$

- V_s Velocity of shear waves.
- G Shear modulus.

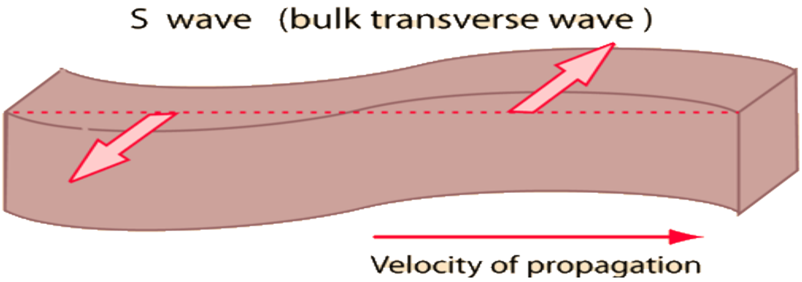


Figure III.3. Propagation of S-waves through material (28).

C) Surface - Rayleigh

Surface waves travel the surface of a relatively thick solid material penetrating to a depth of one wavelength. Surface waves combine both a longitudinal and transverse motion to create an elliptic orbit motion as shown in the image (26).

$$V_r = f \times L_r \ldots \text{Equation III.4.}$$

- V_r Velocity of Rayleigh waves
- f Frequency
- L_r Rayleigh wavelength

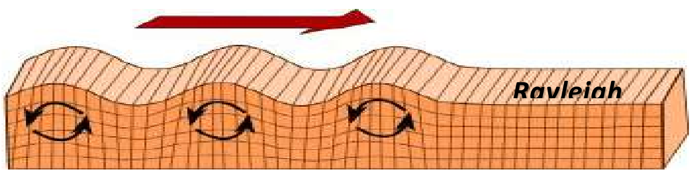


Figure III.4. Rayleigh waves

D) Plate Wave – Lamb

Plate waves are similar to surface waves except they can only be generated in materials a few wavelengths thick. Lamb waves are the most commonly used plate waves in NDT. Lamb waves are complex vibrational waves that propagate parallel to the test surface throughout the thickness of the material. Propagation of Lamb waves depends on the density and the elastic material properties of a component (26).

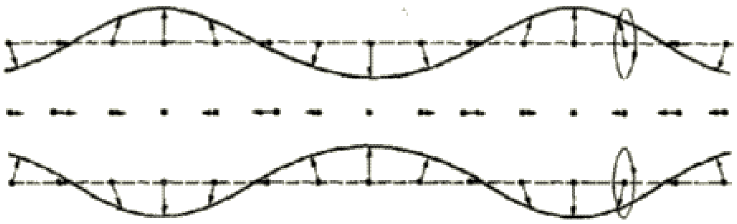


Figure III.5. Plate waves.

III.3.3. Properties of acoustic plane wave

Among the properties of waves propagating in isotropic solid materials are wavelength, frequency, and velocity. The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave. This relationship is shown by the following equation (28):

$$\lambda = \frac{V}{f} \ldots\ldots Equation\ III.5.$$

- $\boldsymbol{\lambda}$: wavelength
- f: frequency
- V: velocity

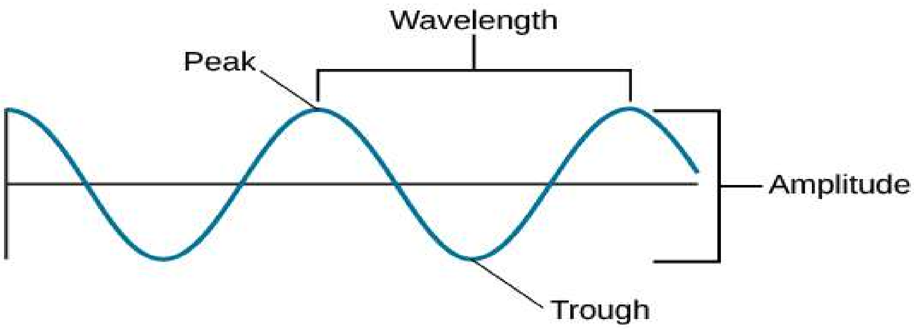


Figure III.6. Waves propagation properties.

For cyclical processes, such as waves, frequency is defined as a number of cycles per unit time, the unit of frequency is the hertz (Hz), named after the German physicist Heinrich Hertz. One hertz means that an event repeats once per second (29).

The Speed of a wave is unaffected by changes in the Frequency.

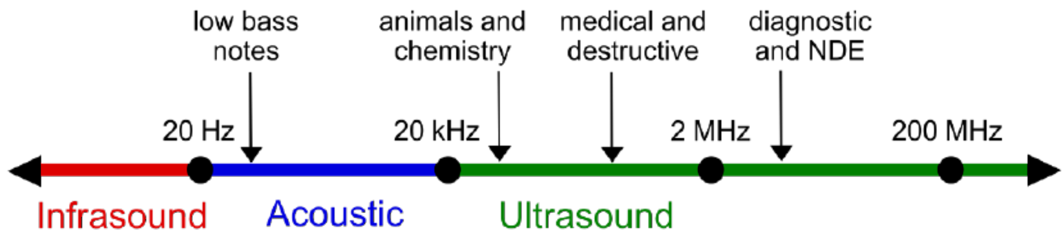


Figure III.7. Range of the frequency spectrum for sound waves (30)

III.4. ULTRASONIC TEST AND METHODS

The ultrasonic tests methods in the civil engineering domain are still focusing on elastic materials (concert), so by using one of these methods it will help us apply it on the viscoelastic materials.

A pulse of longitudinal vibrations is produced by an electro-acoustical transducer held in contact with one surface of the concrete under test. After traversing a known path length in the concrete, the pulse of vibrations is converted into an electrical signal by a second transducer and electronic timing circuits enable the transit time of the pulse to be measured (31).

The concept behind the technology in general is measuring the travel time of acoustic waves in a medium, and correlating them to the elastic properties and density of the material (31).

Several researchers and engineers have studied the use of ultrasonic testing of concrete like: pulse velocity determination, concrete quality assessment, establishing homogeneity and uniformity of concrete, measurement of surface crack depth, prediction of compressive strength of concrete (31).

and these are the different methods following the standard (EN 12504-4):

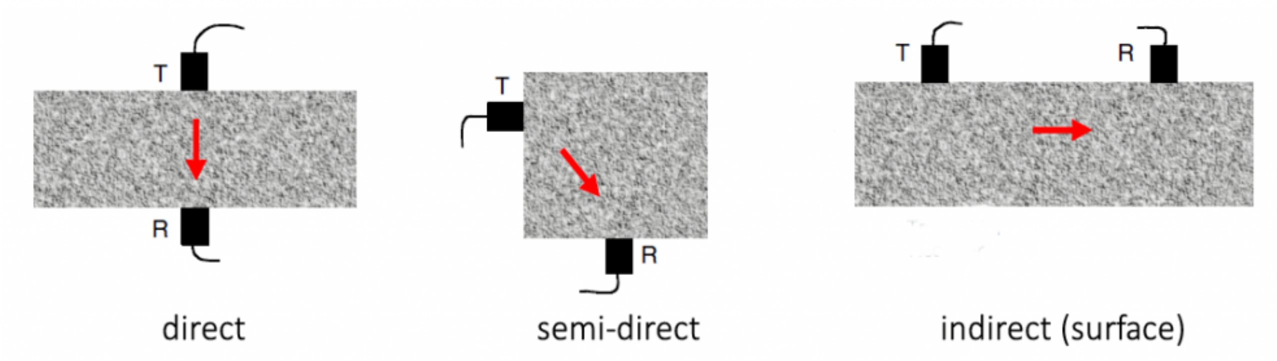


Figure III.8. Transducer positioning (32).

- **R** is the receiver transducer
- **T** is the transmitter transducer

a) Direct transmission

Direct transmission, the path length is the shortest distance between the transducers. The accuracy of measurement of the path length shall be recorded to an accuracy of ± 1 %

b) Semi-direct transmission

Semi-direct transmission, it is generally found to be sufficiently accurate to take the path length as the distance measured from center to center of the transducer faces. The accuracy of path length is dependent upon the size of the transducer compared with the center-to-center distance. Where it is necessary to place the transducers on opposite faces but not directly, opposite each other such arrangement shall be regarded as a semi-direct transmission

c) Indirect transmission

The path length is not measured, but a series of measurements is made with the transducers at different distances apart

The indirect transmission arrangement is the least sensitive and should be used, when only one face of the concrete is accessible, or when the quality of the surface concrete relative to the overall quality is of interest

III.4.1. Equipment

1- Pundit Touchscreen

2- 2 Transducers 54 KHz

3- Calibration Rod (Reference bloc)

4- Couplant

Figure III.9. Ultrasonic tests Equipment. (32)

III.4.2. Measurement

The through-transmission pulse velocities in mortar were measured with a commercially available meter (C372N High performance ultrasonic tester, Matest Company) and a set of associated transducer pairs (54 kHz). Shows the position of the transducers in the direct method. In this device, it allows to measure the ultrasonic velocity inside the material since it gives the travel time of the ultrasonic wave (µs) through the sample. The transition time was recorded and the ultrasonic pulse velocities (m/s) was calculated as follows (31):

$$V = \frac{L}{T} \text{ ... Equation III.6.}$$

- V Velocity (m/s),
- L Length of the straight-wave-path through the specimen, which corresponds to the distance between transducer faces.
- T transit time, (s)

III.4.3. Transit time

Time taken for an ultrasonic pulse to travel from the transmitting transducer to the receiving transducer, passing through the interposed concrete

III.5. RELATION BETWEEN WAVE VELOCITIES IN ASPHALT CONCRETE

The propagation velocities of all of the waves relative to the shear wave velocity are shown as a function of Poisson's ratio in figure.III.10 for the range of poison's ratio of most soils and pavement materials($0.25 \leq \nu \leq 0.45$) , Vr is generally approximated as 0.95 Vs. The exact relationships between Vp. Vr. and Vs over the entire range of Poisson's ratio are listed in Table III.2 (33)

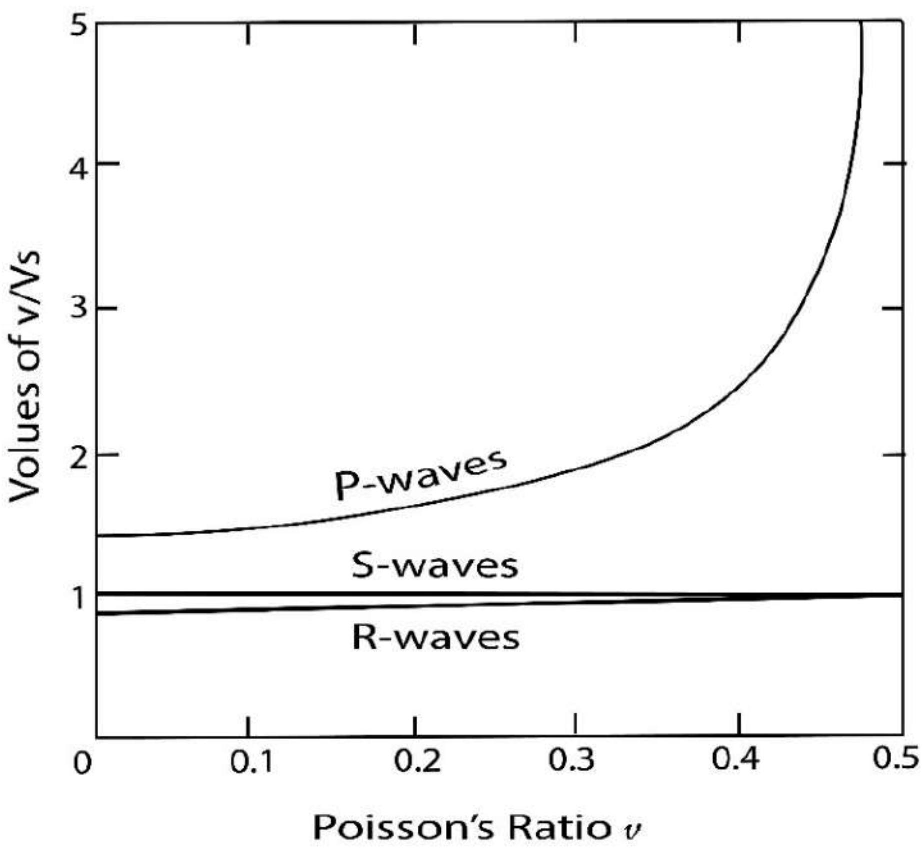


Figure.III.10. Relation between poisson's ratio and wave velocities in an elastic half-space

Table III.2. Relation between wave velocities as a function poisson's ratio.

Poisson's Ratio	V_S/V_P	V_R/V_S	V_R/V_P
0.25	0.5774	0.9114	0.5309
0.26	0.5695	0.9210	0.5245
0.27	0.5613	0.9227	0.5179
0.28	0.5528	0.9243	0.5110
0.29	0.5439	0.9259	0.5036
0.30	0.5345	0.9274	0.4957
0.31	0.5247	0.9290	0.4874
0.32	0.5145	0.9305	0.4787
0.33	0.5037	0.9320	0.4694
0.34	0.4924	0.9335	0.4597
0.35	0.4804	0.9350	0.4492
0.36	0.4677	0.9365	0.4380
0.37	0.4543	0.9379	0.4261
0.38	0.4399	0.9394	0.4132
0.39	0.4247	0.9408	0.3996
0.40	0.4082	0.9423	0.3846
0.41	0.3906	0.9436	0.3686
0.42	0.3714	0.9449	0.3510
0.43	0.3504	0.9463	0.3316
0.44	0.3273	0.9476	0.3101
0.45	0.3015	0.9489	0.2861

III.6. ULTRASONIC RESEARCHES ON ASPHALT CONCERT (AC)

In this section, we are going to present a quick look at some of the researches that done on the asphalt concert as a viscoelastic material in order to measure the dynamic modulus or the complex modulus using ultrasonic devise

III.6.1.Measuring the Complex Modulus of Asphalt Concrete Using Ultrasonic Testing (34).

A new ultrasonic technique is developed for measuring the complex moduli of AC. A theoretical explanation of the measurement process is provided. Two AC specimens were tested using the ultrasonic method and the dynamic modulus method in the indirect tensile test (IDT) mode. Both test techniques were performed at four different temperatures. The master curves were constructed using time-temperature superposition on the IDT test data and the upper asymptotes were extrapolated. The ultrasonic data was shifted to the desired reference temperature and the predicted moduli were compared to those of the IDT test.

It was found that the moduli predicted using the ultrasound measurement agreed well for the specimen with a lower air-void content and differed more for the specimen with a higher air-void content. The phase angles predicted by the ultrasonic method were higher than those obtained from the IDT test. It is believed that this was a result of wave scattering from air-voids and aggregates. Suggestions are made to further increase the accuracy of the technique.

It was found that the upper asymptote of the dynamic modulus and dynamic shear modulus master curves matched well with the ultrasonic prediction for the AC specimen with lower air-void content. The phase angle data obtained from ultrasound tests were higher than the dynamic modulus tests. In both specimens. This phenomenon may be related to increased energy loss due to wave scattering from air voids and aggregates.

III.6.2. Determination of bituminous mixtures linear properties using ultrasonic wave propagation (35)

The results of an experimental campaign performed on several bituminous mixtures using ultrasonic wave propagation are presented in this paper. With regard to compression ‘‘P’’ waves, two methods of measurement which allow obtaining complex moduli of mixtures are performed and compared, namely ‘‘direct measurement of flying time’’ and ‘‘Impact Resonance test’’. The back calculated moduli obtained at different temperatures (-19 °C, 0 °C, 20 °C and 40 °C) show a good fitting compared to both classical tension–compression complex modulus tests and modeling using the linear viscoelastic model ‘‘2S2P1D’’, proposed by the authors. The observed relative errors are a bit higher at high temperature. In a second experimental part, the direct measurement of flying time method is used for shear ‘‘S’’ waves. Considering isotropy hypothesis, the Poisson’s ratio of the specimens could be obtained. The measurements at 20 °C fit well the modeling if the difference between ‘‘P’’ and ‘‘S’’ wave frequencies is taken into account for the linear viscoelastic back analysis.

The techniques using compression waves (direct measurement of flying time and Impact Resonance test) showed that it is possible to determine the complex modulus of an asphalt mixture with a relative error of less than about 20%, which is quite satisfactory considering its huge variation with temperature and frequency. It is shown that loading frequency that has a very limited range due to system limitation or sample size and properties, needs to be

Taken into account to end up with a correct analysis. This remark is the consequence of large viscous effects existing for bituminous materials. This explains why comparisons are made using the linear viscoelastic model 2S2P1D that is calibrated considering an extensive experimental campaign in the quasi-static domain on a wide range of frequencies and temperatures. These non-destructive methods appear to be simple and efficient if care is taken during analysis. In particular, the viscous properties cannot be ignored especially at high temperature.

III.6.3. Dynamic modulus of asphalt mixture by ultrasonic direct test (36).

Experimental procedure followed for direct determination of dynamic modulus of asphalt mixtures by ultrasonic direct test at a specified temperature. Tests were performed on ten cylindrical samples of dense and porous asphalt mixtures manufactured with dolerite and limestone aggregates. Dynamic moduli obtained by ultrasonic transmission, calculated at a frequency of 65 kHz, were compared with values directly determined by standard dynamic tests applied in Spain at frequencies of 2, 5, 8 and 10 Hz. The obtained results demonstrate that the magnitudes for moduli calculated by ultrasonic are higher than those obtained by standard dynamic tests. It is concluded that for asphalt mixtures tested ultrasonically the increase of moduli magnitude can be associated with an increase in the frequency used but may also be due to the different testing methods. Nevertheless, these values can be used as a reference value for dynamic modulus of asphalt pavements at low strain, being necessary to apply a correction factor to replace the low frequency standard dynamic test, which is more expensive, difficult and time consuming.

- Dynamic modulus calculated by ultrasonic is higher than that obtained by dynamic test (taking as a reference the result obtained at 10 Hz). The increase of moduli magnitude can be associated with an increase in frequency of the type of test used but may also be due to different testing methods, varying the frequency dispersion of wave velocity in asphalt material.

- Measurements of dynamic modulus by ultrasonic may replace the low frequency standard dynamic test, which is more expensive, difficult and time consuming, by just applying a correction factor on the calculated modulus. For the two mixes investigated these correction factors were 0.34 (dense mix) and 0.40 (porous mix). So, these values can be used as a reference value for dynamic modulus of asphalt pavements at low strain.

IV.MATERIAL CHARACTERISTICS

IV.MATERIAL CHARACTERISTICS

IV.1. INTRODUCTION

This chapter presents the different materials that were used in this study and their physico-mechanical and chemical characteristics, we used for that a couples of tests to know the aggregate size, the density of the materials, the Resistance attrition and fragmentation, and the Sand equivalent, and the characteristic of pure bitumen, Penetration and Softening point.

Therefore, we will describe the characteristics of the different materials used in the composition of the asphalt mix, this table show the different materials and its origin/source:

Table IV.1 Materials source.

Materials	Source
Gravel class 0/3	Aïn Touta - Batna
Gravel class 3/8	Aïn Touta - Batna
Gravel class 8/15	Aïn Touta - Batna
Bitumen binders	Naftal - Ghardaïa
Lime	Souk Ahras

IV.2. GRANULAR

IV.2.1. Gravel

a) Gradation and size

We tested the two gravel classes, 3/8 and 8/15 of the Ain Toûta de Batna gravel, here's below we present the granular curves of the two classes

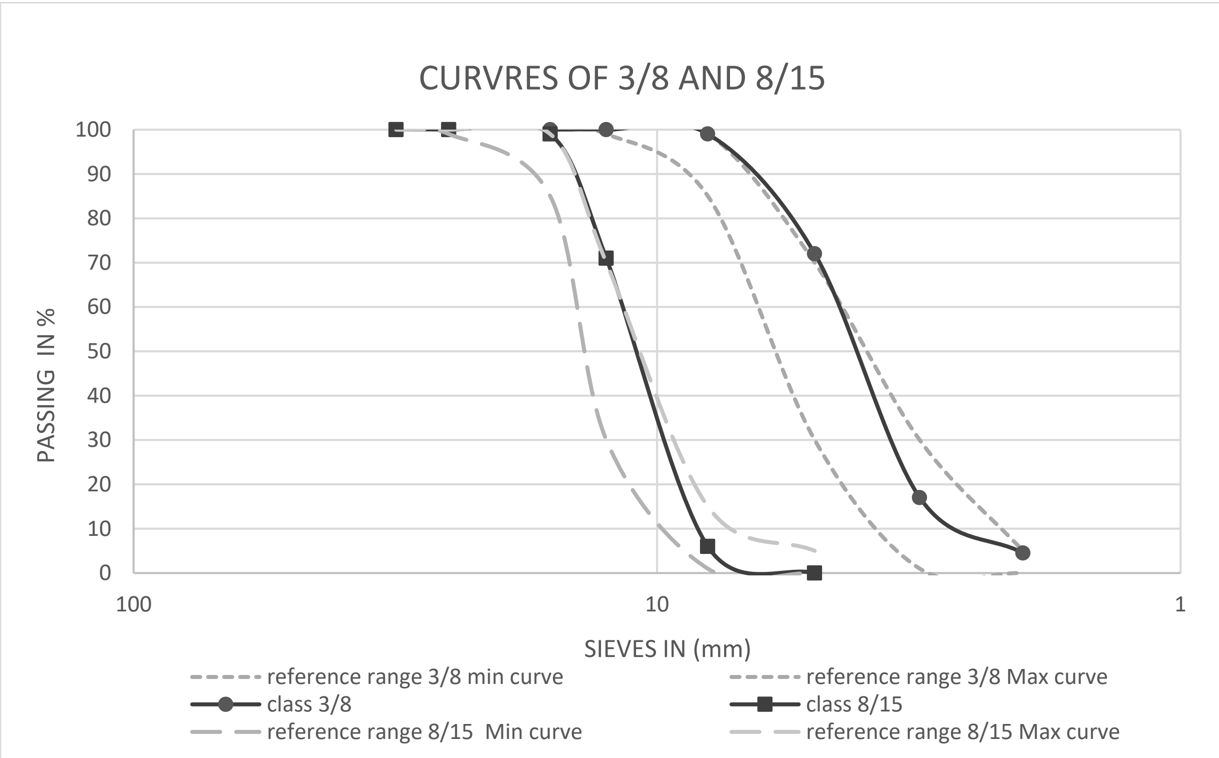


Figure IV.1. The granulometric curves of 3/8 and 8/15.

b) Bulk and absolute density

Bulk density of aggregates is the mass of aggregates required to fill the container of a unit volume after aggregates are batched based on volume.

The absolute density of an aggregate is the ratio of its mass to the mass of an equal volume of water.

Table IV.2. Densities results.

Gravel class	3/8	8/15
M.V. A (g/cc)	1.506	1.46
M.V. R (g/cc)	2.613	2.661

c) Resistance to attrition using Micro-Deval

The resistance to attrition of gravels was determinate using the Micro-Deval coefficient (MDE) which is the percentage of the original sample reduced to a size smaller than 1.6 mm during rolling.

The sample prepared from the mixed fraction to test portion size in accordance with the requirements of EN 932-2. The test portion shall consist of two test specimens, each having a mass of (500 ± 2) g mixed with (2.5 ± 0.05) l of water to each drum.

For test specimen calculate the micro-Deval coefficient, M_{De}, to the nearest 0.1 units using the following equation

$$MDE = \frac{500 - m}{500}$$

m is the mass retained on a 1,6 mm sieve, in grams

Figure IV.2. Micro-Deval apparatus.

Micro Deval Test results from class 3/8 and 8/15 with the Specifications accordance with the requirements of EN 932-2:

Table IV.3. Results of Micro-Deval test.

Gravel class	3/8	8/15	Specifications
MDE (%)	10	11	≤ 20 %

d) Resistance to fragmentation using Los Angeles

The resistance of gravel to fragmentation and chocks is evaluated by Los Angeles (L.A) test, where a sample of aggregate is rolled with steel balls in a rotating drum. After 500 tours which a constant speed of 31 to 33 rpm, and when is complete, the quantity of material retained on a 1,6 mm sieve is determined.

The modified laboratory sample prepared from the mixed fractions to test portion size in accordance with EN 932-2. The test portion shall have a mass of (5000 ± 5) g.

Calculate the Los Angeles coefficient LA from the following equation:

$$L_A = \frac{5000 - m}{5000}$$

m is the mass retained on a 1,6 mm sieve, in grams

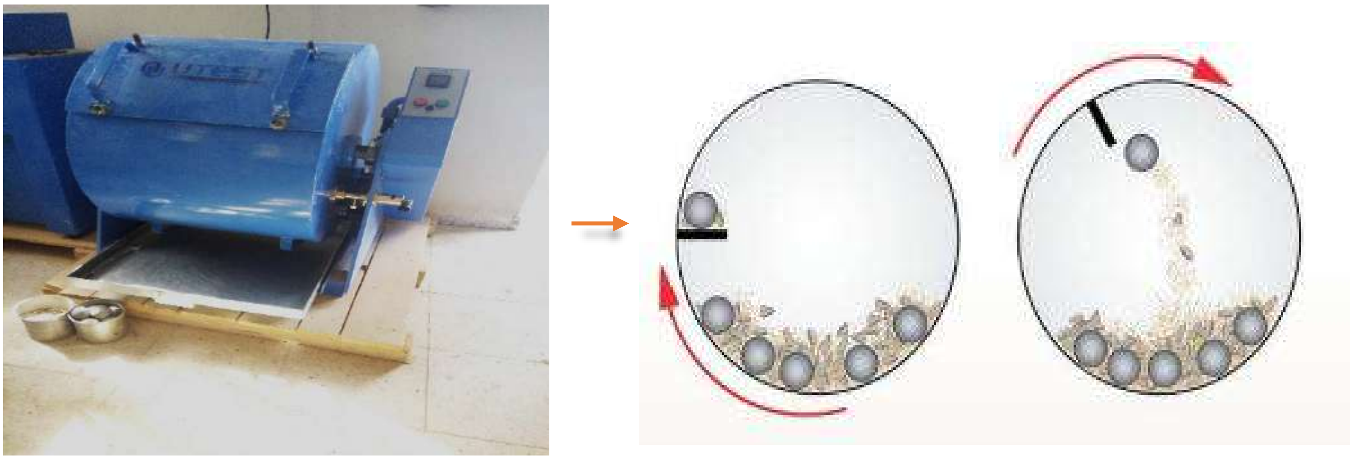


Figure IV.3. Los Angeles test principal and equipment's**.**

Test results from class 3/8 and 8/15 with the Specifications accordance with the requirements of EN 932-2:

Table. IV.4. Results of LA test.

Gravel Class	3/8	8/15	Specifications
LOS ANGELES (%)	20	25	≤ 25 %

IV.2.2. Sand

We also tested a class of crushed sand 0/3 from the same source mentioned above, the next figure, shows the granulometric curve of this class.

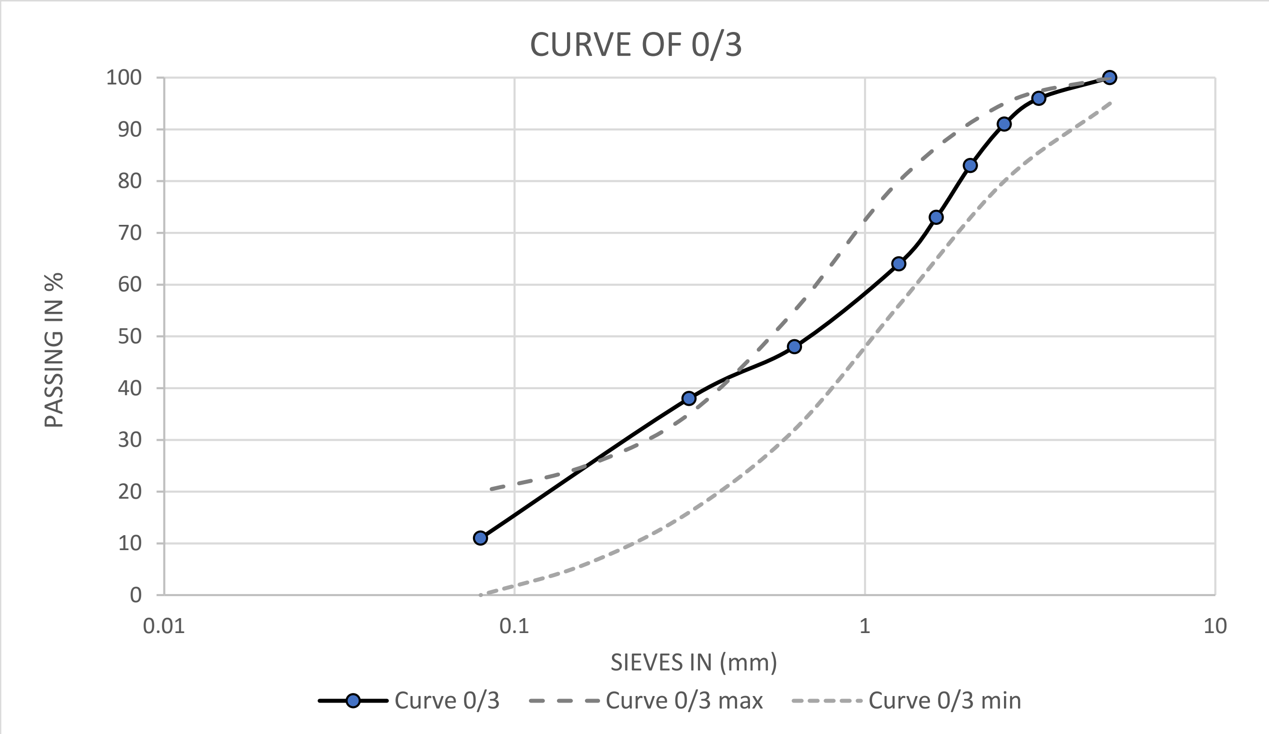


Figure IV.4. The granulometric curve of 0/3.

a) Sand equivalent test EN 933-8

The determination of the sand equivalent value of the 0/3 mm is a determination of cleanness ratio of these sand.

A test portion of sand and a small quantity of flocculating solution are poured into a graduated cylinder and are agitated to loosen the clay coatings from the sand particles in the test portion. The sand is then 'irrigated' using additional flocculating solution forcing the fine particles into suspension above the sand. After 20 min, the sand equivalent value (SE) is calculated as the height of sediment expressed as a percentage of the total height of flocculated material in the cylinder.

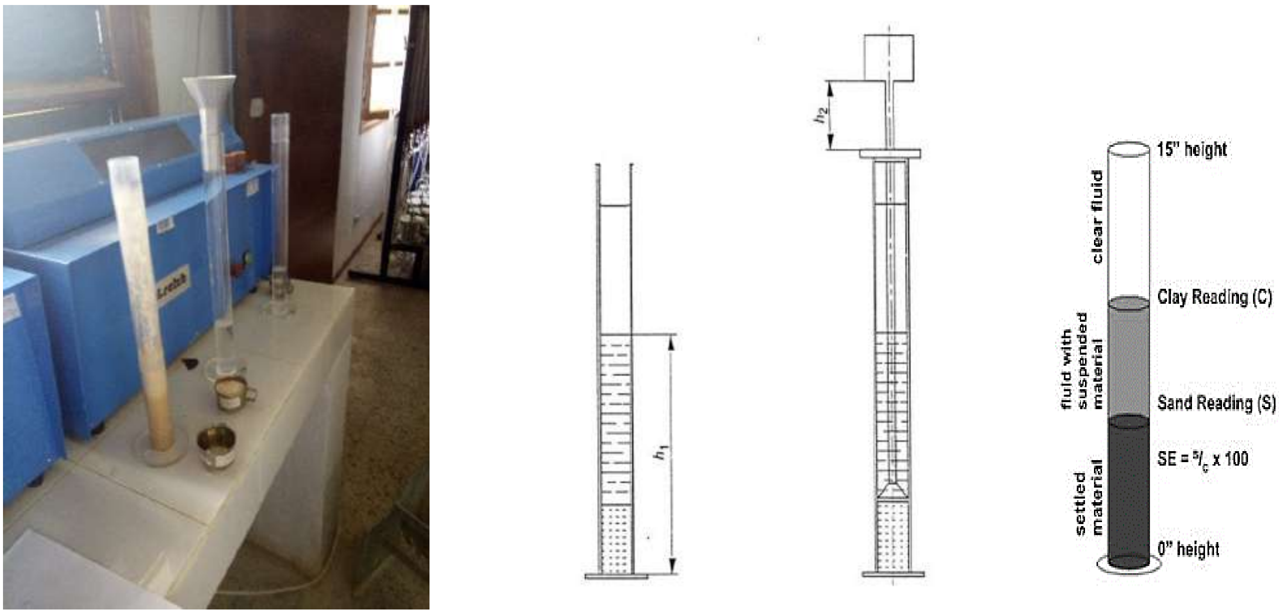


Figure IV.5. Sand equivalent test.

Calculate the sand equivalent value (SE) as the average of the ratios (h2/h1) x 100 obtained on each cylinder and record to the nearest whole number.

Table IV.5. Sand equivalent value 0/3.

Class	SE a 10 %	Specification
0/3	70	≥ 45 %

b) Bulk and absolute density

It's the same as 3/8 and 8/15 aggregate value depends on the method chosen for measuring the mass density of components and in particular that of aggregates

Table IV.6. The densities of 0/3

Class	0/3
M.V.A (g/cc)	1.563
M.V.R (g/cc)	2.557

IV.2.3. Hydrocarbon binders test

This test determining the characteristic of pure bitumen and bituminous binder According to standards EN 12591

Table IV.7. Hydrocarbon binder tests on bitumen.

Test	Results	Specification
Penetration at 25° (1/10mm)	42.33	40 to 50
Softening point (Ring and Ball) (°C)	52.90	47 to 60

V. FORMULA & PERFORMANCE

V. FORMULA & PERFORMANCE

V.1. INTRODUCTION

This chapter presents the experimental set-up realized in our study, which consists of the different steps and tests realized in this research project, as well as the results of each test.

V.2. FORMULATION STUDY

V.2.1. Granular composition

First step is determining the granular composition of the asphalt concrete, in our case we study a Hot Mixture Asphalt (HMA) class 0/14; it composes of three granular class: 0/3, 3/8 and 8/15.

Based on the particle distribution curves of the different granular classes chosen (Figure V.1), a mineral mixture is composed from it.

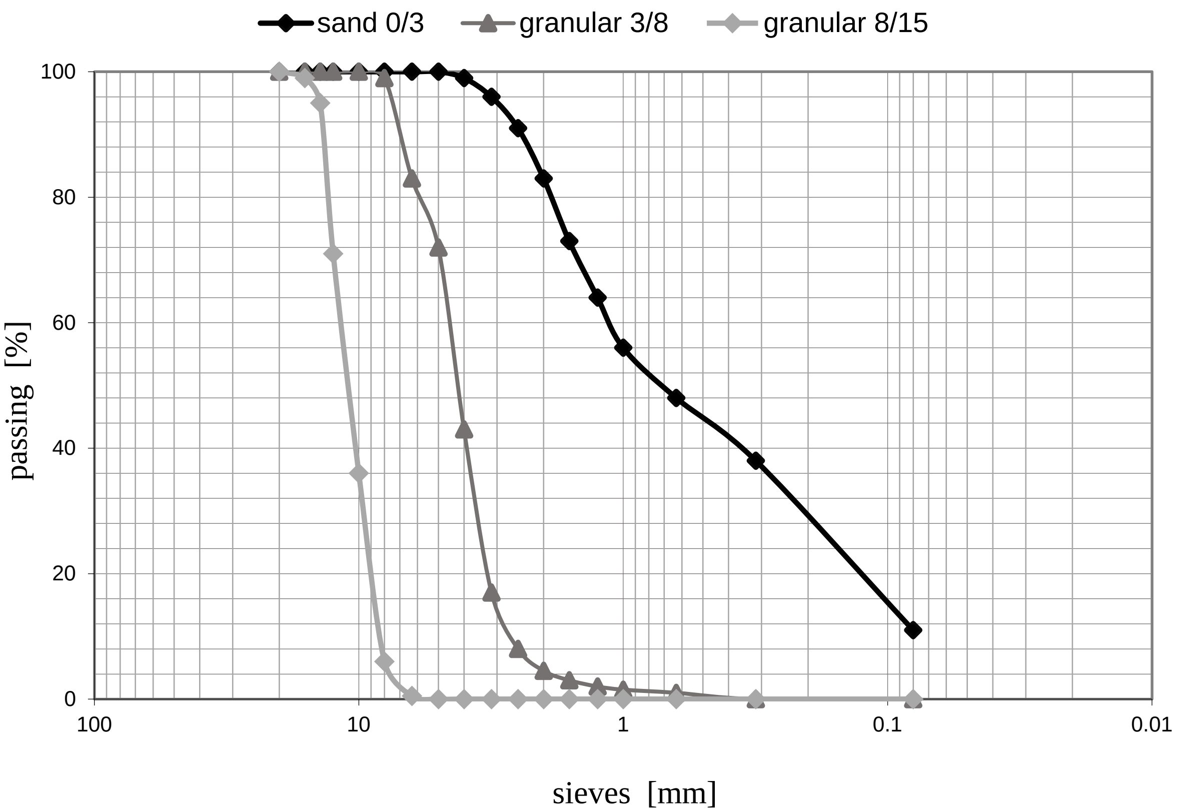


Figure V.1. The particle distribution curves of the components.

Based on the particle distribution curves of the granular classes, the mineral mixture curve will be calculate (figure V.2), the percentage of passers-by a sieve for the mixture curve is the sum of the percentages of passers by the same sieve of the component curves weighted by the respective proportions, and the following figure presents the granular composition proposed in this project study:

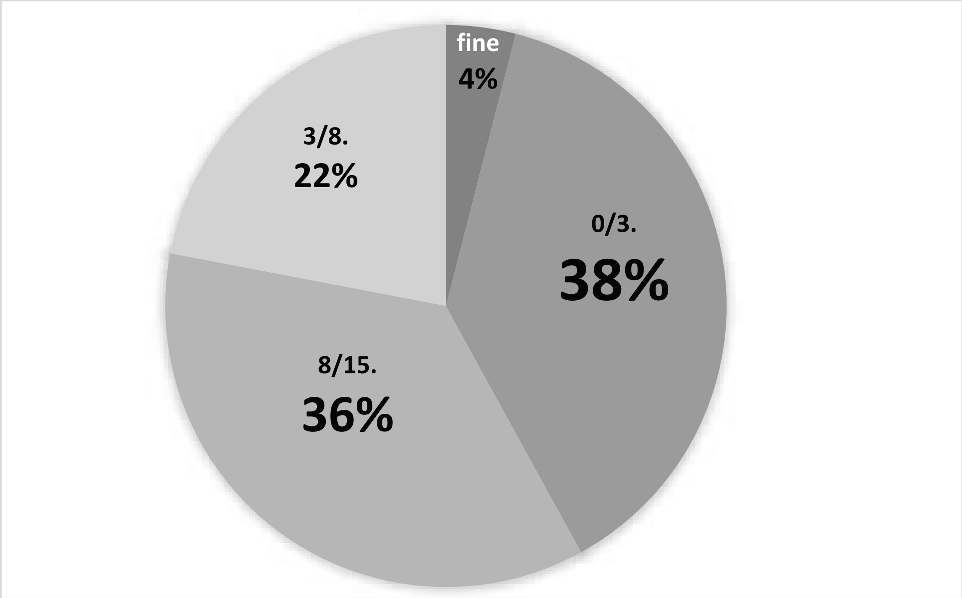


Figure V.2. The mineral composition of bituminous mixture.

The percentages obtained are determined from the grain size curve of each aggregate taking in consideration the reference range 0/14, and the curve is presented in the following figure:

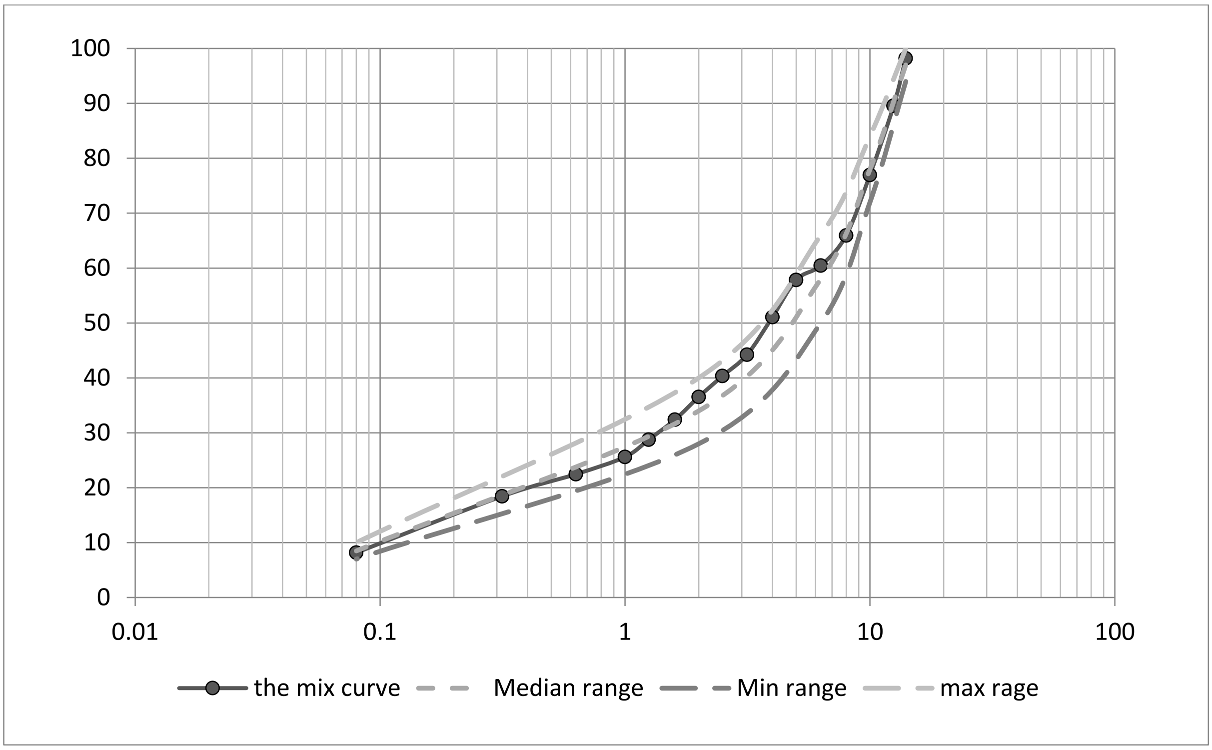


Figure V.3. Mixing curve is included in the reference range.

V.2.2. Binder content

The calculation of the binder content is based on two factors, bulk density corrector coefficient and specific surface area, and these two are:

a) Calculation of corrector Coefficient α:

MVRg =2.67 g/cc

$\alpha = 2.65 / MVRg \rightarrow \alpha = 1.004$

b) Calculation of the specific surface area ∑:

$\Sigma = 0.25G + 2.3S + 12s + 135f / 100 = 0.25(39.56) + 2.3(42) + 12(10.26) + 135(8.18) / 100$

$\Sigma = 13.403\ m^2/kg$

c) Calculation of Binder content:

In order to calculate the richness modulus *K*, we have taken values within the range 3.3 to 3.9 for asphalt concrete, Table V.1 presents the richness modulus value and the binder content we obtained.

Table.V.1 Binder content adopted from the formulation.

Richest modulus	3.44	3.67
corrector Coefficient	1.004	
Specific Surface area (m^2/kg)	13.403	
Binder content (%)	5.8	6.1
Reel density (g/cc)	2.434	2.422

V.3.MIX PERFORMANCE

V.3.1. Marshall Mix Design

The Marshall test was obtained as a reference test to characterize the performance of our proposals. The Marshall Mix design procedure was developed in the late 1930's. It is the most widely used design technique worldwide.

The test method is for determining the stability, flow and the Marshall Quotient values of specimens of bituminous mixtures mixed according to EN 12697-35 and prepared using the impact compactor method of test EN 12697-30. It is limited to hot asphalt concrete. The procedure follows certain steps to produce uniform asphalt mixtures.

a. The steps to produce uniform asphalt mixtures are:

- Aggregate selection: general requirements;
- Gradation (Sieve analysis): produce a combination of aggregate fractions;
- The selection of a design binder content (5.8 and 6.1);
- Mixing: mechanical mixing is used to perform this step and produce a homogeneous mix;
- Compaction: compaction level (number of hammer blows) is specified according to the anticipated traffic level. The automatic Marshall hammer is used to apply 25, 50, and 75 blows for low, medium, and high levels of traffic, respectively (50 blows / face in our case).

b. Apparatus

Specimens shall be compacted in accordance with EN 12697-30 ensuring that 50 blows are applied to each side within the acceptable temperature range given. The compacted specimens shall be unmold ensuring that they are cooled in air to avoid any danger of deformation.

Figure V.4. Marshall automatic compactor.

Water bath, Immerse the cylindrical specimens, on their flat surface not in contact with one another. And put it in the water bath for at least 40 min and not longer than 60 min with maintain the temperature of the water in the bath at (60 ± 1) °C.

Apply the load to the test specimen to achieve a constant rate of deformation of (50 ± 2) mm/min allowing for the transitory period. Continue the application of this load until the maximum reading is obtained on the load measuring device. Record the load indicated. This section of the test shall be carried out within 40 s of removal of the test specimen from the water bath.

Figure V.5. Water bath

Figure V.6. Marshall Machine.

c. Results

Marshall Tests summarizes results obtained of stability en kN (Figure V.7) and plastic flow en mm (Figure V.8) and the Marshall quotient (Figure V.9) by calculation division the stability by the flow, of the asphalt mixtures with the binder content (5.8% and 6.1%).

Table V.2. Results of Marshall Tests for the proposed composition.

Binder content (%)	**5.8**	**6.1**
Stability (kN)	17.277	16.316
Plastic flow (mm)	3.416	3.501
Marshall Quotient (kN/mm)	5.067	4.683

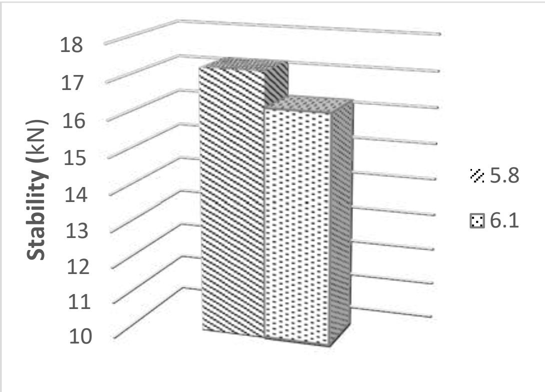


Figure V.7. Stability of the two mixtures.

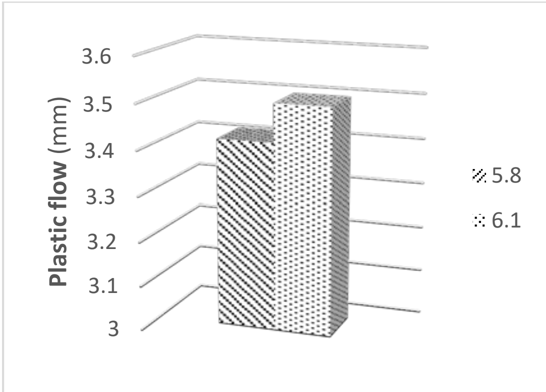


Figure V.8. Plastic flow of the two mixtures.

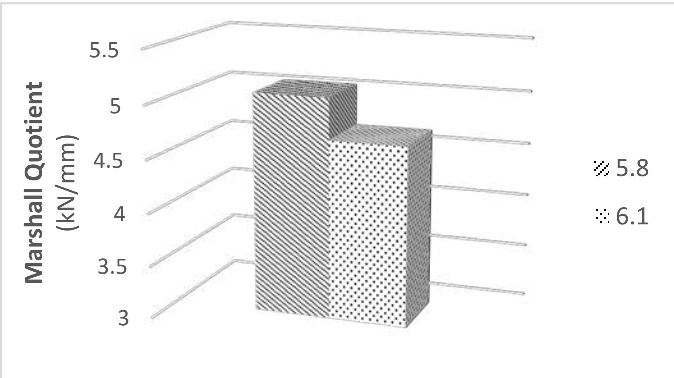


Figure V.9. Marshall Quotient of the two mixtures.

V.4. CONCLUSION

Based on the results we found and measured for the two-asphalt concrete with the same mineral composition with two different contents 5.8 and 6.1 %. We found that the two mixtures answer to the Marshall specification (Stability ≥ 10.5 kN, plastic flow ≤ 4 mm), and as long as the mixture with 5.8 % binder content is more efficient than the mixture with 6.1 % in terms of stability, plastic flow and resistance to plastic flow.

We chose the mixture proposed with the mineral composition (Figure V.2) and 5.8 % of binder content as the subjected mixture of this research.

VI.CHARACTERIZATION OF THE VISCOELASTIC BEHAVIOR USING NDT TEST

VI.CHARACTERIZATION OF THE VISCOELASTIC BEHAVIOR USING NDT TEST

VI.1. INTRODUCTION

After mixing the hot asphalt concert into cylindrical specimens we done a couples of tests to determine the viscoelastic behavior of our mixture the following test are NDT test which means the specimens would not get damaged after doing during the tests, both tests were done in temperature 15°C

The results of these tests are the stiffness modulus measured by the IT-CY test and the ultrasound propagation time for the ultrasonic test

VI.2. INDIRECT TENSION TO CYLINDRICAL SPECIMENS (IT-CY TEST)

The indirect tension tests were performed on six "6" cylindrical specimens as shown in the (Figure VI.1.); the test following the standards EN 12697 – 26 annex C discuss in the $\oint \mathbf{II.5.1.}$, and for that the IT-CY (Figure IV.2) applied a dynamic stress loading each 0.02 second, and measured the horizontal strain by LVDT. Each specimen got measured its stiffness twice in two directions perpendicular each other by 90°.

Figure VI.1. Positioning the direction of the IT-CY Test on a specimen.

The results of the stiffness modulus are shown in the next table summarized with the results of the bulk density (MVA).

Figure VI.2. Cylindrical Specimens

Figure VI. 3. IT-CY Test apparatus

Table IV.1. The results of the stiffness modulus and the density (MVA)

	Stiffness Modulus (MPa)									
Specimens	S1		S2		S3		S4		S5	
MVA	2297.4		2369.1		2284.6		2332.8		2331.7	
Direction	A	B	A	B	A	B	A	B	A	B
Mean	11192	10925	11675	11569	12986	11415	14076	13981	14217	14206
Mean A&B	11059		11622		12201		14029		14211	

the results show a variation in the results, each specimen has a difference stiffness, all the stiffness is higher than 9000 MPa which is mean we could consider are as BBME, and this variation could be helpful in the estimation of this value using US.

VI.3. ULTRASONIC TESTING

This test used the direct method (P-wave) as shown in Figure VI.4 using the ultrasonic device (Figure VI.5), the measures taken on the same cylindrical specimens being used in the IT-CY test, the ultrasound acoustic generated by a 54 kHz probes, and the temperature of specimens was 15ºC after conserving it in climatic chamber during four (4) hours.

Figure VI.4. The direct ultrasonic test "fly time measurement"

Figure VI.5. Ultrasonic device.

The curve shown below shows the amplitude of ultrasound wave in function of time, these measurements is obtained from the ultrasonic device raw data.

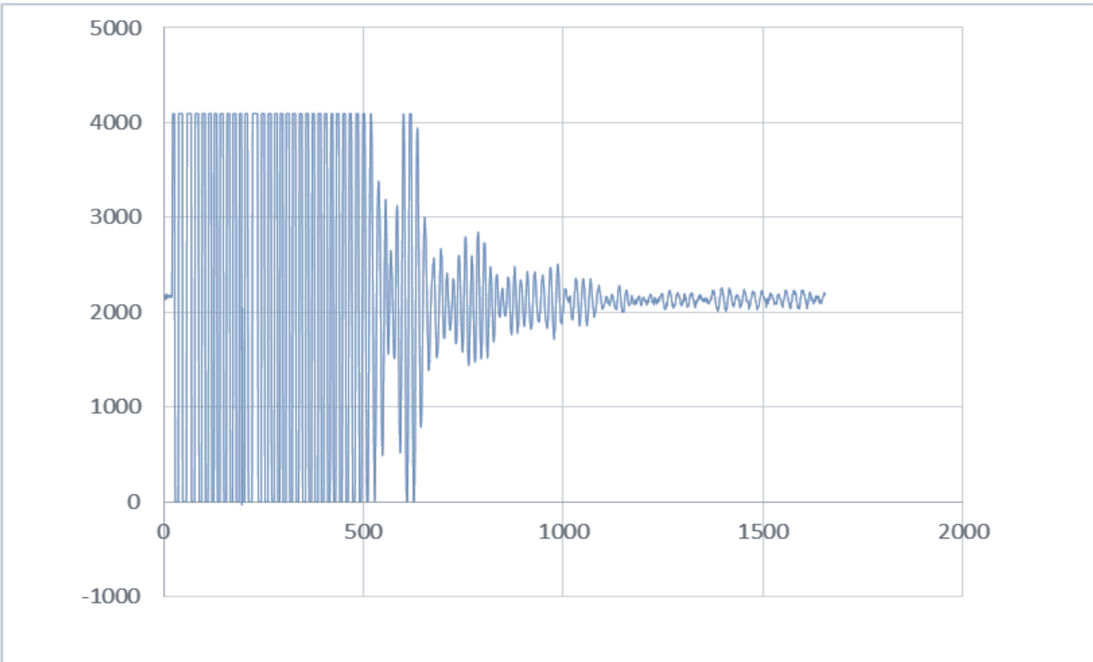


Figure VI.6. Amplitude of ultrasonic wave of specimen N°1.

The table IV.2 show the results of the sound transmission time in the specimens obtained by the ultrasonic device these measurements used in the calculating of velocity.

Table VI.2. The results of time by the ultrasonic test.

Specimens	S1	S2	S3	S4	S5
thickness mm	49.71	50.19	54.31	48.96	48.11
time (ms)	11.9	12.1	12.6	11.1	11.2

The histogram below shows us the results of the P wave's velocity (Vp) calculated according to Equation.III.6 from, ∮ III. 4. and the shear waves velocity (Vs) calculated using the relation between the V_s and V_p mentioned in the Table III.2 from ∮ III. 4.

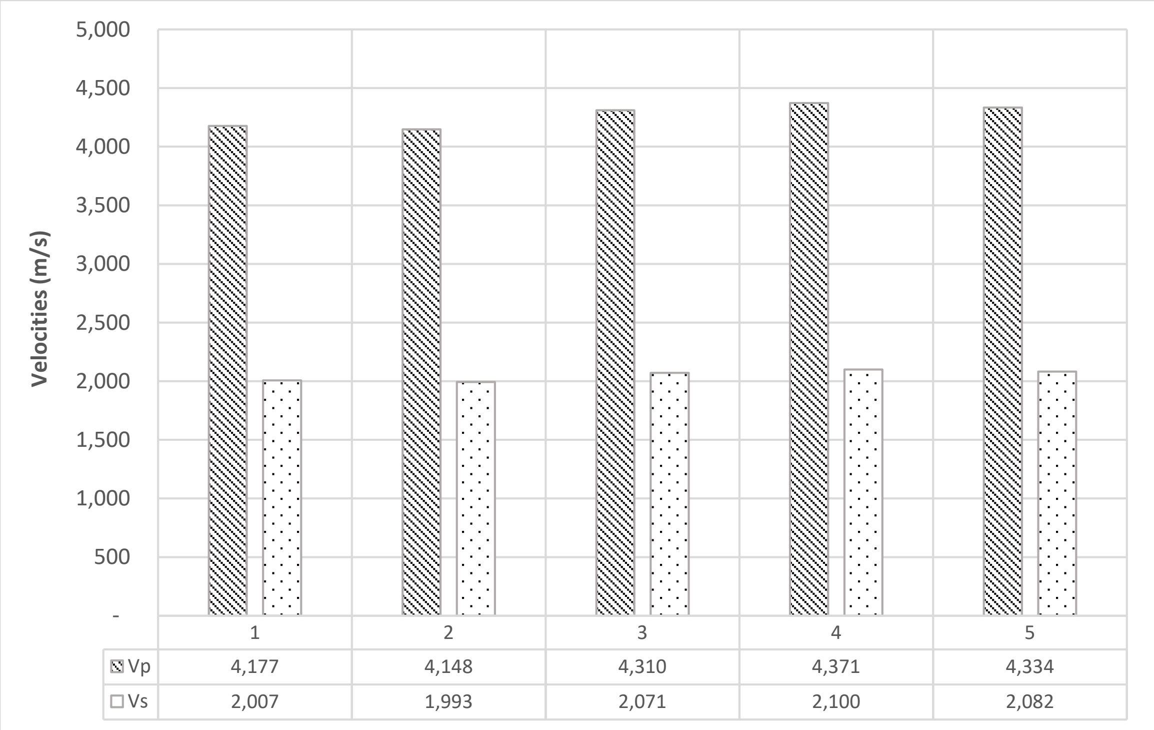


Figure VI.7. The results of Vp and Vs**.**

VII. RESULTS AND CORRELATION

VII. RESULTS AND CORRELATION

VII.1. INTRODUCTION

In this chapter we are going to discuss about the relation between the two measured stiffness of hot mixture asphalt (HMA) using two non-destructive tests NDT, First the mechanical test stiffness (Sm) by indirect tensile (IT-CY) and the other one is the elastic modulus noted by Eu calculated from the velocities of ultrasonic (US) tests.

There're so many researches done on this topic using different methods these were some the researches that helped us in our subject:

- "Dynamic modulus of asphalt mixture by ultrasonic direct test" by J.Norambuena-Contreras, D. Castro-Fresno, and al.
- "Determination of bituminous mixtures linear properties using ultrasonic wave propagation" by Damien Mounier, Hervé Di Benedetto, and all.
- "Measuring the Complex Modulus of Asphalt Concrete Using Ultrasonic Testing" by G.Chehab, J.V. Velsor, and all.
- "Towards a viscoelastic mechanical characterization of asphalt materials by ultrasonic measurements" Nicolas Larcher, Mokhfi Takarli, and all.

VII.2.THE YOUNG MODULUS (EU)

The elastic or young modulus Eu was calculated from the obtained results of the velocity of the primary waves Vp and the shear waves Vs both were calculated from the flying time of the sound waves passed through the asphaltic specimens with the ultrasonic device using the direct method and by following the physics laws of sounds.

Using two hypotheses the one is that the studied materials as **elastics materials** like it mentioned in the researches of: "Dynamic modulus of asphalt mixture by ultrasonic direct test" by J.Norambuena – Contreras, D. Castro-Fresno [J.Norambuena – Contreras et al., 2010].

And the second which is more convincing that our materials are **viscoelastic materials** like it was mentioned in: "Towards a viscoelastic mechanical characterization of asphalt materials by ultrasonic measurements" Nicolas Larcher, Mokhfi Takarli [N.Larcher et al., 2014]. And "Measuring the Complex Modulus of Asphalt Concrete Using Ultrasonic Testing" by G. Chehab, J.V. Velsor [J.V. Velsor et al., 2011].

VII.2.1. The elastic case

In this case our material is a solid elastic isotropic, the P-wave speed (Vp) is related to the modulus of elasticity (E), poisson's ratio (ν = 0.35) and the density (ρ) as given by the following equation:

$$\mathrm{V_p} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \ldots Equation\ \mathrm{VII.1.}$$

From equation.VII.1. The value of Eu is calculated:

$$Eu = \frac{Vp^2 \times \rho(1+\nu)(1-2\nu)}{(1-\nu)} \ldots Equation\ \text{VII}.2.$$

Table.VII.1. Results of measured stiffness (Sm) and calculated elastic modulus (Eu) in elastic case.

Specimens	S1	S2	S3	S4	S5
Sm	11059	11622	12201	14029	14211
Eu	24980	25399	26448	27778	27294

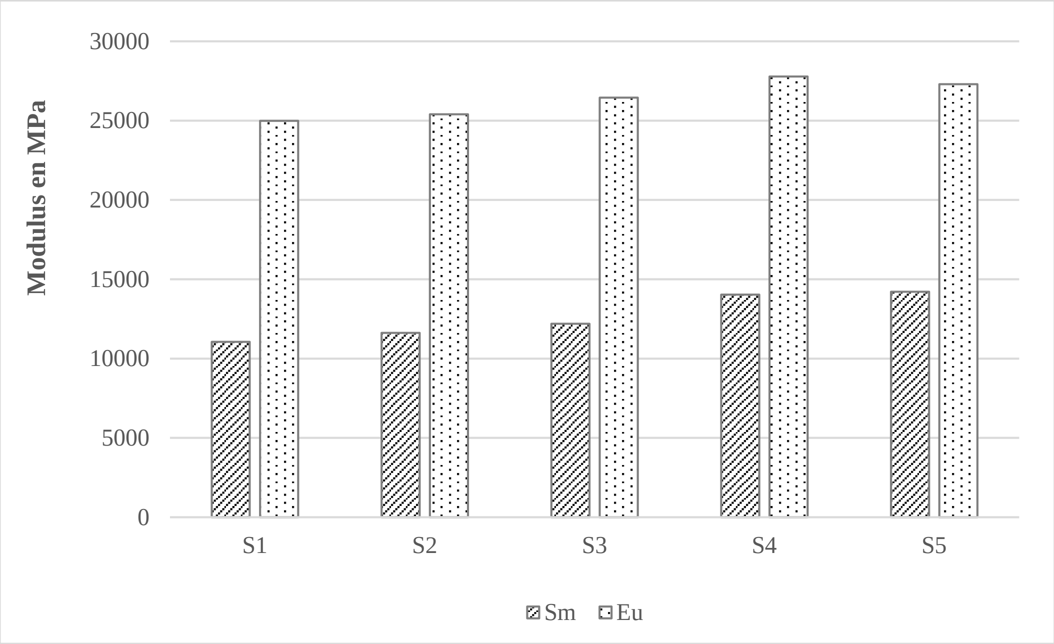


Figure.VII.1. Histogram show the comparison between Sm and Eu in elastic case.

According to the results of the modulus measured by IT-CY and calculated according to physic laws, we could notice that the ultrasound modulus (Eu) comparatively to the mechanical one (Sm). In the elastic materials such as concrete the values has to be equal whish's not our case, but the ratio Sm/Eu varied between 0.44 to 0.52.

From that we conclude that the ultrasound technics could not be used as determinate test and gives directly the value of stiffness in the asphalt concrete, we could put a correlation between the two technics (mechanics and ultrasound), but according to [Mounier, 2012] and [Larcher, 2014] and others researchers this is a wrong correlation since the asphalt concrete is not elastic material. But a viscoelastic material.

Other researchers such as [J.Norambuena-Contreras et al., 2010] said since the relation stiffness, frequency is a positive relation, and the higher value of modulus using ultrasound propagation wave velocity is totally normal, since this value is represent the stiffness at the frequency of the test (54000 Hz in our case), the next figures shows this case.

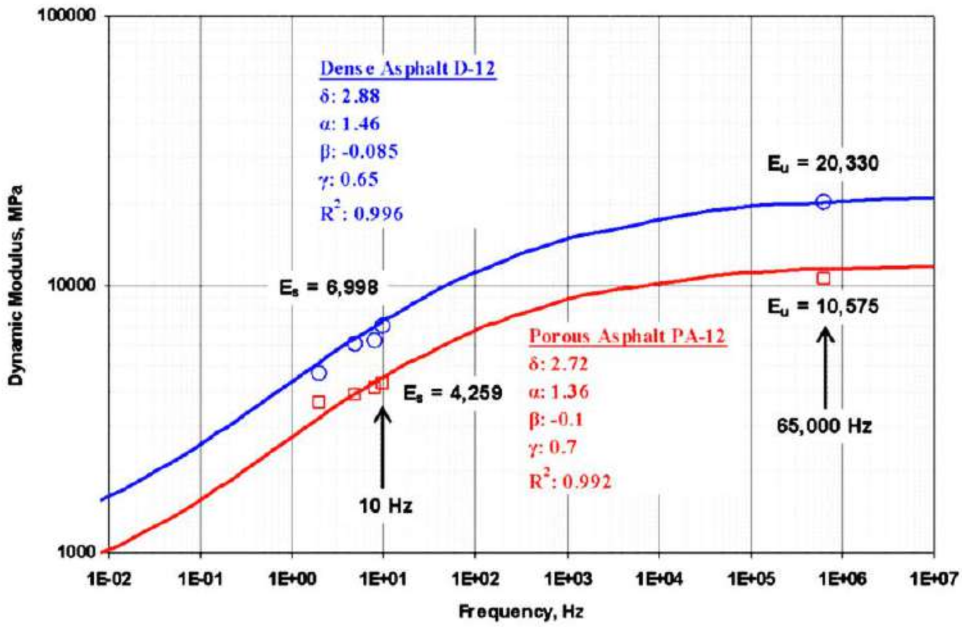


Figure.VII.2. Master Curve of the evaluated mixes at 22ºC (J.N en (36))
(Es: mechanical modulus at 10 Hz and Eu: ultrasound modulus at 65000 Hz)

In this case, and from this consideration, using the IT-CY values such as the 'Sm' and ultrasound values 'Eu', could been exploited to determine the correlation between this two using the scatter curve 'Sm' en function of 'Eu' as shown in the figure VII.3.

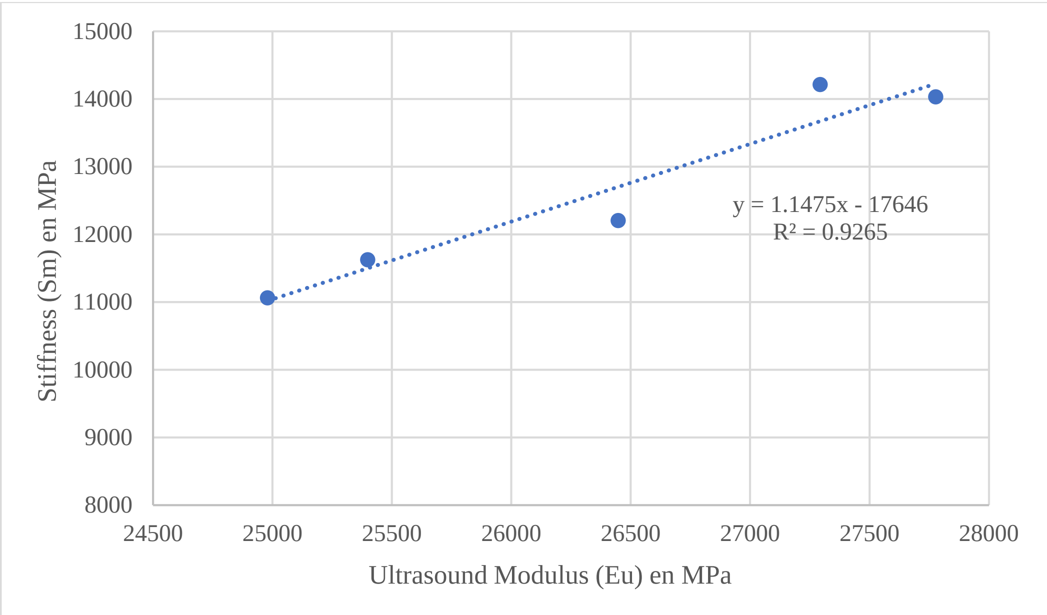


Figure.VII.3. Scatter curve and trend-line curve in elastic case.

The figure.VII.3 is scatter curve where each point is representing a specimen, and their coordinates X; Y is Eu; Sm. Using Excel, we could determine the trend-line curve who has the most opportunity statically to pass through all the points.

And from that we found a curve with coefficient of determination R^2, 0.9265. The formula of this trend-line curve is the formula of the correlation between Eu and Sm, so in the case to consider our asphalt concrete as elastic materials:

$$S_m = 1.1475\, E_u - 17646 \ldots Equation\ \text{VII.3.}$$

We can also write the equation in terms of velocity, V_p:

$$Sm = 0.715 \times Vp^2 \times \rho - 17646 \ldots Equation\ \text{VII.4.}$$

VII.2.2. The viscoelastic case

In this case we deal with the material as viscoelastic and following the researches on that we should consider the fact that there's a loss in wave propagation throw the material which is in the elastic case considered non-existent, $\alpha = 0$, and for determine the value of the loss or as it called the attenuation factor, and for that we used two signals peak's from two specimens (S1, S3) with different thickness in our case is 54.34 and 49.71 mm.

This process requires transforming the sound wave into peaks signals using Fast Fourier Transform (FFT) of each signal Figure.VII.3.

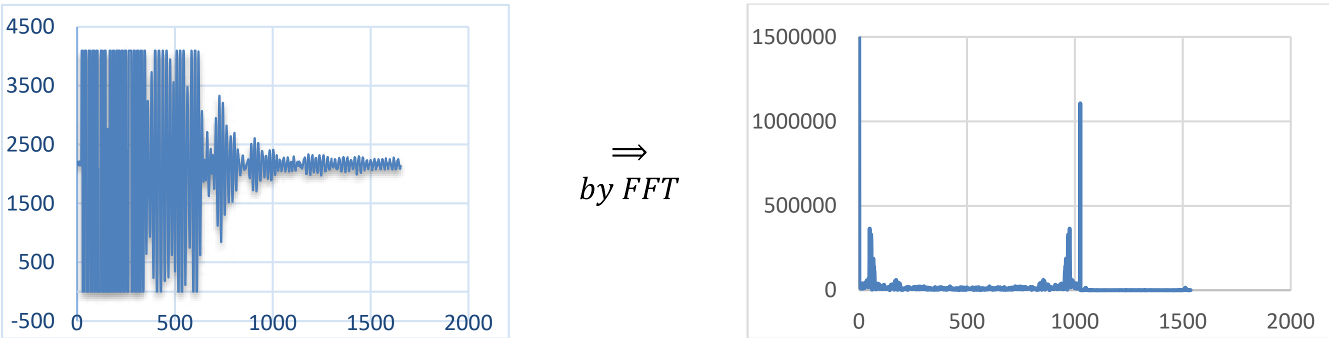


Figure.VII.4. Time ultrasonic waveforms obtained for samples S1 at 15° C, and the Fast Fourier Transform (FFT) amplitudes.

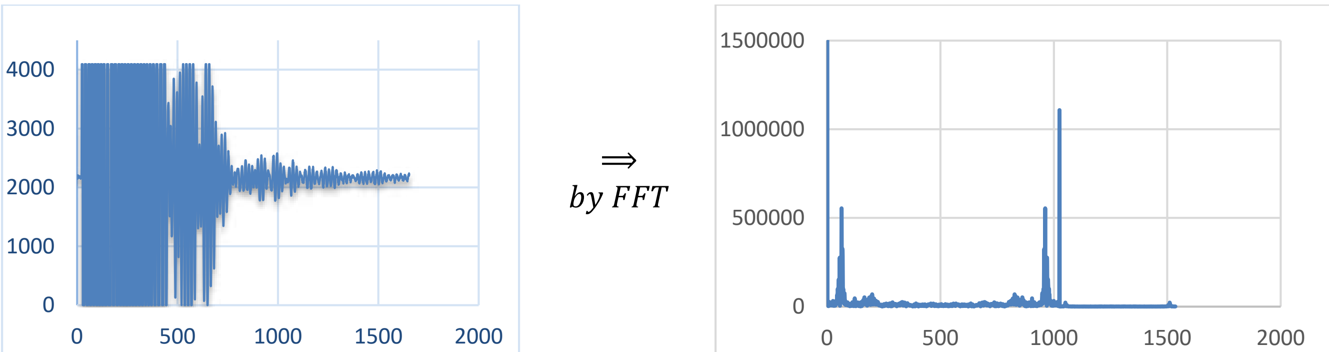


Figure.VII.5. Time ultrasonic waveforms obtained for samples S3 at 15° C, and the Fast Fourier Transform (FFT) amplitudes

The laws of ultrasound physics used in the researcher mentioned in the introduction $\oint VII.1$ gave us a differential equation for the sound wave propagation through the materials, and the solution of this equation is a one-dimensional complex equation:

$$U(x,t) = U_0 e^{-\alpha x} e^{i\omega(x-t)} \ldots \ldots . . equation. VII. 5$$

Assuming there are two waves that have propagated distances, x_1 *and* x_2, respectively, the amplitudes of these two waves would be given by:

$$A_1 = U_0 e^{-\alpha x_1} \ldots \ldots . . equation. VII. 6$$

$$A_2 = U_0 e^{-\alpha x_2} \ldots \ldots . . equation. VII. 7$$

Taking the ratio of Eq.VII.4. & Eq.VII.4, a convenient expression result:

$$\frac{A_2}{A_1} = e^{-\alpha(x_2 - x_1)} \ldots \ldots . . equation. VII. 8$$

Since the Fourier Transform is a linear transform, the amplitude ratio will be conserved and the time-domain amplitudes in Eq.VII.8, can be replaced by the amplitudes of the Fourier transforms in the frequency domain.

And the wave attenuation factor can be calculated by:

$$\alpha = \frac{ln\left(\frac{Magnitude\ FFT\ of\ signal\ L_1}{Magnitude\ FFT\ of\ signal\ L_3}\right)}{\Delta \mathrm{L}} \ldots \ldots . . equation. VII. 9$$

In our case we found that the attenuation factor in our material is α = 0.0002826.

The velocities in the viscoelastic case is given by the next equation:

$$V_p = \frac{1}{\cos\left(\frac{\phi}{2}\right)} \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \ldots \ldots Equation\ \mathrm{VII.}\ 10$$

The wave attenuation factor in the viscoelastic case is given by the equation:

$$\alpha_p = \omega \sin\left(\frac{\phi}{2}\right) \sqrt{\frac{\rho(1+\nu)(1-2\nu)}{E(1-\nu)}} \ldots \ldots . Equation \mathrm{VII.}\ 11$$

From Eq.VII.10 and EqVII.11, we can determine the equation of the phase angle φ of each specimen using the value of wave attenuation factor α

The phase angle equation:

$$\varphi = \tan^{-1}\left(\frac{2\alpha\ V_p \omega}{\left(\omega^2 - \alpha^2 {V_p}^2\right)}\right) \ldots \ldots Equation\ \mathrm{VII.}\ 12$$

By the end, based on the Eq.VII.10 and the values of phase angle φ and P-wave velocities, the ultrasound modulus (Eu) can be calculated by

$$Eu = \frac{Vp^2\left(\cos\left(\frac{\varphi}{2}\right)\right)^2 \times \rho(1+\nu)(1-2\nu)}{(1-\nu)} \ldots Equation\text{VII}.13$$

And the results showing in the table below

Tabel.VII.2. Results of measured stiffness (Sm) and calculated elastic modulus (Eu) in viscoelastic case

Specimens	S1	S2	S3	S4	S5
Sm	11059	11622	12201	14029	14211
Eu	21209	21616	22212	23209	22876

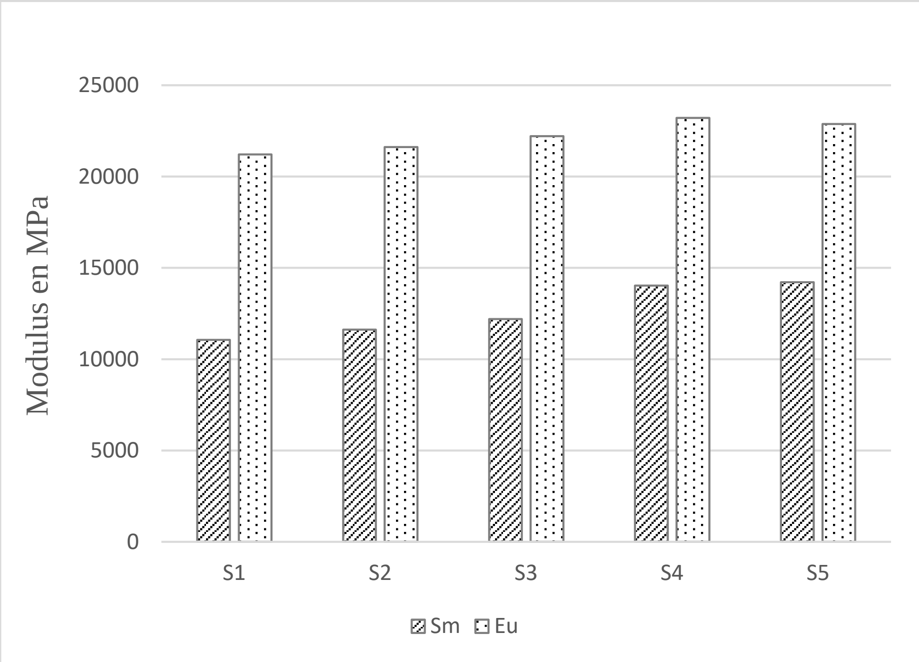


Figure.VII.6. Histograme show the comparison between Sm and Eu in viscoelastic case.

According to the results of the modulus measured by IT-CY and calculated according to physic laws, we notice that the ultrasound modulus (Eu) is also higher comparatively to the mechanical measurement (Sm), in this case the Sm/Eu ratio is between 0.52 to 0.62. So, that confirmed that the ultrasound technics could not be used as determinate the stiffness directly in asphalt concrete, so that require a correlation in this case too.

This measured and calculated values, has been exploited to determine the correlation between this two using the curves Sm in function Eu as shown in the figure VII.7.

We used the same technic to draw the scatter curve using the values presented in the table VII.2, where each point is representing a specimen, and their coordinates X; Y is Eu; Sm (Figure VII.6).

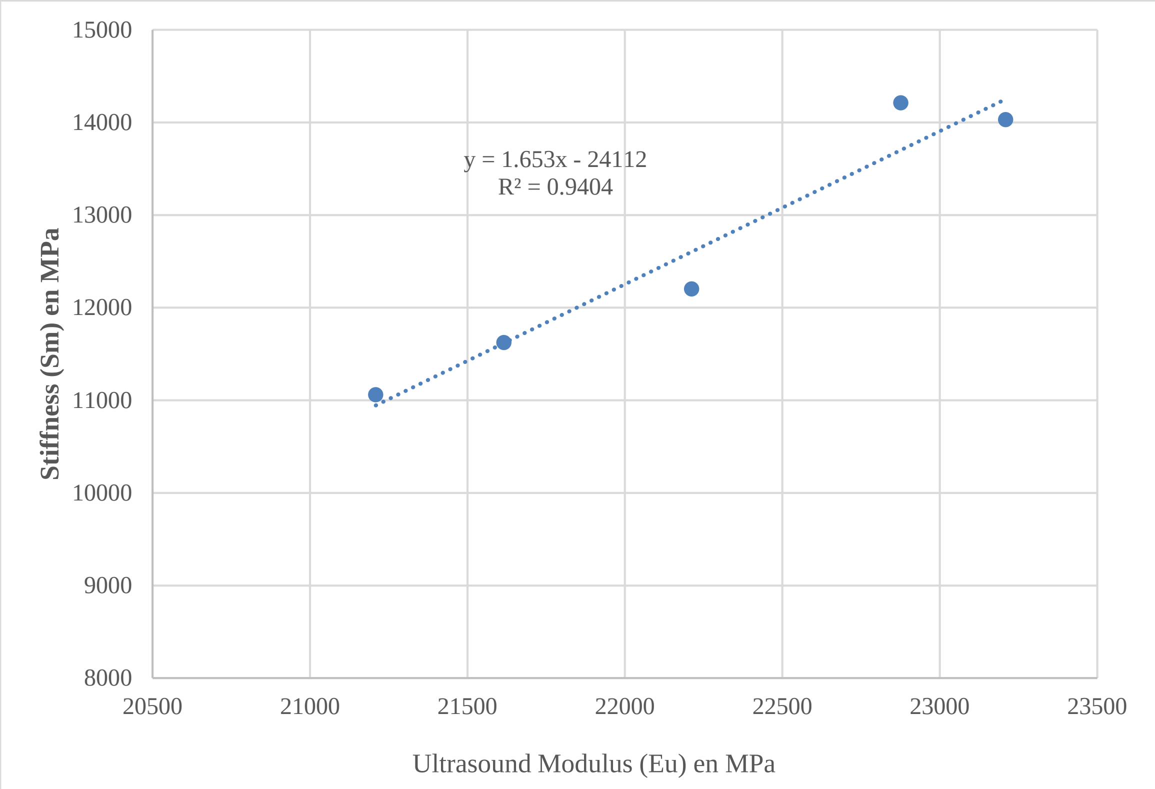


Figure.VII.7. Scatter curve and trend-line curve in viscoelastic case.

Using Excel, we could determine the trend-line curve who has the most opportunity statically to pass throw all the points. And from that we found a curve with coefficient of determination R^2, 0.9404. The formula of this trend-line curve is the formula of the correlation between Eu and Sm, so in the case to consider our asphalt concrete as **viscoelastic behavior materials**:

$$S_m = 1.653\ E_u\ - 24112 \ldots Equation\ \text{VII. 14.}$$

We can also write the equation in terms of velocity, V_p:

$$Sm = 1.03 \times Vp^2 \left(cos\left(\frac{\varphi}{2}\right)\right)^2 \times \rho - 24112 \ldots Equation\ \text{VII. 15}$$

Considering the following parameters

$\nu = 0.35$ And $\alpha = 0.0002826 \implies \varphi_i$

With "i" being the number of the specimens

$\omega = 2\pi f$

VII.3. CONCLUSION

The correlation between the mechanical tests and the ultrasound tests for determining the stiffness modulus on the viscoelastic materials and the (HMA) in particular are still new and in the development, we study the two cases possible theoretically, the elastic case and viscoelastic case.

In the case of elastic hypotheses, we couldn't agree that calculating of the stiffness modulus based on the Eu by ignoring the materials viscoelasticity will give us corrected value. Since our material is not pure elastic this correlation maybe corrected in some cases (such as so low temperature).

For the viscoelastic case we did the researches considering the physics parameters such as the wave attenuation factor α and the phase angle φ and by using the Fast Fourier Transformation FFT, this method is still in development, and need more searching to better understanding more about the factors impact on the measurement and the transformation in this case.

During this research project, we found some obstacles, especially with the isolation phonics of specimen, saving the corrected wave and getting corrected transformation using FFT, and it's because, we still can't say that we totally succeeded in our estimation of modulus, in end we sort with a correlation based on the trend-line equation of our specimens points values, and it's about 56% correct because we rejected 5 from 9 of specimens.

General Conclusion

Roads have an important role in connecting people of all over the world. It also gives an important contribution to the economic growth of countries and the developing of the nation. Considering the asphalt concrete one of the most used material of constructing roads.

In this research we study the evaluation of young modulus or the stiffness value which is a fundamental property of asphalt concrete by using ultrasonic test, and search is in the correlation between it and the mechanical test using indirect tension method (IT-CY) and the ultrasonic test using high frequencies 54 kHz.

We success in both test results to create an equation by examining two hypotheses, the first is Asphalt concrete an "Elastic material" and the second is asphalt concrete a "Viscoelastic material" we then conclude that:

- Based on some non-published test, we found that the Speed of a wave propagate AC is unaffected by changes in the frequency of the ultrasonic wave generated by ultrasonic device;
- The physical and geometrical parameters such as void, thickness and shape of the specimen have absolute critical parameters impact for the ultrasound transmutation and stiffness values;
- Using ultrasonic technics is time gain because you only need the device for estimate the stiffness modulus;
- The elastic case is weak hypothesis because it ignores the physics properties of the viscoelastic material;
- The viscoelastic case considering the physics proprieties of asphalt concrete such as phase angle φ and attenuation factor α give us less high ultrasound modulus values;
- The calculating of the physics proprieties mentions in point below (attenuation factor, phase angle) needs two different specimen thickness's and could determinate by transforming ultrasonic wave into peaks using FFT transformation;
- Last but not least, we establish an equation which could give us an estimated value of the stiffness value by the ultrasonic test, still this equation is correct only in 56% of the cases we study. This false ratio shows that these type studies require more precision, and stable measurement technics such as sound isolation, and learning more about FFT transformation.
- Last, at this point, from our bibliographic research and the experimental work we could say that ultrasound technics is not a measurement technic, it's an estimation technic based on the physical and mechanical parameters of asphalt concrete.

Recommendation and perspectives

Based on this research, and conclusion we sort by in the end of it, we could put some recommendation for researchers in this type of topics.

- Firstly, the ultrasound and sound waves propagate materials specially the asphalt concrete require some sort of isolation phonics, very good comprehension of sound physics laws, and understanding of Fast Fourier Transformation, and why not a software specially for this step.

- Secondly, we recommend for getting best research and published papers consider the asphalt concrete as a viscoelastic material not elastic one, even that this hypothesis make the research more complexes and complicated, still is the closest to the reality.
- Thirdly, other technics of generating a sound wave could be used and studies, and the most famous one is the IR (Impulse Response), some researchers see it as the best way to studies the sound physics.
- Any relation, specially the one we sort in this research is need a verification, and validation steps; and for that we recommend and invite other researcher specially the one who work on asphalt concrete to use it, send their values and search more in this kind of topics.

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EN 1097-7: “Tests for mechanical and physical properties of aggregates - Part 7: Determination of the particle density of filler - pycnometer method”;

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EN 12504-4: “Testing concrete— Part 4: Determination of ultrasonic pulse velocity”; 2004.

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Annexes

Annexes

MATERIAL CHARACTERISTICS

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

ANALYSE GRANULOMÉTRIQUE DES GRANULATS

NF P 18- 560 Septembre 1990

Structure: UNITE D'OUARGLA
N° Dossier interne:
Classe granulaire: 8/15
Prise d'essai: 6000g
Équipements utilisés : BALANCE

Lieu de travail: SALLE DE ROUTE
Date: 24/12/2018
Opérateur: Bencheikh

N° D'inventaire :

Tableau(A.1): ANALYSE GRANULOMÉTRIQUE DES GRANULATS *8/15*

Ouverture **Tamis**	Refus partiel	Refus cumulé	Pourcentage refus	Pourcentage passant	Observations
80					
63					
50					
40					
31.5					
25					
20	0.00	0.00	0.00	100	100%
16	13	13	0.2	99.8	100%
12.5	1729	1742	29.00	71.00	71%
10	2090	3832	64.00	36.00	36%
8	1824	5656	94.00	4.99	6%
6.3	316	5972	99.5	0.73	0.5%
5					
4					
3.15					
2.5					
2					
1.60					
1.25					
0.63					
0.315					
0.160					
0.080					

L'opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

ANALYSE GRANULOMÉTRIQUE DES GRANULATS

NF P 18- 560 Septembre 1990

Structure: UNITE D'OUARGLA
N° Dossier interne: 06/2018
Classe granulaire: 3/8
Prise d'essai: 3200g

Équipements utilisés : BALANCE

Lieu de travail: SALLE DE ROUTE
Date: 24/12/2018
Opérateur: Bencheikh

N° D'inventaire :

Tableau(A.2): ANALYSE GRANULOMÉTRIQUE DES GRANULATS *3/8*

Ouverture **Tamis**	Refus partiel	Refus cumulé	Pourcentage refus	Pourcentage passant	Observations
80					
63					
50					
40					
31.5					
25					
20					
16					
12.5					
10	0.00	0.00	0.00	100	100%
8	22	22	1	99	99%
6.3	515	537	17	83	83%
5	365	902	28	72	72%
4	938	1840	58	43	43%
2.5	1106	2946	92	8	8%
1.25	187	3133	98	2	2%
0.63	47	3180	99	1	1%
0.315					
0.160					
0.080					

L'opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

ÉQUIVALENT DE SABLE
NFP-18 598 Octobre 1991

Structure : D'OUARGLA
N° Dossier interne :
Équipements utilisés:

Lieu de Travail :…
Opérateur : Bencheikh
N° D'inventaire :

Date : 15/12/2018

Tableau (A-9): ÉQUIVALENT DE SABLE

Echantillon	…………….		……………..		……………….	
	Essai 1	Essai 2	Essai 1	Essai 2	Essai 1	Essai 2
Hauteur totale H1 (cm)	11.6	12.7				
Hauteur de sable H2 (cm)	8.1	6.7				
H2 ES = ------ x 100 H1	69.8	52.75				
ES moyen (%)	69.8					

L'Opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

MICRO DEVAL EN PRÉSENCE D'EAU

NFP-18 572 Décembre 1990

Structure : unité d'Ouargla
N° Dossier interne :
Échantillon : classe 8/15
Équipements utilisés : BALANCE

Lieu de travail : salle de route
Date : 29/12/2018
Opérateur :
N° D'inventaire :

Tableau (A-9):MICRO DEVAL EN PRÉSENCE D'EAU

Classe granulaire	Masse abrasive	Poids d'éléments > 1.6 mm m' (g)	Poids d'éléments < 1.6 mm m = M-m' (g)	MDE $=100 \cdot \frac{m}{M}$	Observations
10/14	500	444	56	11.2	

L'Opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

LOS ANGELES

NFP-18 573 Décembre 1990

Structure : UNITE D'OUARGLA
N° Dossier interne :
Échantillon : classe 8/15
Équipements utilisés : BALANCE

Lieu de travail : SALLE DE ROUTE
Date : 24/12/2018
Opérateur : Bencheikh
N° D'inventaire :

Tableau (A-10): LOS ANGELES

Classe granulaire	Nombre de boulets	Poids d'éléments > 1.6 mm m' (g)	Poids d'éléments < 1.6 mm m = M-m' (g)	LA $= 100 . \frac{m}{M}$	Observations
10/14	11	3740	1260	25	

L'Opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

MICRO DEVAL EN PRÉSENCE D'EAU

NFP-18 572 Décembre 1990

Structure : unité d'Ouargla
N° Dossier interne :
Échantillon : classe : 3/8
Équipements utilisés : BALANCE

Lieu de travail : salle de route
Date : 29/12/2018
Opérateur : Bencheikh
N° D'inventaire :

Tableau (A-11):MICRO DEVAL EN PRÉSENCE D'EAU

Classe granulaire	Masse abrasive	Poids d'éléments > 1.6 mm m' (g)	Poids d'éléments < 1.6 mm m = M-m' (g)	MDE = $100 . \frac{m}{M}$	Observations
4/6.3	500	449	51	10	

L'Opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

LOS ANGELES

NFP-18 573 Décembre 1990

Structure : UNITE D'OUARGLA
N° Dossier interne :
Échantillon : classe : 3/8
Équipements utilisés : BALANCE

Lieu de travail : SALLE DE ROUTE
Date : 24/12/2018
Opérateur : Bencheikh
N° D'inventaire :

Tableau (A-12): LOS ANGELES

Classe granulaire	Nombre de boulets	Poids d'éléments > 1.6 mm m' (g)	Poids d'éléments < 1.6 mm m = M-m' (g)	$LA = 100 . \frac{m}{M}$	Observations
4/6.3	7	3985	1015	20	

L'Opérateur

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LABORATOIRE DES TRAVAUX PUBLICS DU SUD

ANALYSE GRANULOMÉTRIQUE DES GRANULATS

NF P 18- 560 Septembre 1990

Structure: UNITE D'OUARGLA

N° Dossier interne:

Classe granulaire: SABLE 0/3

Prise d'essai: 1200g

Équipements utilisés :…………………………………..

Lieu de travail: SALLE D'INTIFICATION

Date: 24/12/2018

Opérateur: Bencheikh

N° D'inventaire :

Tableau(A.3): ANALYSE GRANULOMÉTRIQUE DES GRANULATS SABLE 0/3

Ouverture **Tamis**	Refus partiel	Refus cumulé	Pourcentage refus	Pourcentage passant	Observations
80					
63					
50					
40					
31.5					
25					
20					
16					
12.5					
10					
8					
6.3	0	0	0	100	100
5	0	0	0	100	100
4	13	13	1	99	99
2	197	210	18	83	83
1.25	221	431	36	64	64
0.63	188	619	52	48	48
0.5	34	653	54	46	46
0.4	47	700	58	42	42
0.2	129	829	69	31	31
0.080	243	1072	89	11	11

L'opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

MASSE VOLUMIQUE APPARENTE ET ABSOLUE

MODE OPÉRATOIRE COURS DE LABORATOIRE R.LANCHON

BTS.DUT

Structure : unité d'Ouargla

N° Dossier interne :

Échantillon : 3/8

Équipements utilisés : BALANCE

Lieu de travail : sale de route

Date : 30/12/2018

Opérateur : Bencheikh

N° D'inventaire :

Masse volumique apparente :

Volume du récipient V=5000
Poids P= 3836
P_1+T = 11410.1 P_1=7574.1
P_2+T= 11394.1 P_2=7558.1
P_3+T= 11337.7 P_3=7501.7
P_4+T= 11336.4 P_4=7500.4
Poids moyen M= $(P_1+P_2+P_3+P_4)/4$ =7533.575
Masse volumique apparente P/V =1.506

Masse volumique absolue :

Poids des agrégats secs P_1= 300g
Poids du récipient plein d'eau P_2=
P_3= P_1+P_2=790.3
Poids récipient + agrégats + eau= 675.5
P_4= 675.5
Volume des agrégats V=P_3-P_4=114.8

Masse volumique absolue P1/V =2.613

L'Opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

MASSE VOLUMIQUE APPARENTE ET ABSOLUE

MODE OPÉRATOIRE COURS DE LABORATOIRE R.LANCHON

BTS.DUT

Structure : unité d'Ouargla

N° Dossier interne :

Échantillon : 8/15

Équipements utilisés : balance

Lieu de travail : salle de route

Date :30/12/2018

Opérateur : Bencheikh

N° D'inventaire :

Masse volumique apparente :

Volume du récipient V=5000
Poids P=3836
P_1+T = 11152.5 P_1=7316.5
P_2+T= 11160 P_2=7324
P_3+T= 11121.3 P_3=7285.3
P_4+T= 11114 P_4=7278
Poids moyen $M=(P_1+P_2+P_3+P_4)/4$ =7300.95
Masse volumique apparente P/V =1.46

Masse volumique absolue :

Poids des agrégats secs P_1= 300g
Poids du récipient plein d'eau P_2= 490.3
$P_3= P_1+P_2$= 790.3
Poids récipient + agrégats + eau= 677.6
P_4= 677.6
Volume des agrégats $V=P_3-P_4$= 112.7

Masse volumique absolue P1/V = 2.661

L'Opérateur

Visa du responsable

LABORATOIRE DES TRAVAUX PUBLICS DU SUD

MASSE VOLUMIQUE APPARENTE ET ABSOLUE

MODE OPÉRATOIRE COURS DE LABORATOIRE R.LANCHON

BTS.DUT

Structure : unité d'Ouargla

N° Dossier interne :

Échantillon : sable de dune

Équipements utilisés : BALANCE

Lieu de travail : salle de route

Date : 30/12/2018

Opérateur : Bencheikh

N° D'inventaire :

Masse volumique apparente :

Volume du récipient V= 161.24
Poids P=53.38
P_1+T =305.63 P_1=252.25
P_2+T=305.50 P_2=252.12
P_3+T=305.03 P_3=251.65
P_4+T=305.99 P_4=252.61
Poids moyen M=(P_1+P_2+P_3+P_4)/4 =252.157
Masse volumique apparente P/V =1.563

Masse volumique absolue :

Poids des agrégats secs P_1=300
Poids du récipient plein d'eau P_2= 516.18
P_3= P_1+P_2=816.18g
Poids récipient + agrégats + eau= 698.87
P_4= 698.87
Volume des agrégats V=P_3-P_4= 117.31

Masse volumique absolue P1/V = 2.557

L'Opérateur

Visa du responsable

Annexes

CHARACTERIZATION OF THE VISCOELASTIC BEHAVIOR USING NDT TEST

Table B1 results of Sm and Eu:

Specimens	d (mm)	e(mm)	m(g)	$s(m^2)$	volume (m^3)	MVa (kg/m^3)	Vp	Vs	Sm(MPa)	Eu(MPa)
1	100.45	50.19	942.7	0.00793	0.000397907	2369.14575	4147.9	1992.7	**11622**	**25399**
2	100.55	47	874.4	0.00794	0.000373359	2341.98167	4434.0	2130.1	**13303**	**28690**
3	100.2	54.31	978.8	0.00789	0.00042843	2284.62048	4310.3	2070.7	**12201**	**26448**
4	100.3	52.69	847.4	0.00790	0.000416481	2034.6689	3560.1	1710.3	**7125**	**16069**
5	100.2	69.52	1248.5	0.00789	0.000548416	2276.55785	3737.6	1795.6	**12065**	**19817**
6	100.3	48.96	902.8	0.00790	0.000386997	2332.83287	4371.4	2100.0	**14029**	**27778**
7	99.83	48.11	878.4	0.00783	0.000376723	2331.68661	4334.2	2082.2	**14211**	**27294**
8	100.5	49.71	906.3	0.00794	0.000394494	2297.37264	4177.3	2006.8	**11059**	**24980**
9	99.96	49.5	913.1	0.00785	0.000388617	2349.61118	4500.0	2161.8	**11774**	**29647**

d: Diameter of the Specimen

e: Thickness of the Specimen

m: The Mass of the Specimen

S: Surface the Of Specimen

MVa: Density of Specimen

Sm: Stiffness Modulus by IT-CY

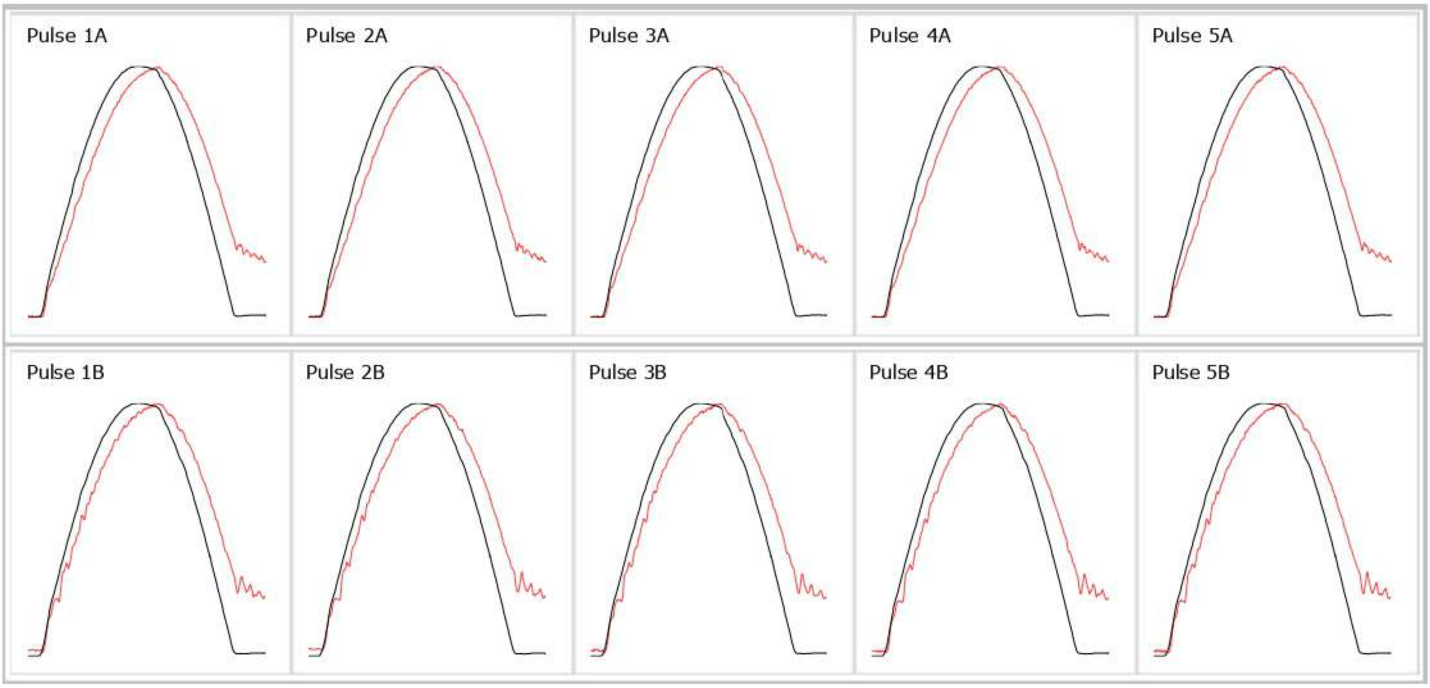
Eu: d Young Modulus By Ultrasonic

Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 16:12
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S1
Client Name	UKMO
Lab Address	LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	50

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	4.386	4.386	4.386	4.386	4.385	4.386	3.515	3.514	3.515	3.514	3.515	3.514	**3.950**
Horizontal Stress (kPa)	553.9	554.0	554.0	553.9	553.8	553.9	443.9	443.8	443.9	443.8	443.9	443.9	**498.9**
Load-Area Factor	0.64	0.65	0.64	0.64	0.64	0.64	0.64	0.64	0.65	0.65	0.65	0.65	**0.65**
Horizontal Deformation (um)	4.82	4.82	4.82	4.82	4.82	4.82	3.91	3.91	3.91	3.91	3.91	3.91	**4.36**
Load Rise Time (ms)	125	124	125	125	125	125	110	110	109	109	109	110	**117**
Measured Stiffness (MPa)	11319	11361	11327	11319	11298	11325	11214	11119	11181	11189	11200	11180	**11252**
Adjusted Stiffness Modulus (MPa)	11660	11749	11668	11660	11638	11675	11572	11475	11590	11599	11610	11569	**11622**

Data File: Taher 200 girations UKMO_2.tdms

Notes:
Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed

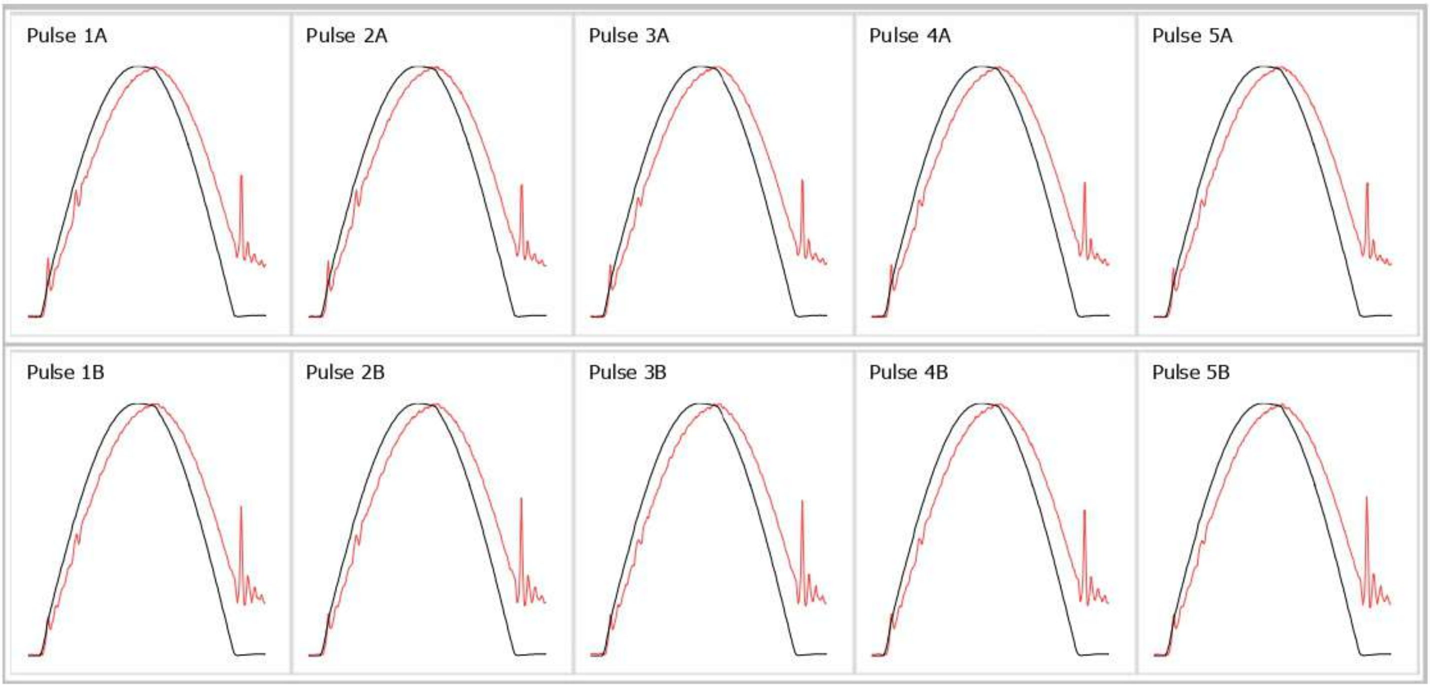
Date

Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 16:07
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S2
Client Name	UKMO
Lab Address	LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	50

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	4.772	4.774	4.774	4.774	4.774	4.774	4.790	4.791	4.790	4.790	4.789	4.790	**4.782**
Horizontal Stress (kPa)	602.8	602.9	602.9	602.9	603.0	602.9	605.0	605.1	605.0	604.9	604.9	605.0	**603.9**
Load-Area Factor	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	**0.64**
Horizontal Deformation (um)	4.68	4.68	4.68	4.68	4.68	4.68	4.71	4.71	4.71	4.71	4.71	4.71	**4.69**
Load Rise Time (ms)	124	124	124	124	124	124	123	123	123	123	123	123	**124**
Measured Stiffness (MPa)	12687	12682	12669	12635	12661	12667	12658	12648	12624	12656	12601	12637	**12652**
Adjusted Stiffness Modulus (MPa)	13071	13065	13052	13016	13042	13049	13039	13028	13004	13038	12979	13018	**13033**

Data File: Taher 200 girations UKMO_1.tdms

Notes: Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed

Date

cooper

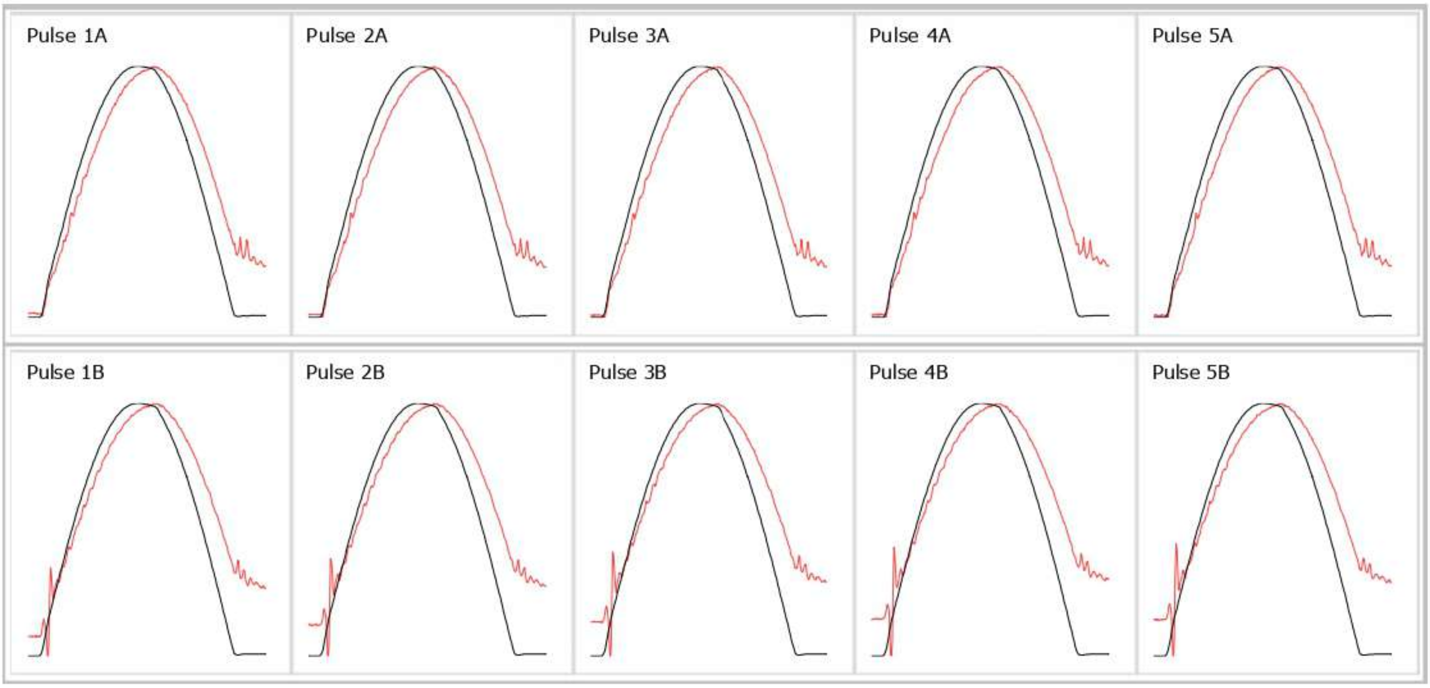
Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 14:43
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S3
Client Name	UKMO

Lab Address: LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	54

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	5.113	5.113	5.113	5.114	5.113	5.113	4.793	4.793	4.793	4.792	4.793	4.793	**4.953**
Horizontal Stress (kPa)	598.1	598.1	598.1	598.2	598.1	598.2	560.7	560.7	560.7	560.6	560.7	560.7	**579.4**
Load-Area Factor	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	**0.64**
Horizontal Deformation (um)	4.66	4.66	4.66	4.66	4.66	4.66	4.87	4.87	4.87	4.87	4.87	4.87	**4.76**
Load Rise Time (ms)	124	125	124	124	124	124	125	125	125	125	125	125	**125**
Measured Stiffness (MPa)	12617	12597	12627	12618	12593	12611	11323	11193	10994	10876	11013	11080	**11845**
Adjusted Stiffness Modulus (MPa)	12987	12994	12999	12989	12963	12986	11667	11533	11326	11204	11345	11415	**12201**

Data File: Taher Master Ukmo_2.tdms

Notes: Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed

Date

cooper

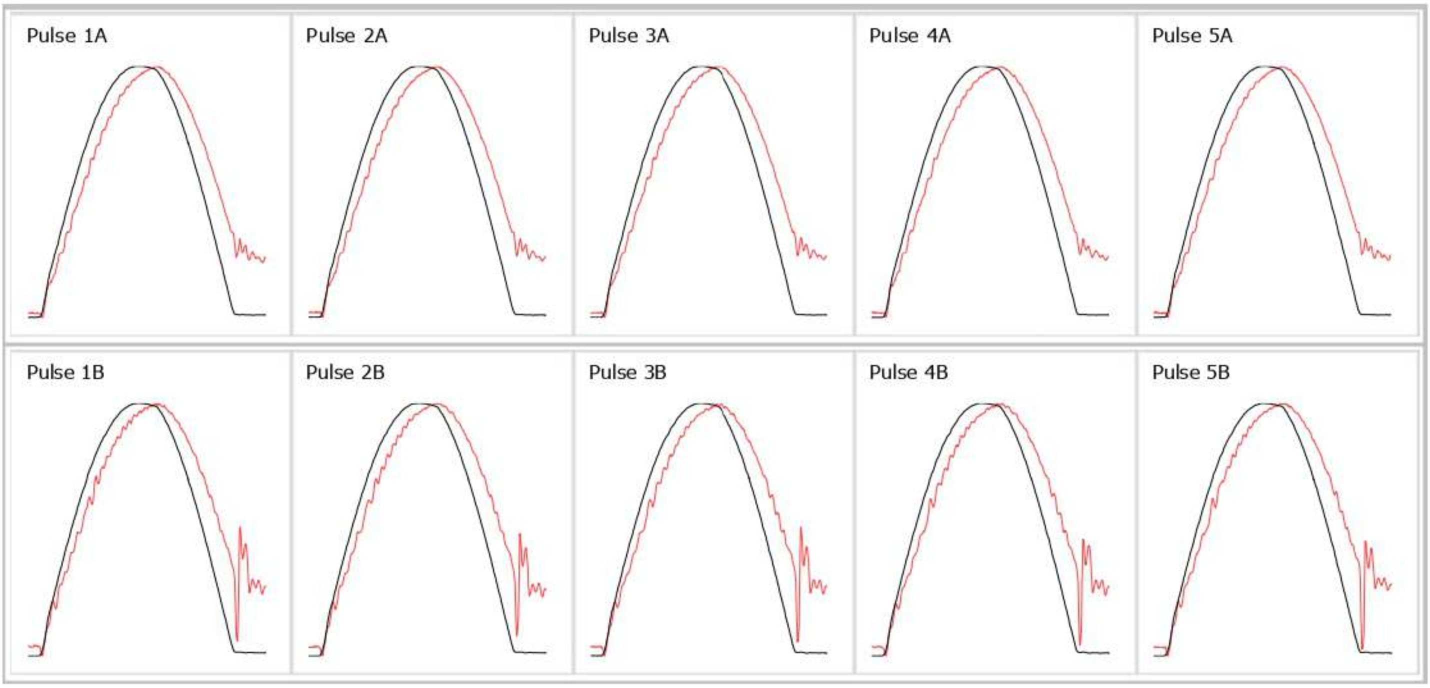
Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 14:31
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S4
Client Name	UKMO

Lab Address	LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	53

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	2.996	2.995	2.995	2.997	2.996	2.996	2.800	2.799	2.800	2.800	2.801	2.800	**2.898**
Horizontal Stress (kPa)	360.9	360.8	360.8	361.0	360.9	360.9	337.3	337.2	337.3	337.3	337.4	337.3	**349.1**
Load-Area Factor	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	**0.65**
Horizontal Deformation (um)	4.93	4.93	4.93	4.93	4.93	4.93	5.03	5.03	5.03	5.03	5.03	5.03	**4.98**
Load Rise Time (ms)	125	125	125	125	125	125	126	126	126	125	125	126	**125**
Measured Stiffness (MPa)	7236	7177	7177	7146	7133	7174	6621	6655	6594	6614	6550	6607	**6891**
Adjusted Stiffness Modulus (MPa)	7482	7421	7420	7388	7375	7417	6852	6889	6825	6833	6766	6833	**7125**

Data File: Taher Master Ukmo_1.tdms

Notes:
Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed:

Date:

cooper

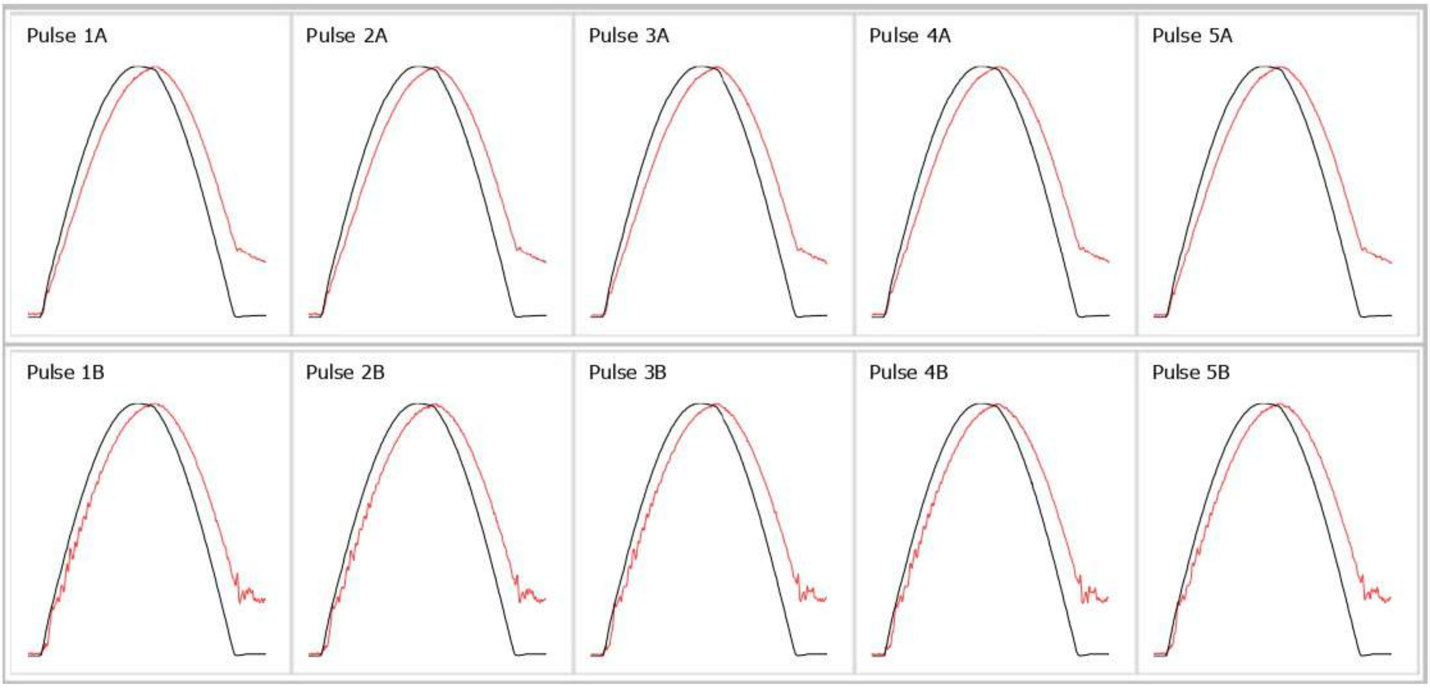
Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 14:51
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S5
Client Name	UKMO

Lab Address: LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	70

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	5.900	5.899	5.899	5.900	5.899	5.899	5.956	5.955	5.953	5.954	5.953	5.954	**5.927**
Horizontal Stress (kPa)	539.2	539.1	539.1	539.2	539.1	539.1	544.3	544.2	544.1	544.1	544.0	544.1	**541.6**
Load-Area Factor	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	**0.64**
Horizontal Deformation (um)	4.54	4.54	4.54	4.54	4.54	4.54	4.49	4.49	4.49	4.49	4.49	4.49	**4.52**
Load Rise Time (ms)	124	124	124	124	124	124	123	123	123	123	123	123	**123**
Measured Stiffness (MPa)	11661	11628	11648	11609	11638	11637	11892	11818	11805	11759	11725	11800	**11718**
Adjusted Stiffness Modulus (MPa)	12006	11973	11994	11953	11984	11982	12243	12167	12154	12106	12073	12149	**12065**

Data File: Taher Master Ukmo_3.tdms

Notes: Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed:

Date:

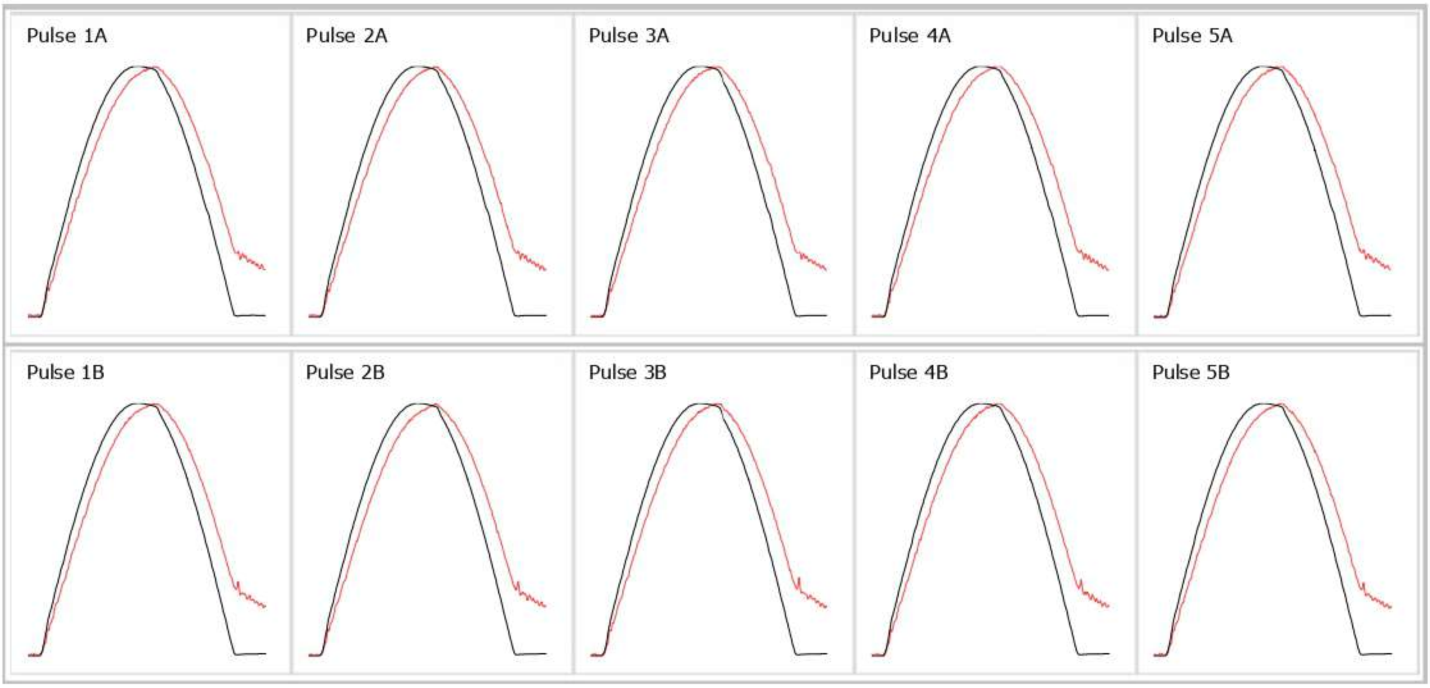
Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 15:52
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S6
Client Name	UKMO

Lab Address: LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	49

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	5.001	5.000	5.000	5.001	5.002	5.001	4.983	4.983	4.984	4.985	4.985	4.984	**4.993**
Horizontal Stress (kPa)	648.3	648.2	648.2	648.3	648.5	648.3	646.0	646.0	646.1	646.2	646.3	646.1	**647.2**
Load-Area Factor	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	**0.64**
Horizontal Deformation (um)	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	**4.67**
Load Rise Time (ms)	123	123	122	123	123	123	124	124	124	124	124	124	**123**
Measured Stiffness (MPa)	13646	13620	13678	13655	13649	13650	13605	13503	13610	13580	13554	13571	**13610**
Adjusted Stiffness Modulus (MPa)	14079	14052	14081	14087	14080	14076	14019	13912	14023	13989	13963	13981	**14029**

Data File: Taher 80 girationss_4.tdms

Notes: Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed

Date

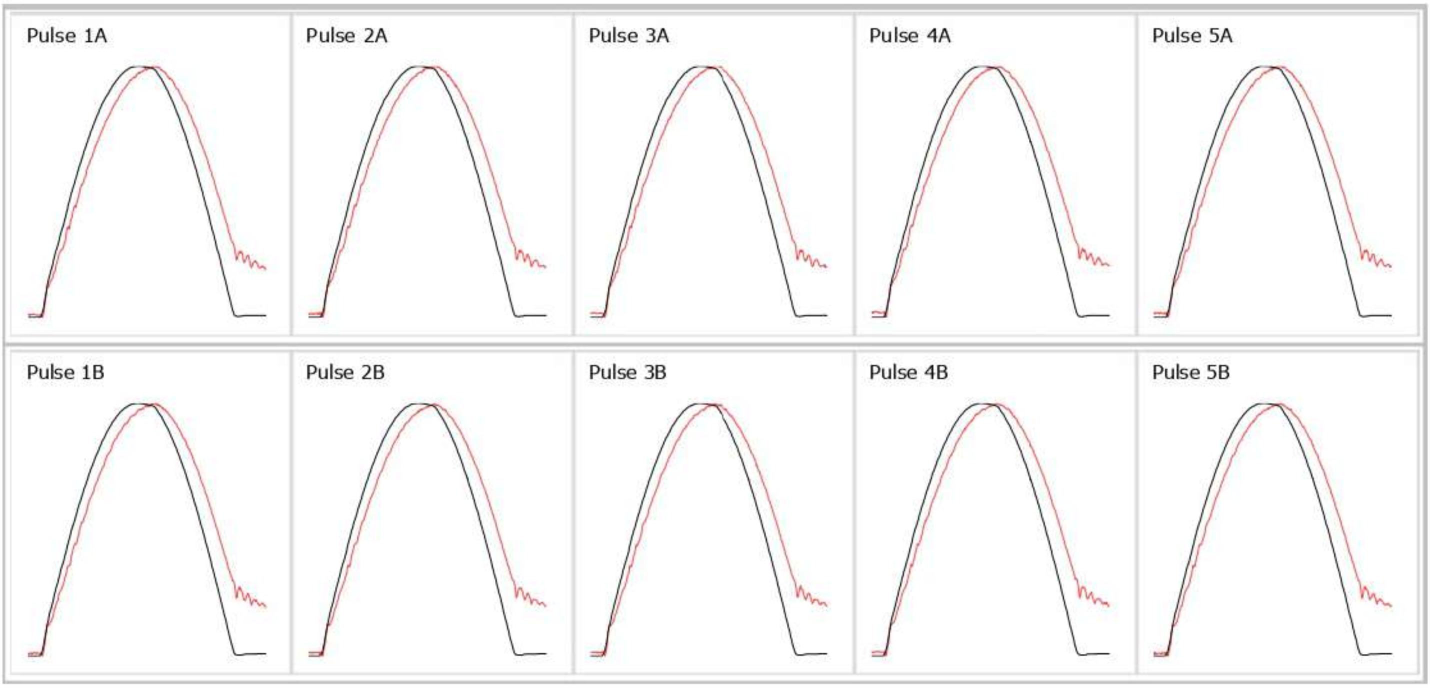
Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 15:37
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S7
Client Name	UKMO

Lab Address: LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	48

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	4.980	4.981	4.979	4.979	4.979	4.980	4.997	4.996	4.995	4.997	4.996	4.996	**4.988**
Horizontal Stress (kPa)	660.1	660.2	660.0	660.0	660.0	660.1	662.3	662.2	662.1	662.4	662.2	662.3	**661.2**
Load-Area Factor	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	**0.64**
Horizontal Deformation (um)	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	**4.68**
Load Rise Time (ms)	125	125	125	125	125	125	124	124	124	124	124	124	**124**
Measured Stiffness (MPa)	13814	13814	13775	13684	13719	13761	13859	13754	13764	13740	13792	13782	**13772**
Adjusted Stiffness Modulus (MPa)	14270	14271	14233	14136	14174	14217	14285	14177	14187	14163	14216	14206	**14211**

Data File: Taher 80 girationss_2.tdms

Notes:
Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed

Date

cooper

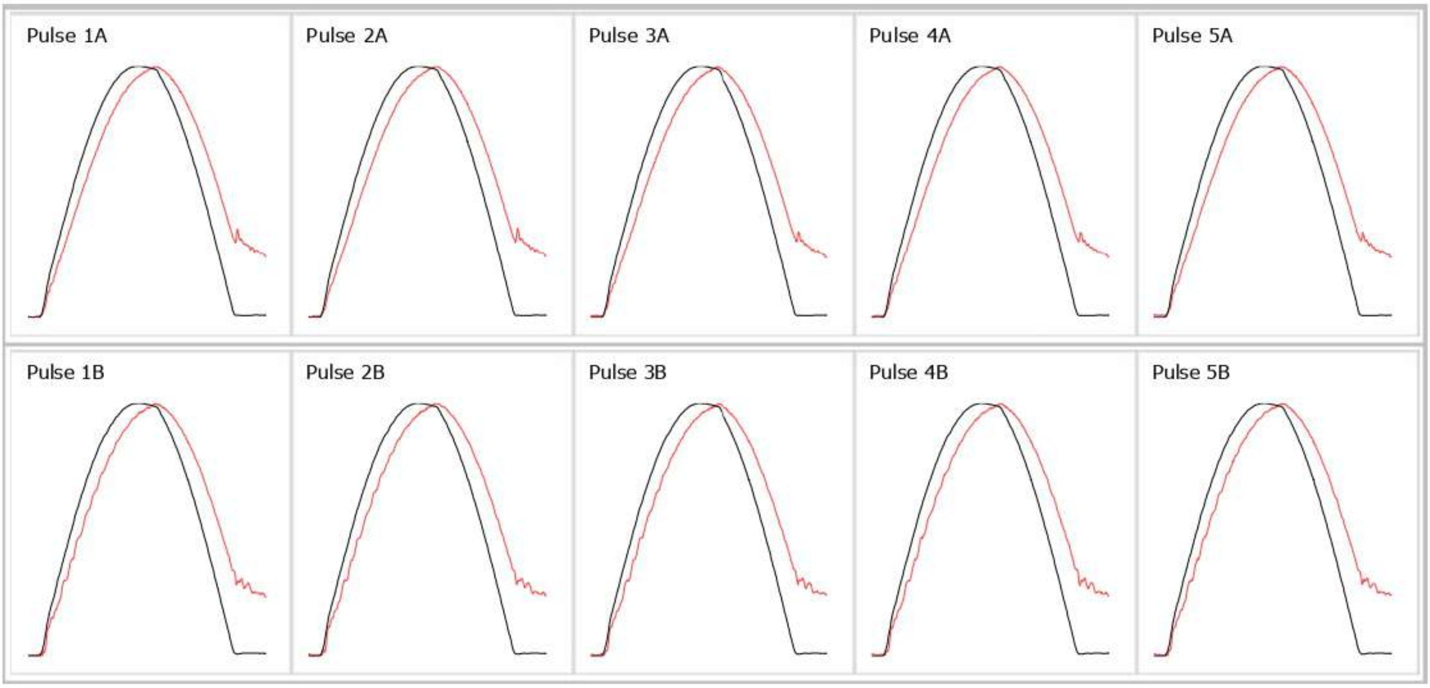
Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 15:04
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S8
Client Name	UKMO

Lab Address: LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	50

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	4.129	4.129	4.128	4.128	4.126	4.128	4.107	4.106	4.108	4.108	4.108	4.107	**4.118**
Horizontal Stress (kPa)	526.1	526.1	526.0	526.0	525.8	526.0	523.3	523.2	523.4	523.5	523.5	523.4	**524.7**
Load-Area Factor	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.64	0.65	0.65	**0.65**
Horizontal Deformation (um)	4.77	4.77	4.77	4.77	4.77	4.77	4.87	4.87	4.87	4.87	4.87	4.87	**4.82**
Load Rise Time (ms)	124	124	124	124	124	124	124	124	124	125	124	124	**124**
Measured Stiffness (MPa)	10878	10871	10796	10797	10784	10825	10601	10574	10544	10555	10548	10564	**10695**
Adjusted Stiffness Modulus (MPa)	11246	11238	11161	11163	11152	11192	10973	10945	10913	10880	10917	10925	**11059**

Data File: Taher Master Ukmo 80 girationss_1.tdms

Notes: Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed:

Date:

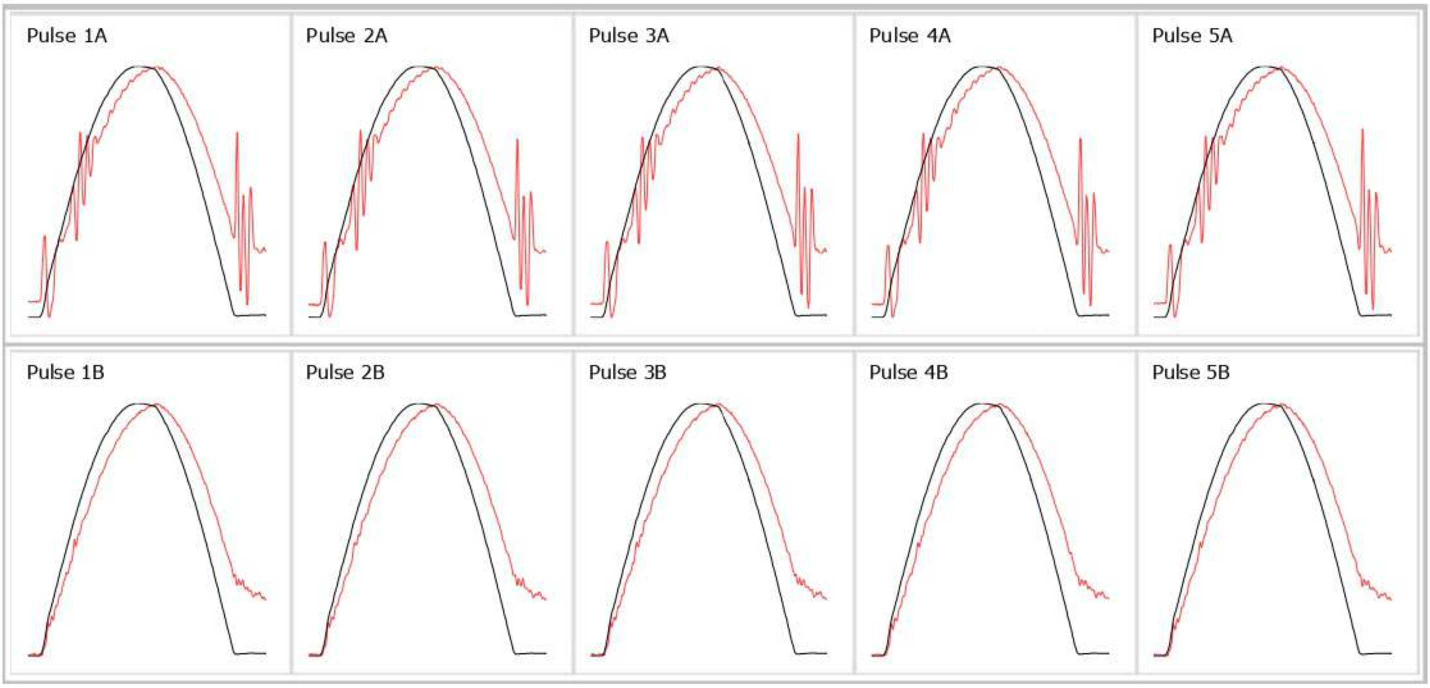
cooper

Stiffness Modulus: EN 12697-26: Annex C. April 2005

Date of Test	27 Mar 2019 @ 15:23
Report Number	Taher Master / 2019
Operator	User
Specimen ID	Taher Master Ukmo S9
Client Name	UKMO
Lab Address	LTP Sud

Test Temperature (°)	15
Bulk Density (kg/m3)	0
Diameter (mm)	100
Thickness (mm)	50

Conditioning Pulses	10
Poissons Ratio	0.35
A & B Target Rise Time (ms)	124
A & B Target Deformation (um)	5



Test Results

	1A	2A	3A	4A	5A	Mean A	1B	2B	3B	4B	5B	Mean B	**Mean A&B**
Load Peak to Peak (kN)	4.216	4.216	4.217	4.217	4.217	4.217	4.438	4.438	4.438	4.437	4.437	4.438	**4.327**
Horizontal Stress (kPa)	537.3	537.3	537.4	537.4	537.3	537.4	565.5	565.6	565.5	565.4	565.3	565.5	**551.4**
Load-Area Factor	0.65	0.64	0.64	0.64	0.64	0.65	0.64	0.64	0.64	0.64	0.64	0.64	**0.64**
Horizontal Deformation (um)	4.73	4.73	4.73	4.73	4.73	4.73	4.79	4.79	4.79	4.79	4.79	4.79	**4.76**
Load Rise Time (ms)	124	125	125	125	125	125	125	125	125	125	125	125	**125**
Measured Stiffness (MPa)	11197	11253	11159	11233	11120	11193	11637	11623	11580	11628	11640	11622	**11407**
Adjusted Stiffness Modulus (MPa)	11598	11611	11511	11587	11472	11556	12008	11992	11949	12000	12013	11992	**11774**

Data File: Taher Master Ukmo 80 girationss_3.tdms

Notes:
Record details about the specimen in this area:
Bulk Density:
Poisson's Ratio:
Description of asphaltic material:
How it was mixed:
How it was compacted:
How bulk density was determined:
How the specimen was stored:

Signed:

Date:

cooper

ملخص:

ترمي هذه الدراسة التجريبية إلى محاولة تقييم معامل الصلادة للخرسانة الزفتية المستعملة في طبقة السير عن طريق استعمال جهاز قادر على إنتاج موجات الفوق الصوتية، والمستعمل عادة في الخرسانة الهيدروليكية، مستندين في ذلك على سرعة إخراق الموجة الصوتية للمادة الإسفلتية (Vp) مستعملا الوضعية المباشرة، والذي تعتبر السند الأساسي في حساب معامل الصلادة في حالتين كل على حدة، كل حالة تمثل فرضية لسلوك المادة:

الأولى باعتبار الخرسانة الزفتية مادة مرنه والحالة الثانية هي باعتبار الخاصية الاصلية للمادة وهي لزجة-مرنه .

لهذا الغرض، تم قياس معامل الصلادة بالطريقة الميكانيكية على بتردد 10 هرتز وعلى درجة حرارة 15 درجة المئوية، وحسابه بالموجات الفوق صوتية في نفس درجة الحرارة وعلى تردد 54 kHz.

ولهذا السبب كل هذه القياسات والتجارب هي بغرض معرفة العوامل المؤثر على سرعة اختراق الموجات الفوق الصوتية للمواد الإسفلتية، وكذا استخدام القوانين الفيزيائية وعملية التحويل فوري السريع للموجات الصوتية، وذالك لتقدير قيمة معامل يونج بواسطة العلاقة بينه وبين معامل الصلادة المقاس باستخدام طريقة جهاز نوتنغهام من اجل تحقيق معادلة لحساب أو تقديره بالجهاز الفوق صوتي و هو ما تحصلنا عليه في النهاية.

الكلمات المفتاحية: اختبار فوق صوتي، أمواج صوتية، الاختبارات غير مدمرة، الخرسانة الأسفلتية، معامل الصلادة، ترر د، صوت

Abstract:

This experimental study aims to attempt an estimated value of the stiffness modulus in asphalt concrete that used in the surface course using an ultrasonic device, which commonly used in the hydraulic concrete, usually based on the velocity of pulse wave (Vp) passed through the asphalt concrete using the direct method, which is basics to calculate modulus in two case individually, each one represented an hypothesis for the material behaviours:

The first one consider the asphalt concrete as an elastic materials, and the second consider the asphalt concrete as viscoelastic materials.

Therefore, both the mechanical and ultrasonic test realised at the temperature 15°C, at sound frequency 54 kHz for ultrasound test, and 10 Hz for tests of indirect tensile test at cylindrical specimen.

And for that reason, all this measurement, and tests are studies for the parameters effects on the transmission of sound in the asphalt concrete, and using sound physics laws and parameters and the FFT transmission of the sound wave to estimate young modulus and determine its correlation between it and with the one measured using Nottingham Asphalt Tester (NAT) to achieve an equation for calculated and estimate the stiffness using the ultrasonic device which is the one we got in the end.

Keywords: Ultrasonic Test, Wave sound, NDT, Asphalt concrete, stiffness, modulus, frequency, sound, IT-CY, NAT,

Résumé:

Cette étude expérimentale vise à évaluer le module de rigidité du béton bitumineux utilisé dans la couche de surface en utilisant le dispositif de ultrasons, couramment utilisé dans le béton hydraulique, habituellement basé sur la mesure de la vitesse des ondes de pulse (Vp) passer à travers le béton bitumineux à l'aide de la méthode transmission directe, ce qui la base pour calculer le module de Young en deux cas individuellement, chaque cas base sur un hypothèse de comportement de matériaux:

La première considère le béton bitumineux est un matériau élastique et la deuxième considère la propriété le béton bitumineux un matériau viscoélastique.

Par conséquent, toutes les essais mécaniques et ultrasoniques ont été étudiées à la température 15°, avec une fréquence sonique de 54 kHz pour les expériences ultrasons, et 10 kHz pour les essais de traction indirecte sur éprouvettes cylindriques.

Pour cette raison, toutes ces mesures et essais au but d'étudier les facteurs qui influent sur la vitesse de transmission de sons dans l'enrobés, l'utilisation des lois physiques et la transformation de Fourier rapide des ondes sons pour estimer la valeur du module de Young et détermine la corrélation entre celui-ci et le module mesuré selon l'appareil Nottingham Asphalt Tester (NAT) afin d'obtenir une équation permettant de calculer le module de rigidité par le dispositif à ultrasons, ce qui le cas de cette étude.

Mots clés: NAT, béton bitumineux, fréquence, ultrasons ; ondes, module de Young, sons.